Soil survey investigations for irrigation

FAO
SOILS
BULLETIN
42

FOOD
AND
AGRICULTURE
ORGANIZATION
OF THE
UNITED NATIONS

FOREWORD

The pressing need for increased agricultural production in the years ahead can only be met by more efficient use of our land and water resources including more widespread and better irrigation in those regions where rainfall is inadequate. It has been estimated that some 92 million hectares of land are irrigated in the developing countries, of which half urgently need improvement, and that irrigation of an addition 22 million hectares is projected by 1990. Production gains will be shortlived unless the attendant hazards of salinization, waterlogging and lowered fertility are kept in check by effective planning and management based on a thorough understanding of the soil conditions.

Soil survey and land classification are generally accepted essential preliminaries to investment in irrigation development. The classical techniques developed in temperate regions for rainfed agriculture may be less suitable for assessing the potential for irrigation in tropical and arid regions. This publication aims to describe the special requirements of soil survey for irrigation development, and assumes that the reader is familiar with basic soil science and soil survey techniques. It does not deal with other aspects of soil studies such as soil conservation or soil fertility maintenance on irrigated lands.

No book can substitute for experience gained in the field but this one attempts to highlight soil characteristics which are significant under irrigation and to suggest ways of recognizing and mapping them. The opening chapter emphasizes the breadth of considerations for evaluating land for irrigation and the role of the soil surveyor in the required team of specialists. The next two chapters discuss the significant characteristics of soils and topography. Chapter Four describes the assessment of drainage and reclamation and Chapter Five water quality and climate. Chapter Six describes field methods of soil survey and Chapter Seven interpretation of the data and land evaluation for different conditions. The appendices give examples of land classification and specifications for various environments and procedures for measurement of permeability and infiltration rates.

Acknowledgment is due to the Bureau of Reclamation of the U.S. Department of the Interior for its generous help in the preparation of this document.

Appreciation is also expressed for the contributions made by several authors. Preliminary drafts were prepared by Dr. Claude L. Fly and Ir. W.F. van Beers and consolidated by Dr. R.B. Miller. Within the Bureau of Reclamation the principal contributors were Mr. Harold Parkinson and Mr. William B. Peters, under the leadership of the late Dr. John T. Maletic. Within FAO, the document has been the responsibility of the Soil Resources Development and Conservation Service of the Land and Water Development Division, and in particular of Mr. A.J. Smyth who largely contributed those sections for which FAO was responsible and edited the draft edition issued in 1974. Acknowledgment is due to those who sent valuable comments on that draft, which have been utilized by Mr. M.F. Purnell and Mr. A. Ashby when editing the present issue.

In preparing this document the aim has been to present guidance that is as factual and unambiguous as possible. Other recent FAO publications dealing with crop water requirements, water quality, drainage testing, salinity and alkalinity and land evaluation, have obviated the need for much detailed consideration in this document. Nevertheless, there are sections in which the advice is less clear cut than the authors would wish and FAO would welcome comments and suggestions which may serve to improve future publications on this subject.

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CHAPTER 1

GENERAL CONSIDERATIONS

1.1 INTRODUCTION

Survey investigations to determine the suitability of land for irrigation are beyond the ability of one individual and require the cooperative effort of a team of specialists. This Chapter examines the purpose and nature of the soil surveyor's contribution to the work of such a team and considers certain aspects peculiar to soil surveys.

1.2 ROLE OF THE SOIL SURVEY IN IRRIGATION INVESTIGATIONS

1.2.1 The Need for Soil Surveys

Knowledge of the soils within a potential irrigation area is essential for economic and technical reasons. The high cost of development of irrigated agriculture requires justification by assessment of the risks and benefits, and the design of the irrigation scheme itself is dependent on detailed knowledge of soils lying within the irrigable area.

Storie (1964) listed the following principal uses and reasons for soil studies in irrigation investigations:

i. to ensure selection of soils for irrigation that are productive;

ii. to aid in the location of canals and other irrigation works;

iii. to determine irrigation needs of specific soil types;

iv. to determine drainage needs of specific soil types;

v. to determine alkali reclamation needs;

vi. to determine overall land levelling needs;

vii. to determine erosion control needs;

viii. to help in determining the size of farms;

ix. to aid in appraising land value in order to allocate the costs of development on the basis of ability to pay;

x. to aid in determining crops suitable for particular soils;

xi. as an aid in devising individual farm management needs, such as use of fertilizers, use of soil amendments, subsoiling, safe land levelling, type of irrigation and/or drainage, etc.

Data from soil surveys are valuable, but usually insufficient alone, for meeting the foregoing requirements.

The classification of land suitability for irrigation can be approached in one of two ways:

a. by carrying out a systematic soil survey, the findings of which are interpreted in the light of other physical, social and economic factors;

b. by mapping the interpretative land units directly without preliminary soil survey, but having considered all pertinent environmental factors.

The second approach can save time and money, but is acceptable only when enough is known of the nature of the planned development, the crops and management practices, and of the soil characteristics to permit the selection of soil diagnostic criteria. The applicability of the data is, however, strictly limited to the specific purpose and conditions in mind.

The first approach, that of conducting a systematic soil survey, leads to the mapping of individual soil bodies which can be used in the planning of many different forms of land use and management practices. Basic data of this nature are of particular value in developing countries where it is not always possible to make an early prediction of the most desirable form of land use. They are also of great service in selecting representative areas for pilot projects from which quantitative agronomic and economic data can be obtained for purposes of assessment and planning.

Other advantages accruing from a separate soil survey include:

1) the development of a working legend which limits subjective decisions, ensures uniformity, and can be used again in adjacent areas;

2) the provision of suitable soil data for correlating soil conditions within the project area with soils elsewhere whose potential is known;

3) recognition of the manner in which important soil properties change across the survey area in relation to other environmental factors, including perhaps performance of existing crops, so permitting the logical siting of special investigations;

4) identification of areas of soil likely to present management problems.

FAO therefore strongly recommends that a systematic soil survey to distinguish and characterize soils in terms of all important surface and subsurface characteristics should form part of irrigation investigations.

1.2.2 The Concepts of 'Soil' and 'Land'

In order to clarify the contribution of the soil surveyor in evaluating land for irrigation, the conceptual differences between soil and land should be understood.

No single definition of soil will satisfy everyone (Simonson 1968; US Soil Survey Staff 1951, 1960), but the following is offered so that the soil surveyor can identify those properties of the environment which it is his duty to distinguish, characterize, interpret and map.

> "A soil is a three-dimensional body occupying the uppermost part of the earth's crust and having properties differing from the underlying rock material as a result of interactions between climate, living organisms, parent material and relief and which is distinguished from other 'soils' in terms of differences in internal characteristics and/or in terms of the gradient, slope-complexity, microtopography, stoni-

ness and rockiness of its surface" (Smyth 1972, adapted and developed from U.S. Soil Survey Staff, 1960. "Soil Classification: 7th Approximation", USDA Washington).

'Land' is a broader concept, even more difficult to define briefly yet precisely. The following definition, also drafted from the surveyor's viewpoint, is offered to clarify discussion:

"A tract of land is defined geographically as a specific area of the earth's surface; its characteristics embrace all reasonably stable, or predictably cyclic, attributes of the biosphere vertically above and below this area including those of the atmosphere, the soil and the underlying geology, the hydrology, the plant and animal populations and the results of past and present human activity, to the extent that these attributes exert a significant influence on present and future uses of the land by man" (Smyth 1972, adapted from Christian (1963) quoted in Christian and Stewart 1968).

Soil is of special importance to the land classifier. For mapping purposes it is among the most stable attributes of land and yet flexible in its response to man and offering the possibility of improvement, so giving purpose to land classification (Vink 1960). Although the concept of soil embraces many surface and subsurface characteristics, a soil survey normally includes study of additional criteria used to define the concept of land. Interpretation of the data in terms of potential land use must be related to specific socio-economic conditions; therefore cooperation with other specialists is required.

1.2.3 The Soil Surveyor's Contributions to a Team Approach

From the outset, the soil surveyor must at all times work closely with numerous other specialists of whom not all are permanent members of the team. **Their advice will be needed as indeed will his.**

i. Geographical distribution of physical constraints

The surveyor's first responsibility is to identify significant differences within the soil body so as to enable him to demarcate those areas which for all practical purposes are uniform. In deciding which differences are significant for the purpose of the survey, he may find that some factors affecting the best choice of soil mapping criteria may be beyond his scope to assess and require consultation, e.g. water quality, hydrology, drainage possibilities or soil requirements of chosen crops.

Surface and subsurface differences in the soils require to be identified and mapped as these may often affect differences in land development costs to be taken into consideration at the land classification stage. Evidence of erosion or deposition and knowledge of the frequency of flooding are additional factors which influence soil potential and shall therefore be recorded on soil maps. In deciding whether a certain surface characteristic should be mapped and if so what ranges of its expression should be distinguished at a given intensity of survey, it is impossible to avoid an element of interpretation, and in detailed maps the phases should be those which distinguish lands on which different management practices or even different uses will be required.

General land form (topography) as distinct from minor surface irregularities (microtopography) is not a soil characteristic although it may be used in low intensity mapping for distinguishing areas having broadly different kinds of soil. In the detailed studies, significant changes in land form are often associated with changes in drainage or surface slope, and these should be indicated by soil or slope phase boundaries on the soil maps. Land forms require careful study since they exert a controlling influence on the shape and size of areas with uniform possibilities for development.

Changes in vegetation should be noted but would only be included in soil maps if they had clearly induced changes in the internal characteristics of the soils. They would be mapped separately if they were of practical importance in land classification, as they would be in relation to the cost of clearing. Local variations in climate likely to **influence** productivity or management, e.g. air drainage, would also need recording for land classification purposes.

Inevitably there is some overlapping of activities of the soil surveyor, drainage enginner, hydrologist and geologist in the matter of establishing and evaluating distinctions in the drainage characteristics of different lands, as an integrated prediction of moisture regimes and movements after irrigation is required. While it is not possible to define the depth below the surface to which the soil surveyor's observations should extend, the level would certainly be deeper where irrigation rather than rainfed agriculture is foreseen. The throughness of subsoil investigations must not be sacrified to cost and availability of time or drilling equipment, since failure to detect the presence of impermeable layers or a rising water table would have very costly consequences.

The main soil units shown on the map indicate areas of uniformity with respect to the diagnostic criteria chosen for the internal characteristics of the soil which, in turn reflect important differences in the underlaying geology and water regime. Phases of these main soil units are also mapped to distinguish features of practical importance in using the soils, e.g. surface characteristics.

Since the size and distribution of land units corresponds closely to their physical characteristics, their boundaries usually coincide with boundaries on the soil map. Not all the latter, however, appear on the land classification map because some soil units with similar productive capacities in relation to development cost may be combined. Sometimes at the land classification stage additional boundaries may have to be inserted, e.g. land that is too high to be irrigable or with different clearing costs.

It is important that the data in maps and reports should provide answers to foreseeable questions relating to the soils and other observed features of the project area.

ii. Interpretation of physical constraints

The second main responsibility of the soil surveyor is to interpret the significance of the constraints he has mapped in terms of different combinations of irrigation methods, kinds of crop and methods of management which seem to be physically, socially and economically relevant. This first qualitative interpretation of the survey data enables the most promising kinds of land use to be identified and which will become the subject of quantitative land classification leading to investment and actual development.

In this essentially cooperative multidisciplinary task, the services of the soil surveyor will be required, for example, in connection with the variation to be expected within areas mapped of necessity as homogeneous, and in connection with estimating costs of moving safe amounts of soil in land levelling operations. Similarly when cost and yield estimates are being prepared, data may have to be drawn from distant places, and the soil surveyor must assist by ensuring that the environments are truly similar.

1.3 SPECIAL FEATURES OF SOIL SURVEY FOR IRRIGABILITY ASSESSMENT

1.3.1 General

The assessment of soil capability usually involves prediction of their properties and behaviour under some future system of management. The changes associated with the introduction of irrigation are generally much greater than those under rainfed agriculture, and accurate prediction requires a correspondingly wider and sounder knowledge of the soils and substrata. The criteria used to differentiate soil mapping units and the emphasis placed on each therefore differ in the two cases.

1.3.2 Changes Associated with the Introduction of Irrigation

Changes in the environment and in soils are brought about by changes in the soil/water regime, vegetation and by land forming and other management practices associated with efficient irrigation. Although it is difficult to predict them even qualitatively, the general trend of the changes should be assessed.

i. Land forming

Immediate and profound changes follow land clearing, land conditioning, land levelling and the construction of facilities for irrigation, drainage and soil conservation. Prior to interpretative land classification, the soil surveyor in consultation with other specialists should decide what operations are desirable and safe for each soil unit. Predicted behaviour and productivity should be based on their expected subsequent characteristics.

ii. Alteration of physical/chemical processes

Drainage must be provided whenever there is a risk of induced waterlogging and it may be required with any irrigation scheme. Coupled with the periodic addition of water, it usually results in a substantial net increase in the volume, rate and frequency of downward water movement in the soil **which** is one of the most potent soil forming factors.

Changes in the water regime bring about numerous changes in the physical and chemical characteristics of the soil, the distribution of salts, the biological population and the ease of water movement in the soil (Maletic 1967). Their effect upon plant growth may be favourable or adverse, depending on the quantity and quality of the irrigation water, efficiency of the drainage system and the balance between water entering the soil from all sources and that leaving by evapotranspiration and drainage. Salinity is closely related to quantity of irrigation water, efficiency of drainage and height of water table, and the soil surveyor and his colleagues must seek to predict the salt balance or salt distribution under irrigation.

With the introduction of irrigation the soil assumes the status of a parent material subjected to new, more active soil forming processes which, in time, will produce a very different soil. The potential impact of these changes on crop productivity must be recognized.

iii. Alteration of microclimate

Dry soils become cooler with irrigation and wet soils become warmer with drainage, while the moist atmosphere surrounding an irrigated crop serves as a protection from extremes of temperature.

iv. Alteration of biological processes

Increased plant growth resulting from the introduction of irrigation, and usually new inputs and improved techniques, leads to an increased supply of residues, particularly roots, to the soil. The very rapid increase in the biological and microbiological organisms and concurrent breakdown and incorporation of organic matter have a marked effect on topsoil structure and soil fertility.

1.3.3 Special Investigations Required for Irrigation Planning

i. Characteristics of the soil surface

Characteristics of the soil surface which require special study include general land form, slope, microtopography, air drainage, flooding, evidence of erosion/deposition and surface rockiness or stoniness. Their expression has an important bearing on the feasibility of irrigation, the nature and size of problems associated with bringing and distributing water, methods of irrigation and design of irrigation works. Assessment of the hazards of erosion after irrigation has been introduced, and necessary safeguards, is also required.

ii. Characteristics of the solum (the soil proper)

In contrast to surveys of rainfed areas, the capacity of the soil to accept, transmit or retain relatively large amounts of water in a relatively short time should be measured for each soil mapping unit of significant area. The surface infiltration rates and the ease of water movement through unsaturated and through saturated soil layers (hydraulic conductivity) need to be measured quantitatively. Such measurements should be replicated in the field using water of the same quality as will be available for irrigation to ensure that they are representative. Laboratory determinations serve to confirm the field data and are valuable in predicting the effect of changing conditions on soil properties.

The amount, kind and distribution of clay minerals are specially important in relation to water movement, retention and availability of plants, and hence the required frequency and volume of irrigations. In addition to laboratory determinations of soil moisture content and moisture release at different tension values, field tests are required to determine the amount of water held 48-72 hours after a thorough wetting. Studies of cracking and structural changes under differing moisture conditions may reveal a need for special management practices to reduce surface sealing or a need for pre-wetting (pre-irrigation) of deeply cracking clays. The nature of the clay-sized particles may also have an important bearing on the quality of the irrigation water that can be safely used. Special attention should be given to the nature and distribution of soluble salts and to the content of adsorbed sodium in addition to the normal investigations on the exchange complex.

iii. Characteristics of the soil and substrata

The escape of excess water and the possibility of lacking soluble salts are dependent on the permeability of layers below the soil. For sound evaluation of the drainage characteristics, investigations are recommended to a minimum depth of 3 m and occasionally more. Within these depths, impermeable and slowly permeable layers or transitions between layers of contrasting grain size which will impede vertical water movement must be identified. Salinity of these layers must be investigated because of the risk of water rising through capillarity or a rising groundwater table, and also to provide a basis for predicting the influence of drainage flows on downstream water quality.

iv. Characteristics for paddy rice

If it is proposed that the use of the land to be irrigated is for rice, the special requirements of this crop must be considered. Chief among the physical requirements is the capacity to maintain water on the surface. The infiltration rate and permeability must be determined and, where rice is already grown, the extent to which puddling and the development of a subsurface impermeable layer, not only helps to maintain surface water but also, in some cases, provides a firm base permitting tillage and weeding. Destruction of such impermeable layers by levelling and construction of bunds can be harmful, though in some cases it is desirable to break them up in order to deepen the surface rooting layers. The chemistry of paddy soils is also different from that of well drained crops. The pH commonly varies seasonally, solubility of some elements is affected sometimes giving rise to toxicities and imbalances, and changes develop in texture, structure and mineral nutrient status (see section **2.3.4 iv).** The literature on paddy soils should be consulted for details (e.g. Brinkman 1977; Matsuo et al. 1976). If dryland crops are to be grown in rotation with the rice, the likely rise and fall of the water table, the water holding capacity and the drying period of the soil are **particularly** important.

1.3.4 Shortcomings to Avoid in Soil Surveys

The most usual causes of failure to provide the information needed for land classification for irrigation can be summarized from the preceding sections as follows:

- an unwise decision on the required intensity of the survey and/or an unsuitable selection of differentiating criteria for soil mapping units, so making adequate interpretation impossible;

- inadequate recognition of the changes that will result from irrigation or drainage;

- inadequate attention to specific soil characteristics, particularly those associated with soil/moisture relationships or related to differences in potential cost of land development;

- sampling to inadequate depths;

- failure to establish the required parameters of the survey in consultation with other specialists;

- failure to interpret the soil survey findings in terms easily understood by other specialists.

They emphasize the need for the careful organization of the survey and its integration with the work of other members of the development team.

1.4 PLANNING AND ORGANIZING SURVEYS

1.4.1 Planning the General Approach

Surveys of high intensity as required for final development planning are costly in time and money and should be restricted to areas of proven high potential. As much of the cost may be incurred in the assembly of staff and equipment at the site, it may be desirable to anticipate a later extension of the irrigation project area, if elevation and other criteria so permit, by taking into the survey additional neighbouring land.

Detailed study should be given to areas with specific development possibilities identified by preliminary surveys which may be undertaken in two or more stages. The first, reconnaissance survey, at a scale smaller than 1:100 000 identifies areas showing development promise which in the second, medium intensity, detailed reconnaissance, pre-investment survey, are mapped at scales of 1;50 000 to 1:100 000 so identifying specific areas with development possibilities. For investment feasibility studies of large projects (over 10 000 ha) medium to high intensity surveys (1:25 000 or 1:20 000) may be economic, while actual irrigation development usually requires high to very high intensity (map scales from 1:20 000 to 1:5 000). For smaller areas time and money can be saved by proceeding directly from medium to high intensity.

The inter-dependence of the soil surveyor and other specialists of the team requires that the survey should start early, but with provision for the appointment of consultants to assist the surveyor as the need arises pending the arrival of other team members. He should remain with the team at least until the physical and economic basis of land classification has been firmly established and all major relevant problems have been solved.

The team leader must be a strong and competent administrator, and an able scientist in his own field with a sound knowledge of the other disciplines involved.

An integrated survey raises the problem of obtaining agreement on the findings and especially on the emphasis of recommendations. These difficulties can be reduced by frequent team meetings for report and discussion before final conclusions are drawn.

The staged approach in which soil classification is developed by successive approximations in surveys of increasing intensity makes progressively greater demands for specialists covering a wider range of disciplines. The speed and timing of the work of each is dependent on that of his colleagues and, preferably, they should work at their most efficient pace as individuals, or in small groups in closely related fields.

1.4.2 Stages Leading to Land Classification

Required soil survey procedures are described in some detail in Chapter Six. Here, only a summary is given of the main lines of work involved at each stage of a systematically organized soil survey.

i. Advance planning

The overall aims of proposed irrigation investigations involving soil survey must be defined in advance as precisely as possible. The nature of these aims will decide the probably minimum area of planning interest (see discussion of survey intensity in Chapter Six, Section 6.2) and thus the required scale of soil and land classification maps. A decision on mapping scale, viewed in the light of experience in comparable surveys and the available knowledge of soil and geological conditions, provides the only basis for estimating soil survey requirements in terms of staff, time and budget. In making these estimates it must be recognized that the intensity of survey needed to produce accurate maps of the required scale can only be determined on the basis of actual experience on the project site.

As far as possible, necessary administrative and technical support must be arranged and transport and basic equipment, including base maps and aerial photography, provided in advance of the arrival of the soil survey team.

ii. Preliminary investigations

Through a study of existing literature, preliminary air photo interpretation and a rapid field reconnaissance of the entire survey area, the soil surveyors should:

- evaluate the proposed development scheme and consider whether other development possibilities exist for which interpreted soil data could be provided conveniently;

- identify the soil and environmental criteria which will determine soil capability for each differing development possibility and which will be used, therefore, as a basis for distinguishing soil mapping units (see also **Section** 6.5);

- determine the distribution of these diagnostic criteria and the extent to which is reflected in air photo patterns, thereby obtaining a preliminary assessment of the density and nature of soil observations and sampling likely to be required.

Decisions reached at this stage must be flexible, permitting change in the light of more detailed studies .

iii. Preparation of the soil survey work plan

On the basis of the preliminary investigations a soil survey work plan is drawn up, defining:

- the required intensity of survey; including the nature of soil mapping units and the nature and density of field observations, field tests, and sampling for laboratory determination;

- timing of all phases of survey, including air photo interpretation, field work, cartography and reporting;

- preliminary annotated soil mapping legend (based on landform, geology and the diagnostic criteria identified in preliminary field investigations);

- preliminary outline of final soil survey and land classification report (to underline the range and nature of the information which must be gathered during the course of the survey);

- list of equipment required for all stages of work.

iv. Survey operations

Systematic survey of the character and distribution of the soils, which involves:

- detailed air photo interpretation and systematic field checking of the nature and homogeneity of the soil units identified;
- continual refinement of the soil mapping legend; establishing, through soil correlation, the range of diagnostic criteria permitted in each mapped unit;
- initiation of specialized field investigations (deep boring, infiltration tests etc.) on identified units;
- soil sampling for laboratory analysis and physical characterization.

The collection of information on land use, crop yields and other socio-economic factors required for interpreting the potential of grouped soil and land mapping units must commence as early in the survey as possible. As soon as sufficient data are available, the grouping of soil units for interpretative purposes should be attempted on a trial basis to ensure that the intensity of survey and laboratory investigation is sufficient, and not excessive, for planned interpretation purposes.

v. Soil survey interpretation

When the map of basic soil units is complete, it is necessary to provide interpretation in language understandable to people who are not soil scientists but who need information on soil conditions and the significance of the diverse characteristics for irrigated agriculture, engineering or other purposes. The soil units may be grouped for interpretative purposes in various ways related to the requirements of different land uses (e.g. specific crops requirements under various kinds of management), provided that the criteria selected for separating the basic soil units distinguish between these requirements. Such groupings may also be used for land classification, but the soil surveyor should not merely classify the land without providing explanations of the reasons why certain soil characteristics are interpreted as influencing soil suitability for specific uses.

vi. Land classification

Once physically feasible lines of development and management practices have been identified by soil survey interpretation, land classification relating to specific development possibilities can be undertaken. With respect to land classification for irrigation suitability the work will entail (see USBR (1953) Vol. V chapter 2.2):

- a study of land resources and experiences in a fully developed area having physical and climatic conditions similar to the area under investigation;
- analysis of the probable influence of specific physical factors on the economics of production and costs of land development in the area under investigation;
- development of an appropriate set of land classification specifications which clearly set forth the criteria which will be used for

grouping or subdividing soil mapping units in accordance with economic concepts involving soil productivity, costs of production, land development costs, and allowable internal drainage characteristics;

- field studies leading to interpretation of the soil mapping units in accordance with land class specifications and the insertion of additional boundaries as needed to produce an arable classification of the land. (The term 'arable' is used in the connotation of suitable for irrigation development rather than suitable for farming alone. See also USBR (1953), Vol. 5, Chapter 2.1);
- review of the arable land classification in terms of water service, drainage, water supplies and associated economic constraints to produce land classification for irrigation in terms of the project plan of development.

vii. Reporting

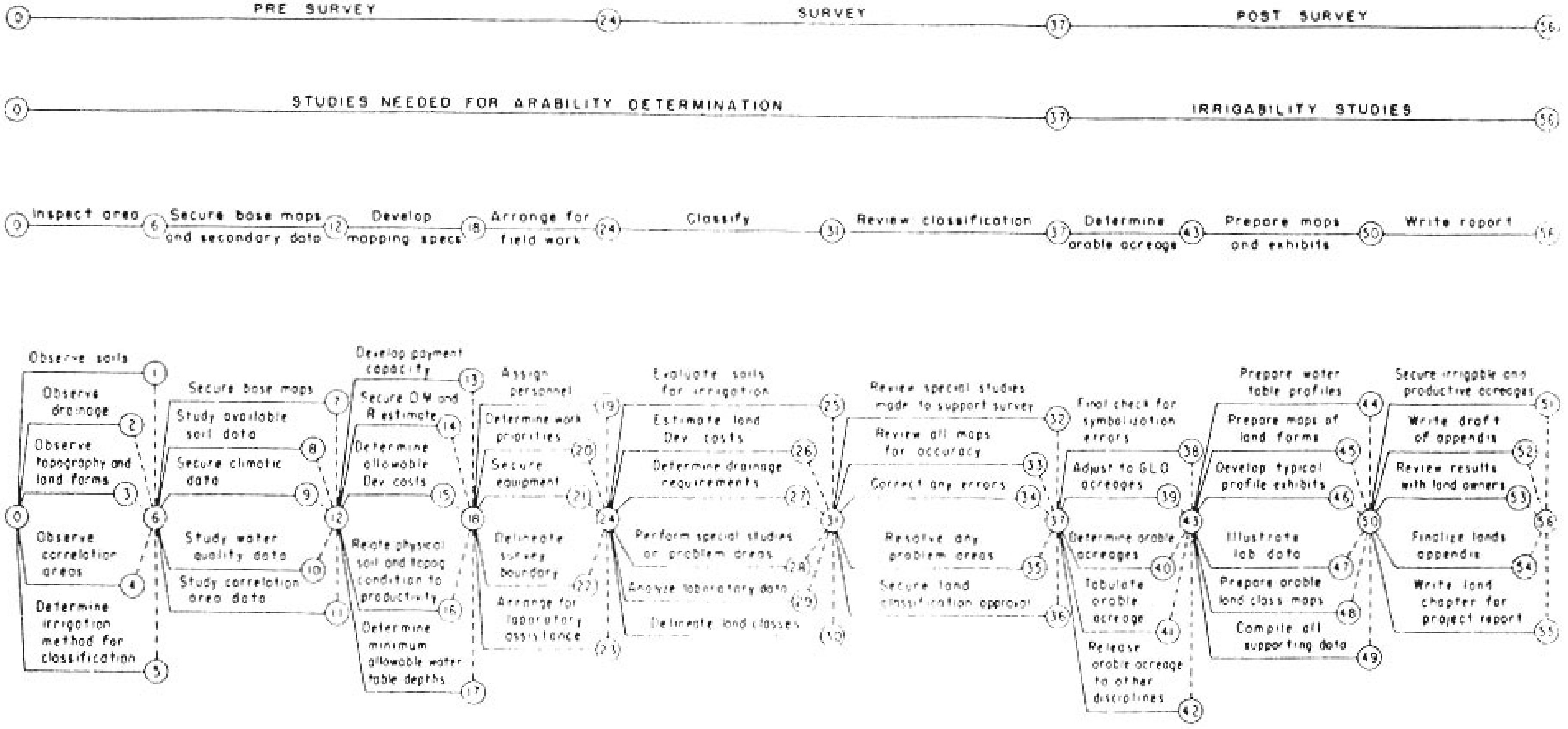
Assembly of a final report must clearly await completion of the land classification and mutual agreement between specialists on the nature and emphasis of recommendations. Verbal and interim reports with supporting maps may be required, however, at various stages in the study and the information needed for a final report must be actively considered at the outset, and during all stages of the work. Otherwise, when the survey is completed, preparation of a final report may be delayed and gaps in knowledge which can no longer be filled may be recognized for the first time.

1.4.3 Network Analysis in Planning Surveys

The aim of network analysis is to ensure thoughtful planning and completion of all necessary work at the appropriate time. It begins with identification of the major objectives and estimation of the time to complete each, and in its final form includes all supporting activities. It sets out work programmes briefly and logically to the mutual benefit of team members. An allowance of slack time must be made for unforeseen problems that commonly arise in connection with soil and drainage investigations. The estimated completion dates for each phase of the work show whether staffing is adequate throughout to meet the completion date for the whole project.

The most basic form of network analysis is a single line entry showing each major phase of the work and its estimated completion date. Most work programmes include supporting activities to be performed concurrently and whose completion is necessary before work can begin on the next major phase. Thus, field survey activities can only start after completion of the pre-survey work phase which in turn requires execution of supporting activities such as supply of vehicles, maps, spades etc. Figure 1 b illustrates certain pre-survey supporting activities which, being performed concurrently, are shown as parallel lines in the network analysis. The earliest date on which a new activity can commence is determined by the time taken to complete the slowest activity on which the new activity depends. The longest path through the network determines the earliest possible completion date for the whole programme. Figure 1 a gives an example of a network analysis prepared by the USBR for an irrigation investigation in Korea (LC in the Figure denotes land classification).

Figure 1(b) U.S.B.R. LAND CLASSIFICATION WORK PERFORMANCE NETWORK



CHAPTER 2

SOIL CHARACTERISTICS

2.1 INTRODUCTION

This chapter discusses in greater detail the soil characteristics summarized in section 1.2.2 and emphasizes those of importance to irrigated agriculture, although it is also essential to record those, such as nutrient status, surface tilth, etc., which are more significant to agricultural uses that do not involve such drastic modification of the soils. Full documentation of all the soil characteristics is necessary because it is useful to other disciplines concerned with planning, and may be needed to consider alternative development possibilities if irrigation is shown to be unfeasible. The record of pre-irrigation conditions is also useful for determining changes resulting from water application and predicting whether they will be favourable or unfavourable.

2.2 PHYSICAL CHARACTERISTICS

2.2.1 Effective Soil Depth

The depth of soil that can be effectively exploited by plant roots is an important criterion in selecting land for irrigation. Root penetration, however, is often inhibited by mechanical factors (hard or impenetrable horizons), chemical factors (zones of high lime or gypsum content) or poor drainage.

While a depth of 150 cm is ideal in a well drained friable soil, **experience** has shown that many irrigated annual and perennial crops produce excellent yields with a well drained effective root zone depth of 90 cm. When close attention is given to irrigation and crop management, most crops give good to excellent yields with effective soil depths of only 45 cm, while well managed grass and rice yield well with soil depths of 30 cm.

A soil depth of 90 cm is often chosen as the minimum for Class 1 (highest level) production under average management. Lesser depths are commonly assigned a lower rating because of a smaller range of suitable crops or lower net income. Soil depth must also be assessed relative to waterholding capacity; when both are low and infiltration is high, sprinkler irrigation may be the best method of water application.

2.2.2 Organic Matter Content

Organic matter in a soil affords a clue to soil genesis and therefore helps to distinguish soils that may behave differently, but is rarely useful in predicting yields of irrigated crops. It is very seldom a proper criterion for grouping soils in categories of varying suitability for irrigation.

In areas where irrigation is contemplated, the organic matter content is likely to be low and confined to a shallow surface horizon which will be much disturbed by land grading operations. The introduction of irrigation and associated new crop management methods greatly affects the equilibrium level of topsoil organic matter.

A high organic matter content may be of indirect importance in evaluating the nature and influence of other soil characteristics, e.g. texture, waterholding capacity, cation exchange capacity and clay mineralogy.

Soils with very high organic matter content (peat soils, Histosols) present great problems for irrigation because of their instability, and require special management techniques, such as sub-irrigation.

2.2.3 Soil Structure and Porosity

Soil structure refers to the nature and degree of aggregation of soil particles and porosity refers to the nature and amount of voids between and within these particles. An abundance of large air filled pores is associated with stable aggregates and a productive soil.

Under nonirrigated conditions a well aerated soil is readily identified visually by texture, structure, colour, porosity and root behaviour. The addition of water could, however, induce adverse chemical or physical conditions and so affect aeration. Thus, a dense horizon at 60 cm posing no problem under light rainfall might result in a perched water table under irrigation, so reducing aeration. Careful judgement of these profile characteristics is required as there are no absolute definitive criteria. Other guides to aeration are given by measurements of bulk density and pore space and of infiltration and permeability rates (see sections 2.5.1 and 2.5.2).

i. Bulk density

Bulk density (or volume weight) is defined as the dry weight of a unit volume of soil and is usually expressed in g/cm^3. Because bulk densities may vary with moisture content, the volume of the sample is preferably measured at about field capacity, but for swelling clays it should be determined at several moisture contents. Bulk densities of highly productive soils usually range from 1.0–1.5 (medium to fine texture) and 1.1–1.65 (coarse texture). Excessive bulk densities inhibit root penetration and proliferation (Zimmerman and Kardos 1961) and may impede drainage. Infiltration and permeability rates are usually low in medium or fine textured soils with bulk densities exceeding 1.65.

Since bulk densities are generally favourable, they are seldom used as a criterion for irrigation suitability, but high densities at any depth in the solum may justify a lower suitability rating.

ii. Pore space distribution

Pore space and bulk density are closely and inversely related. Soils with low porosity generally contain little air space at field capacity – a feature claimed by some to be an important criterion for evaluating productivity (Vomocil 1957). Vomocil cited optimum values of 8% for sugarbeet, 12% for potatoes, 6–10% for Sudan grass and 10–15% for wheat and oats.

Assuming an absolute density of 2.61 for soil without pore space, total porosities associated with bulk densities of 1.1–1.6 would be from 58–39%. In well drained soil the pores are filled with air or water. At field capacity the pores filled with air are considered to be noncapillary and those filled with water are capillary pores. The former can be estimated from a comparison of moisture content at field capacity with total porosity calculated from bulk density.

The distribution of visible pores can be indicated from field examination. Non capillary porosities should be high in the upper 30 cm and ideally 50% of total porosity (Baver <u>et al</u>. 1972). This value is frequently attained in the plough zone but not at greater depths. In highly productive medium to fine textured soils it is usually 10–30%, but in very slowly permeable subsoils it can be as low as 2%.

Porosity and bulk density data should be considered jointly in relation to irrigation suitability.

iii. Soil tilth

Soil tilth is a product of organic matter content, texture, consistence, etc. which, under good management, combine to form a surface or near surface physical condition of the soil favourable to plant growth. Being dependent on management, it is not a suitable criterion for assessing soil, but may be regarded as an indicator of general physical and chemical properties. Poor tilth may be indicative of sodicity.

2.2.4 Particle Size Distribution (Texture)

Texture is one of the most basic soil characteristics for consideration in soil appraisal. It influences such complex soil qualities as infiltration, moisture and nutrient retention, drainage, tilth and susceptibility to erosion. Its effect on these qualities may be modified by soil structure, nature of the clay minerals, and organic matter and lime contents.

Because of the need to relate the textural classification to soil physical properties, including soil-water relationships, the method used for particle size distribution analysis is important. Experience in the U.S. Bureau of Reclamation has shown that organic matter and lime should not be removed prior to analysis: the texture as modified by these substances is the better criterion of irrigability.

Soils of all textural classes, except perhaps coarse sand, are irrigable by an appropriate method when there is an economic incentive and no impedance to root growth. Those at the extremes of the textural range require good management and perhaps additional inputs. The extremes of texture acceptable within a specific project require considerable judgement backed by the performance of similar soils (local or elsewhere) under comparable conditions, taking into account climate, water quality, method of irrigation, cropping pattern and erosion hazard.

Satisfactory textural diagnostic criteria for the separate suitability classes of an irrigability classification are difficult to establish, bearing in mind the economic significance implied, and only an empirical approach is likely to yield reliable guidelines, which should be tested by field trials in each new area.

2.3 CHEMICAL CHARACTERISTICS

2.3.1 Soil Reaction (pH)

The degree of acidity or alkalinity of a soil is usually expressed as a pH value which is defined as the negative logarithm of the hydrogen ion activity. This definition can be represented by the equation:

$$pH = -\log_{10} a_{H^+}$$

in which a_{H^+} is the activity or effective concentration of hydrogen ions (H^+) in the soil suspension. Since single-ion activity coefficients cannot be measured (Black 1968, Peech 1965), the practical measure of soil reaction refers to a scale of pH corresponding to standard buffer solutions.

In the laboratory, the electrometric method is most commonly used to measure the potential of a glass electrode against a calomel reference cell. In the field colorimetric methods using dyes whose colour changes in response to hydrogen ion activity are convenient and reasonably accurate. Black (1968), Jackson (1958), Peech (1965) and White (1969) have presented information on soil pH measurements useful in soil analysis.

The best method of measuring soil pH, especially the choice of suspension medium and the soil:liquid ratio, is controversial. The significance of a liquid junction potential has been a source of disagreement (Jenny et al. 1950, Coleman et al. 1951, Peech and McDevit 1951, Peech et al. 1953, Marshall 1953, 1964). To avoid large errors so introduced, the pH can be measured in 1M KCl (Clark 1966) or 0.01M $CaCl_2$ (Coleman and Thomas 1967), in addition to in water. The significance of a pH value may therefore differ according to the method of determination, but comparison of values obtained by different methods may yield additional interpretative guidance. Examples of such comparisons follow.

The pH of soil measured in 1M KCl is generally lower than values obtained in water of the same soil-solution ratio. Exceptions are certain highly weathered soils with a mineralogy dominated by oxide clays (Acrox suborder of the U.S. Soil Taxonomy) and certain extremely saline soils. In suspension, the highly weathered oxide clays have a positive electrical charge or are electrically neutral and their pH in 1M KCl is higher or equal to their pH in water (U.S. Soil Survey Staff 1960). In the case of extremely saline soils, the pH in water may not differ from that in 1M KCl, irrespective of the type of clay mineralogy. Salts in a solution of neutral or alkaline soil tend to decrease pH. Salts also influence pH measurements made at varying soil-water ratio suspensions. The soil-water ratio affects the solubility of salts and their concentration which in turn affects the equilibrium between cations in solution and those on the exchange complex. Salt-affected soil characteristics that influence the results of pH measurements include: the composition of the exchangeable cations, the nature of the cation-exchange materials, the composition and concentration of soluble salts, and the presence or absence of gypsum and alkaline-earth carbonates (Richards et al. 1954). Whitney and Gardner (1943) found that the pH of calcareous soils is a function of the carbon dioxide pressure and that the pH change resulting from an increase in the soil-water ratio was largely due to the dilution of carbon dioxide previously absorbed by the soil.

The increase in soil pH as the moisture is increased from near saturation to a 1:5 or 1:10 dilution, or the dilution pH as compared to the salt concentration of the saturation extract and other soil-water ratio extracts, is useful in classifying salt-affected soils associated with calcareous and sodic conditions of some arid areas. This tendency of certain salt-affected soils to exhibit changes in pH upon modifying the soil-water ratio is sometimes used as a guide in the indirect characterization for exchangeable sodium versus residual gypsum status. Soil exhibiting high values of pH in water (1:5) especially in the range above 9.3 are usually low in gypsum content. They may or may not contain appreciable amounts of exchangeable sodium. Factors which affect the relationship between pH measured in water suspensions at various ratios and the exchangeable sodium level include the particle size distribution, the presence of magnesium carbonate, the concentration and composition of soluble salts, and the content of gypsum. Such relationships should not be applied in soil evaluation until their reliability has been established for local conditions.

In recent years, many investigations have been conducted on the measurement of soil pH in dilute solutions of $CaCl_2$. These measurements especially in 0.01M $CaCl_2$ have been shown by Schofield (1955) to offer several advantages from both theoretical and practical standpoints. Of importance is that soil pH in 0.01M $CaCl_2$ is independent of the soil solution ratio, in contrast to in 1M KCl (Peech 1965), and the errors resulting from the junction potential are essentially eliminated. Black (1968) states that this method appears "to be the best now available for measuring soil pH on a practical basis if the objective is to obtain an estimate of the pH of the soil solution where the water content of the soil corresponds to field conditions."

As a general guide the following statements can be made:

i. through much of the soil pH range values of 0.01M $CaCl_2$ are about 0.5 pH units lower than in a 1:2 soil-water suspension;

ii. values of soil pH in 0.01M $CaCl_2$ less than 4.8 indicate neutral salt exchange activity; (this is that portion of the soil acidity that can be extracted with a neutral, unbuffered salt such as 1.0M KCl. In many soils, the neutral salt exchange acidity is comprised almost entirely of monometric Al ions. Several workers report finding substantial amounts of exchangeable hydrogen in neutral salt extracts, however, and some have reported neutral salt exchange acidity due to iron and manganese. In relating a pH of 4.8 to the presence of neutral salt exchange acidity mention of the quantity of exchange acidity involved is deliberately avoided. For the same value of soil pH below 4.8, exchange acidity may range from less than 1 meq/100 g of more than 14 meq/100 g. This fact emphasizes the need for further testing of selected samples to measure the quantity of exchange acidity and of exchangeable aluminium);

iii. calcareous non-sodic soils have pH in 0.01M $CaCl_2$ of about 7.5 while sodic soils are usually above 7.5 (this relationship does not hold for the pH in water, which is strongly influenced by the salt content);

iv. pH values of water saturated soil paste above 7.6 usually indicate the presence of alkaline-earth carbonates, but a non-calcareous non-sodic soil may have a pH as high as 7.4;

v. soils with pH value less than 7.5 almost always contain no alkaline-earth carbonates and those less than 7.0 contain significant amounts of exchangeable hydrogen or aluminium;

vi. pH (paste) values above 8.5 commonly indicate an exchangeable sodium percentage above 15; with values below 8.5 the exchangeable sodium percentage may or may not exceed 15;

vii. an increase of 1.0 or more in pH between the paste and 1:5 soil-water suspension may indicate significant quantities of soluble or exchangeable sodium but should be verified for local conditions;

viii. the relationship between pH and exchangeable sodium percentage depends on the salinity. For fine-textured soils approximate estimates of ESP can be conveniently made by correlating pH and electrical conductivity (EC) with the ESP for local conditions (Dieleman et al. 1963; Nachtergaele 1976).

It must be noted that soil pH measurements performed in the laboratory are not necessarily relevant to the evaluation of soils for rice production since soil pH is likely to change under flooded conditions in response to reduction processes. According to Ponnamperuma (1964), the changes in pH are determined by (a) the initial pH of the soil, (b) the nature and control of oxidized soil components, and (c) the kind and content of organic matter. Soils with the lowest pH before flooding usually have the greatest increase in pH after flooding for prolonged periods of time, since the pH increases to near neutrality.

In summary, it may be said that soil pH measurements chiefly serve the purposes of irrigation suitability surveys by providing a general indication of soil reaction; i.e., whether soil acidity, soil alkalinity or soil sodicity, might prevail. In certain cases where empirical relationships can be established, soil pH measurements are used to appraise correctable soil deficiencies relating to economic correlation, such as needs for soil amendments (lime for acid soils and able hydrogen or aluminium ions rather than by nutrient bases. Such soils tend to be unproductive. If the exchange complex includes no exchangeable hydrogen or aluminium, the soil is said to be 'base saturated'. Highly productive soils are usually at least 50% base saturated with a preponderance of calcium.

The exchange complex, through equilibrium with the soil solution, is generally regarded as the main source of nutrients for the support of plant growth and essential microbiological processes in the soil. A balance between different nutrient bases in the exchange complex is no less important than the level of individual nutrients but present knowledge permits very few general statements to be made regarding desirable levels or ratios of plant nutrients in the exchange complex. As most irrigation suitability surveys foresee the introduction of regular additions of required mineral fertilizers, only extremes of cation imbalance are likely to be important criteria. In very acid soils, for example, the levels of exchangeable calcium and aluminium may be significant. Nearly all crops require a minimum level of exchangeable calcium and are injured by an excess of exchangeable aluminium. If other factors are favourable, a level of 6 meq/100 g of soil of exchangeable calcium is generally sufficient to ensure crop production. On the other hand, soils with more than 2 meq/100 g of soil of exchangeable aluminium are generally toxic. Dressings of lime to correct calcium deficiency or aluminium toxicity should be recommended with caution on severely leached soils (Millar 1955). Their cost is a factor in evaluating suitability for irrigation.

Cation imbalance may also have detrimental effects on soil structure and thus upon infiltration capacity, permeability, soil tilth and susceptibility to erosion. Excessively high amounts of exchangeable sodium or of sodium plus magnesium, are so important in irrigation suitability assessment that the "exchangeable sodium percentage" is discussed separately in the sub-section which follows.

iii. Exchangeable sodium percentage (ESP)

The exchangeable sodium percentage is the degree of saturation of the soil exchange complex with sodium and may be calculated by the formula:

$$\text{ESP} = \frac{\text{Exchangeable sodium (meq/100 g soil)} \times 100}{\text{Cation exchange capacity (meq/100 g soil)}}$$

Either ESP or the milliequivalents of exchangeable sodium are usually good indicators of the structural stability of a soil and of the physical response that may be anticipated when water is applied. Most soils containing expanding type clay minerals exhibit unfavourable physical properties at levels of ESP greater than 15% or of exchangeable sodium greater than 3 meq/100 g of soil. In general, physical properties become increasingly unfavourable with increasing levels of exchangeable sodium but, at a given level of ESP, physical properties are usually poorer in soils with expanding 2:1 clay minerals than in soils with clay minerals of the non-swelling or mixed types.

Laboratory studies can be used to determine critical limits for the influence of exchangeable sodium on the physical character of individual soils.

In addition to the possible deleterious effects that high ESP levels may have on the physical properties of a soil, some crops have a low tolerance for exchangeable sodium. Bower (1959) has developed the data able hydrogen or aluminium ions rather than by nutrient bases. Such soils tend to be unproductive. If the exchange complex includes no exchangeable hydrogen or aluminium, the soil is said to be 'base saturated'. Highly productive soils are usually at least 50% base saturated with a preponderance of calcium.

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Laboratory studies can be used to determine critical limits for the influence of exchangeable sodium on the physical character of individual soils.

In addition to the possible deleterious effects that high ESP levels may have on the physical properties of a soil, some crops have a low tolerance for exchangeable sodium. Bower (1959) has developed the data shown in Table 1 to reflect these differences and Lunt (1963) has prepared the summary literature on crop reduction due to ESP shown in Table 2.

Table 1 TOLERANCE OF VARIOUS CROPS TO ESP

Tolerance to ESP and range at which affected	Crop	Growth responses under field conditions
Extremely sensitive (ESP = 2 - 10)	Deciduous fruit Nuts, avocado, cassava	Sodium toxicity symptoms even at low ESP values
Sensitive (ESP = 10 - 20)	Beans	Stunted growth at low ESP values even though the physical condition of the soil may be good
Moderately tolerant (ESP = 20 - 40)	Clover, oats, tall fescue, rice, dallis grass	Stunted growth due to both nutritional factors and adverse soil conditions
Tolerant (ESP = 40 - 60)	Wheat, cotton, alfalfa, barley, tomatoes, beets	Stunted growth usually due to adverse physical conditions of soil
Most tolerant (ESP more than 60)	Crested and fairway wheatgrass, tall wheatgrass, rhodes grass	Stunted growth usually due to adverse physical conditions of soil

Table 2 INFLUENCE OF ESP ON CROP REDUCTION

50% Crop reduction at ESP of 15 or less	50% Crop reduction at ESP of 15-25	50% Crop reduction at ESP 35
(Sensitive)	(Intermediate)	(Tolerant)
Avocado	Dwarf kidney bean	Alfalfa
Green beans	Red clover	Barley
Corn	Cotton	Beets
Tall fescue	Lemon	Carrots
Peach	Lettuce	Dallis grass
Sweet orange	Oats	Onion

It is emphasized that the relationships shown in Tables 1 and 2 should only be used for general guidance. Under local conditions individual crops may respond differently to ESP. On certain strongly cracking clays (Vertisols) in the Sudan, for example, Robinson (1971) found that a range of ESP between 6 and 25 was optimum for cotton and that satisfactory yields of long staple cotton were obtained on soils with an ESP of 35 or more in the upper 60 cm. This is because the water-holding capacity increases with

ESP and the effect on permeability, though measurable, is of little importance since the hydraulic conductivity is in any case very low as a result of the pressure of the overburden on the plastic wet soil (Abedine _et al_. 1969).

In developing interpretations of irrigation suitability it is important to bear in mind that the value of ESP that will develop in the soil in equilibrium with the irrigation water has greater significance than the ESP of the soil prior to irrigation.

If the soil drainage is good and the sodium adsorption ratio of the irrigation water is known the approximate equilibrium level of ESP can be predicted. This is discussed later in the context of water quality (section 5.2). More information is also given by FAO (1976) and FAO/Unesco (1973).

2.3.3 Salinity

Salinity - an excess of soluble salts - is probably the most widespread soil quality adverse to crop growth in arid irrigated areas. It is fortunate that owing to their solubility, such salts are mobile and can be removed by leaching where drainage conditions are satisfactory. Accordingly, their presence at the time of a soil survey may not be very significant to irrigation development if leaching conditions are favourable.

An excess of soluble salts in the soil is often associated with an excess of exchangeable sodium in the exchange complex (high ESP, see previous section). Recognizing the existence of soils having either or both of these defects Richard _et al_. (1954) defined a simple three-class classification of salt affected soils: saline soils, saline-sodic soils, and sodic soils. Their definition of these soils was:

> "_Saline soil_ - A nonsodic soil containing soluble salts in such quantities that they interfere with the growth of most crop plants. The electrical conductivity of the saturation extract is greater than 4 mmhos per centimeter (at 25° C) and the exchangeable sodium percentage is less than 15. The pH reading of the saturated soil is usually less than 8.5
>
> _Saline-sodic soil_ - A soil containing sufficient exchangeable sodium to interfere with the growth of most crop plants and containing appreciable quantities of soluble salts. The exchangeable sodium percentage is greater than 15, and the electrical conductivity of the saturation extract is greater than 4 mmhos per centimeter (25° C). The pH reading of the saturated is usually less than 8.5.
>
> _Sodic soil_ - A soil containing sufficient exchangeable sodium to interfere with the growth of most crop plants, without appreciable quantities of soluble salts."

The primary deleterious effect of excessive salinity is to raise the concentration of the soil solution. In consequence, the flow of water into the plant by osmosis is reduced or reversed and the plant is starved of water even though the soil is moist. Some ions, particularly sodium, chloride and sulphate, have specific toxicity for certain crops.

The variation among plants in their tolerance to salinity (Table 3) affects the choice of cropping pattern when evaluating the possible effects of salinity.

Table 3 RELATIVE TOLERANCE OF VARIOUS CROPS TO SOIL SALINITY

<table>
<tr><th colspan="3">Fruit Crops</th></tr>
<tr><th>High salt tolerance</th><th>Medium salt tolerance</th><th>Low salt tolerance</th></tr>
<tr><td>Date Palm
$EC_e x10^3 = 8$</td><td>$EC_e x10^3 = 8$
Pomegranate
Fig
Olive
Grape
Cantaloup
$EC_e x10^3 = 4$</td><td>$EC_e x10^3 = 4$
Pear
Apple
Orange
Grapefruit
Prune
Plum
Almond
Apricot
Peach
Strawberry
Lemon
Avocado
$EC_e x10^3 = 2$</td></tr>
<tr><th colspan="3">Vegetable Crops</th></tr>
<tr><td>$EC_e x10^3 = 12$
Garden beets
Kale
Asparagus
Spinach
$EC_e x10^3 = 10$</td><td>$EC_e x10^3 = 10$
Tomato
Broccoli
Cabbage
Bell pepper
Cauliflower
Lettuce
Sweet corn (maize)
Potatoes
Carrot
Onion
Peas
Squash
Cucumber
$EC_e x10^3 = 4$</td><td>$EC_e x10^3 = 4$
Radish
Celery
Green beans
$EC_e x10^3 = 3$</td></tr>
<tr><th colspan="3">Field Crops</th></tr>
<tr><td>$EC_e x10^3 = 16$
Barley (grain)
Sugar beet
Rape
Cotton
$EC_e x10^3 = 10$</td><td>$EC_e x10^3 = 10$
Rye (grain)
Wheat (grain)
Oats (grain)
Rice
Sorghum (grain)
Maize
Flax
Sunflower
Castorbeans
Soybeans
$EC_e x10^3 = 6$</td><td>$EC_e x10^3 = 4$
Field beans
Sugar cane
Cassava</td></tr>
</table>

Table 4 cont.

Forage Crops		
$EC_e x10^3 = 18$	$EC_e x10^3 = 12$	$EC_e x10^3 = 4$
Alkali sacaton Saltgrass Nuttal alkali grass Bermuda grass Rhodes grass Fescue grass Canada wildrye Western wheatgrass Barley (hay) Birdsfoot trefoil	White sweetclover Yellow sweetclover Perennial ryegrass Mountain brome Strawberry clover Dallis grass Sudan grass Hubam clover Alfalfa (Calif.common) Tall fescue Rye (hay) Wheat (hay) Oats (hay) Orchardgrass Blue grama Meadow fescue Reed canary Big trefoil Smooth brome Tall meadow oatgrass Cicer Milkvetch Sourclover Sickle milkvetch	White Dutch clover Meadow foxtail Alsike clover Red clover Ladino clover Burnet
$EC_e x10^3 = 12$	$EC_e x10^3 = 4$	$EC_e x10^3 = 2$

Source: Richards et al. (1954)

Note: The numbers following $EC_e x10^3$ are the electrical conductivity values of the saturation extract in millimhos per centimeter at 25° C associated with 50% decrease in yield.

Inadequate drainage and a rising water table after a few years of irrigation may lead to the entry of saline water into the root zone. The salinity level and sodic conditions at the time of the survey are not stable characteristics of the soil and both can be changed with irrigation, salinity being generally the easiest and cheapest to correct. Important considerations in the evaluation of saline or sodic soils include: water quality to be used for irrigation; infiltration and permeability rate of the soil; levelling required to provide a suitable surface for leaching; ability of substrata to transmit the necessary leaching water; the level of salinity or sodic conditions; availability or absence of gypsum to replace sodium in sodic soils and the expected cropping system.

Improved drainage is likely to be required for soils with salinity problems and may be needed for sodic problems. Reclamation costs associated with drainage improvement, land levelling and necessary soil amendments should be estimated when determining the land class for soils which are saline or sodic at the time of the survey. Such lands should not be downgraded if no special extra drainage works or irrigation applications are required. Thus, a saline soil that can be leached in a short time by ordinary irrigation application could be assigned a Class 1 rating if all other factors were favourable. Most sodic soils would not qualify for a Class 1 rating because of the cost of soil amendments or profile modification.

Additional information on the reclamation of saline and sodic soils is given in Chapter 4.

2.3.4 Toxic Substances

Substances other than exchangeable sodium and exchangeable aluminium can harm plants. Some, such as boron, occur naturally in irrigation water while others (arsenic and copper) are introduced by the spraying of herbicides and insecticides, or by industrial air pollution (fluorine).

Different plants very in their tolerance to toxic substances, and toxicity varies according to amounts of other substances in the soil. It is often uncertain whether toxicity symptoms are caused by an element present in excess or by it having replaced some element essential to plant growth. Furthermore, changes in toxicity may accompany changes in soil pH or redox potential. For example the solubility at low pH of Al, Mn, Cu, Ni, Zn and other metals may raise their concentration in the soil solution to toxic levels. On the other hand, an increase in pH associated with an increase in exchangeable sodium can affect biological processes and lead to production of toxic concentrations of nitrite ion (Chapman 1966). Few general guidelines can be given to likely toxic levels of individual substances.

The soil surveyor should be alert to signs of possible toxicity in the natural vegetation. Plants may be absent, restricted to a particular range of species, stunted or showing symptoms of toxicity or nutrient deficiency. Geological formations may suggest areas likely to be affected. Ultrabasic rocks, in particular serpentine, are liable to give rise to soils with high, possibly toxic levels of Cr, Ni, Mg and Mn (Bear 1957, Pratt 1966, Vanselow 1966). Soils in the vicinity of deposits of ores, notably Zn, are also suspect, while peats often show very marked nutrient imbalance or toxic accumulations. Where toxicity is suspected, the soil surveyor should request special trace element analyses.

i. Arsenic

Arsenic occurs naturally in many soils but rarely in toxic quantities. Toxicity is usually attributed to the accumulation of arsenical insecticides.

The tolerance of individual crops varies with the textural class of the soil. Among the most tolerant (Bear 1957, Liebig 1966) are: Potato (*Solanum tuberosum*), tomato (*Lycopersicon esculentum*), carrot (*Daucus carota*) and tobacco (*Nicotiana tabacum*), while among the fairly tolerant plants are maize (*Zea mays*), beet (*Beta vulgaris*) and squash (*Cucurbita maxima*). The least tolerant include beans (*Phaseolus vulgaris* and *P. lunatus*), onion (*Allium* sp.), pea (*Pisum sativum*), cucumber (*Cucumis sativus*), alfalfa (*Medicago sativa*), wheat (*Triticum* spp.), barley (*Hordeum vulgare*) and Sudan grass (*Sorghum sudanense*).

ii. Boron

Boron in the soil solution is very toxic to plants even at low concentrations; some indications of crop tolerance (from Bradford 1966) are:

> boron-sensitive plants: lemon (*Citrus limon*), strawberry (*Fragaria* spp), lupin (*Lupinus hartwegi*), grape (*Vitis vinifera*), kidney bean (*Phaseolus vulgaris*), cowpea (*Vigna unguiculata*); boron-semitolerant: barley (*Hordeum vulgare*), pea (*Pisum sativum*), sweet potato (*Ipomea patatas*), onion (*Allium cepa*), red pepper (*Capsicum frutescens*), corn

(*Zea mays*), sorghum (*Sorghum vulgare*), alfalfa (*Medicago sativa*), tobacco (*Nicotiana tabacum*), tomato (*Lycopersicon esculentum*); boron-tolerant: turnip (*Brassica rapa*), beet (*Beta vulgaris*), muskmelon (*Cucumis melo*), sugar beet (*Beta saccharifera*), and cotton (*Gossypium hirsutum*).

It is a widespread source of trouble and may be inherent in soil-water systems or accumulate through irrigation or land management. Excess boron is common among arid soils where natural drainage and leaching are inadequate and among soils derived from recent deposits of volcanic origin, marine sediments and parent materials rich in boron (Bradford 1966, Mitchell 1958). The main source of excessive boron affecting crops is irrigation water from wells and thermal springs, but boron may accumulate from the use of potassium fertilizers with boron impurities. The assessment of boron equilibrium levels is discussed in section 5.2.6 iii.

iii. Nickel and chromium

Toxicity of nickel and chromium is inherent in soils derived from serpentine. Nickel is toxic at very low concentrations and the degree of toxicity appears to be related to the exchangeable form. However, on serpentine soils toxicity is closely associated with chromium and a high ratio of exchangeable magnesium to calcium (Vanselow 1966). Low productivity on serpentine soils may also be attributed to excess manganese and a deficiency of molybdenum (Bear 1957). Such toxicities can often be identified from the state of the natural vegetation.

iv. Toxic substances (sulphides and iron) affecting wetland rice

Wetland rice (*Oryza sativa*) is grown in a flooded waterlogged soil in which the root zone is relatively devoid of oxygen. The associated reduction processes usually benefit the rice by modifying soil reaction and nutrient availability, but sometimes they result in the production of toxic hydrogen sulphide and iron compounds. The harmful effects on the rice plant have been termed "physiological diseases" (Tanaka and Yoshida 1970).

Hydrogen sulphide (H_2S) is harmful even at very low concentrations. It affects the rice plant through several physiological mechanisms and can cause Akiochi disease. Toxicity develops in the presence of sulphate and is usually limited to soils high in organic matter and low in easily reducible iron, particularly muck soils or soils of low cation exchange capacity and low base saturation (Tanaka and Yoshida 1970, Williams and Joseph 1970, Ponnamperuma 1965). Sulphide toxicity may be counteracted by applying materials containing iron (Villegas and Fener 1970). It may be noted that deficiency of sulphur also occurs in wetland rice, for example in the lower Amazon.

Many rice soils contain large amounts of iron compounds that are easily reduced and become soluble under flooded conditions. According to Ponnamperuma (1965) iron reduction and solubility are controlled by soil reaction, organic matter content, cation exchange capacity and duration of submergence. Reduction is facilitated by low pH and high organic matter content.

Iron in solution is beneficial to rice except in certain acid soils, especially acid sulphate soils high in active iron, or soils with low cation exchange capacity and active manganese, in which iron toxicity can develop.

Physiological disorders caused by excessive iron have been termed bronzing and Akagore Type I (Baba et al. 1965). Some investigators consider these to be different disorders; Tanaka and Yoshida (1970) believed them to have similar causes but with symptoms modified at least partly by varieted differences.

Other substances, including organic acids and carbon dioxide can be toxic to rice but seldom occur in harmful concentrations. Aluminium and manganese are rarely toxic, in fact the latter plays a key role in the chemical kinetics of rice soils.

2.4 MINERALOGICAL CHARACTERISTICS

2.4.1 Mineralogy of the Sand and Silt Fractions

Minerals present in the sand and silt fractions of a soil are primarily indicative of the soil parent material and of the degree of weathering. Quartz is often the dominant mineral. The presence of feldspars, or micas, or other ferromagnesian minerals, all of which are relatively easily weathered, may indicate a relatively young soil, or layer. Alternatively, it can reflect a lack of active soil forming processes due, perhaps to lack of moisture. A wide variety of so-called 'heavy minerals' such as zircon, garnet, tourmaline and magnetite, tend to accumulate in the sand fraction as a soil ages and, by their relative abundance, may provide useful clues to the genetic relationships between soil horizons. Carbonates and gypsum have a special significance and are discussed in sections 2.4.3 and 2.4.4.

The presence of easily weathered minerals is indicative of a reserve of fertility. Nevertheless, in itself, the mineralogy of the sand and silt fractions is not normally an important criterion in judging the suitability of soils for irrigation. Its importance lies in the clues it can sometimes provide to soil genesis. These may be of great assistance in soil classification and mapping, especially in complex alluvial areas which are so frequently considered for irrigation development.

2.4.2 Mineralogy of Clay Fraction

The kinds of clay mineral present determine many of the physical and chemical characteristics of a soil and thus exert a most important influence on its suitability for irrigation. The nature of the clay in itself is not, however, a convenient criterion for judging irrigation suitability. This is partly because the clay fraction of a soil is usually composed of a mixture of clay minerals, rather than a single mineral, and partly because the influence of clay type is very closely integrated with other soil characteristics. These considerations greatly complicate the precise assessment and interpretation of the nature of the clay and make it almost impossible to establish required ranges of clay type for different classes of soil suitability. Many of the factors which are closely related to clay type, such as hydraulic conductivity and cation exchange capacity, can be measured independently more conveniently.

General understanding of the nature of the clay is nonetheless essential for irrigation suitability evaluations for it provides some of the most important clues to predicting the behaviour of soils after irrigation is introduced. For this purpose, knowledge of the exact proportions of clay minerals present is less important than an understanding of the general nature of the clay. Sufficient observations should be made to indicate whether clay minerals of the 1:1 layer (kaolinite) or 2:1 layer (montomorillonite, illite, vermiculite) types predominate.

In the absence of X-ray and differential thermal analysis equipment for the precise determination of clay minerals, inferential evaluations should be made. It is well known that 1:1 layer clay minerals have only slight stickiness, a small amount of shrinkage on drying, a small surface area, and low cation exchange capacity. Most 2:1 type clay minerals, such as montmorillonite, have opposite properties. A further clue to the type of clay mineral is given by knowledge of the quantity of permanent charge CEC and of pH dependent CEC (see section 2.3.2 i).

Rich and Thomas (1960) also state that the sorption of anions by the clay fraction is another means of differentiating soils high in kaolinite, gibbsite, and iron oxides. Soils with these clay minerals often have anion exchange capacities greater than their cation exchange capacities. Clays of the 2:1 layer type have little or no sorption of chloride or sulphate ions.

In general, soils in which 1:1 layer clay minerals together with iron and aluminium oxides predominate have excellent soil-water relationships and easy workability associated with their high degree of aggregation and non-swelling nature. Swindale and El-Swaify (1968) have demonstrated that such soils are usually permeable at higher exchangeable sodium levels than soils dominated by 2:1 layer clay minerals and so may be safely irrigated using water with a higher sodium adsorption ratio (see sections 5.2.3 and 5.2.4). On the other hand, the 1:1 layer clays have low cation exchange capacity and a low capacity for moisture retention. The moisture and nutrient requirements of crops on these soils can be met under modern irrigated agriculture but not without additional cost. Difficulties of tillage and drainage are the principal problems associated with the 2:1 lattice clays, due to their swelling nature and sticky consistence (Dudal 1965).

2.4.3 Content of Carbonates

Calcium carbonate commonly accumulates in soils developed under arid and semi-arid climates and may be present in soils developed from limestone in all climatic zones. The accumulations may be diffused throughout the soil profile, or may take the form of soft concretions, or nodules, or may be concentrated in a continuous horizon ('caliche' or 'croûte calcaire') of varying hardness and at varying depth below the surface. The amount of carbonate present, the form of its distribution in the profile and the depth to the lime-rich horizons are all important factors in judging the suitability of a calcareous soil for irrigated agriculture.

The presence of $CaCO_3$ affects both the physical and the chemical characteristics of a soil. Continuous horizons of carbonate accumulation may not restrict water movement severely but may prevent root penetration. Discrete particles of carbonate also affect moisture characteristics and tend to create a less fertile environment for plant roots. The finer the particle size of the carbonates the more active are these effects. Carbonate concretions or nodules are less active than similar concentrations in diffused form. This is reflected in field tests with acid which yield much more violent effervescence from finely divided carbonates than from soils with an equal content of carbonate in larger and harder particles. Especially important is the amount of carbonate present in particle sizes less than 0.02 mm. In general, if the texture of the non-carbonate material is coarse, nearly all the carbonate can be assumed to be of sand size or coarser. In fine textured soils, however, much of the carbonate content may be in the silt and clay fractions.

In discussing particle size distribution (section 2.2.4) it was suggested that mechanical analysis of the whole soil, without prior removal of lime, gave more significant values for assessing the suitability of soils for irrigation. For highly calcareous soils this is particularly true but for these soils it is also desirable to obtain a measure of the size distribution of the carbonate particles alone (by difference after dissolving the carbonates in acid). This information is needed to make a confident prediction of the behaviour of such soils. Knowledge of the presence of a high content of very fine $CaCO_3$ particles, for example, gives warning of a risk that lime-induced chlorosis will affect many crops on the soils in question (see Yaalon 1957).

The presence of carbonates reduces the ability of calcareous soils to retain moisture especially at high tensions. The moisture characteristic curves (moisture content percent plotted against soil moisture tension) of highly calcareous soils, regardless of texture, are similar to those of coarse textured non-calcareous soils; most of the retained water being lost at low tensions. About 50% of the available moisture will be depleted at tensions of 1 and 5 atm respectively, regardless of the soil texture. These characteristics imply a need for more frequent irrigation at relatively low moisture tensions (less than 1 atm) on highly calcareous soils (Massoud 1973).

Calcium carbonate can have the effect of increasing moisture diffusivity in soil, causing water movement to be faster than in non-calcareous soils of similar particle size distribution. Again this effect is a function of the amount of $CaCO_3$ present and the particle size. Up to 10 or 15% $CaCO_3$ may assist formation of stable aggregates associated with relatively large pores and rapid water movement. With an increased content of $CaCO_3$ up to 20 or 25%, precipitation of carbonate within capillary tubes tends to increase the proportion of very small pores and reduce diffusivity. At still larger carbonate contents the effects depend on the size of the carbonate particles themselves; the coarser the size the higher will be the diffusivity (Massoud 1973).

Surface crusting can be a serious problem in newly-irrigated calcareous soils, especially those of low organic matter content. Crusts not only affect infiltration and soil aeration but also impede or prevent the emergence of seedlings. Heavy applications of water on soils with a high content of fine-grained carbonate encourages the formation of thick crusts on drying. Therefore, soils which have a tendency to crust will require a frequency of irrigation sufficient to prevent drying and hardening of the surface (Massoud 1973). Characterization of such soils in the course of a soil survey should include separate determination and description of the thickness, bulk density, strength, mechanical composition and carbonate content of the surface crust. The seriousness of a crusting problem will depend upon a combination of these factors but bulk density values of 1.6 or higher, in all but very sandy soils, should be viewed with suspicion. Whether, in fact, lime will be deposited or removed from the soil by irrigation water depends upon water quality and is discussed in some detail in Chapter 5 (section 5.2.3).

The physical characteristics of calcareous soils often change when they are irrigated. From a favourable virgin condition the soils become more coherent and resistant to root penetration especially in the part of the profile subjected to wetting and drying. The effect is likely to be more marked if the organic matter content of the soil is low. Careful timing of tillage operations and careful seedbed preparation must be foreseen. The optimum moisture range for ploughing calcareous soils is very narrow and occurs within 4 to 5 days after irrigation, whereas 7 to 8 days after irrigation the ploughing operation is often rather difficult. The assessment of required erosion control measures on highly calcareous soils should take account of the fact that soil aggregates which are stable and consolidated by carbonates in the dry state tend to disintegrate when wet.

Calcareous soils usually have a pH of the saturated paste in the range of 7.6-8.4. In instances where magnesium carbonate is an important constituent, the pH may reach 9.0 or higher. Despite their high pH, soils rich in magnesium carbonate are often very fertile. Nutrient deficiencies of phosphorus, iron and micro-nutrients are common in plants grown on calcareous soils. High lime content usually results in a need for later inputs of fertilizers, and is a dilutant factor for roots seeking nutrition. Accordingly, a highly calcareous soil can be expected to be less productive than slighly calcareous soils if all other factors are equal.

Indurated horizons of lime enrichment commonly occur in arid regions and may vary in thickness from 1 to 300 cm or more. It is the experience of the U.S. Bureau of Reclamation in 'caliche' areas of the Western United States that these rock-like materials are generally pervious to water but highly restrictive to roots. They frequently rest on impermeable bed rocks. Costs of drainage construction in caliche are similar to those incurred in excavation of bed rock.

From the foregoing discussion it is apparent that knowledge of the depth to lime-rich horizons, whether or not they are indurated, is of the greatest importance in planning land-shaping operations prior to irrigation. Redistribution of the relatively more fertile surface layers leading to exposure of lime-rich horizons below can create serious problems of soil management.

Crops which perform particularly well on calcareous soils include olives, grape vines, almonds and most legumes.

2.4.4 Content of Gypsum

Soils containing gypsum ($CaSO_4 2H_2O$) are widespread in arid and semi-arid areas. A small amount of gypsum is favourable to crop growth in that it serves as a relatively soluble source of calcium to replace sodium in the exchange complex and thus acts to preserve soil structure. Sodic soils containing gypsum are relatively easy and inexpensive to reclaim. High percentages of gypsum in the soil, however, can cause serious problems especially in irrigated agriculture and, in some areas, the content of gypsum must be regarded as an important criterion in judging the suitability of soils for irrigation.

Van Alphen and Romero (1971) in a valuable publication on the characteristics and behaviour of these soils concluded that up to 2% gypsum in the soil favours crop growth, that between 2 and 25% has little or no adverse effect if in powdery form, but more than about 25% can cause substantial reductions in crop yield. They attributed these yield reductions in part to imbalanced ion ratios with particular reference to K/Ca and Mg/Ca ratios. They also noted that gypsum is readily redistributed in the soil and frequently forms cemented and indurated layers. With gypsum percentage between 14 and 80% these layers form a mechanical impediment to root growth and have adverse properties of water retention and transmission.

Van Alphen and Romero (loc. cit.) also drew attention to the dangers of subsidence which accompany injudicious irrigation of highly gypsiferous soils. Excess water percolating beyond the root zone may dissolve gypsum in the subsoil leading to subsidence. Since the subsidence pattern is very irregular the land may need to be re-levelled every year with associated problems of maintaining an adequate rooting depth. The hazards of subsidence may be especially critical in relation to hydraulic structures. A localized leak leading to the gypsum dissolving and subsidence of the ground may cause serious damage to structures that have not been designed with this hazard in mind. The engineering problems on gypsiferous soils are further complicated by the corrosive effects on concrete of sulphates released from gypsum.

At the same time it needs to be emphasized that substantial areas of highly gypsiferous soils are being successfully irrigated. In the Carlsbad, New Mexico, area of the United States, for example, where the gypsum content is particularly high, irrigation has been successfully practised for over 50 years. In this area alfalfa and cotton are the principal crops. It has been observed that roots seldom penetrate zones having more than about 70% gypsum. However, successful alfalfa production occurs with as little as 45 cm of soil over a deep horizon containing 90% gypsum (no root penetration). Crop yields are about half those usually obtained with good quality soil and water in a similar climate, but some of the loss of yield in the Carlsbad area must be attributed to the presence of other salts. Experience in the Ebro Valley in Spain showed that the cost of fertilizer and proper soil and water management on gypsiferous soil was about 20% higher than on deep, non-gypsiferous soils elsewhere in the Valley (van Alphen and Romero 1971).

2.5 SOIL-WATER RELATIONSHIPS

2.5.1 Infiltration Rate

The infiltration or intake rate is important for selection of suitable methods and designs for irrigation systems and management techniques. The initial intake rate rapidly decreases as the soil is wetted and intake reaches a steady state after some hours, which is known as the basic or equilibrium rate. Soils with high basic infiltration rates may be unsuitable for flood or furrow irrigation and drip irrigation or sprinkler irrigation may be preferable.

The maximum rate at which water enters a soil, or infiltration capacity (Richards 1952), is a dynamic property varying with season and management. The main factors affecting it are permeability of the profile, condition of the soil surface and soil-moisture content.

The least pervious layer at shallow depth regulates the vertical permeability, and so the infiltration rate. Structure, sodicity and bulk density influence the infiltration rate by their relation to pore size and cleavage planes. The infiltration rate is decreased by higher bulk density caused by pressure from tractors or cattle. Dry weather increases the initial infiltration capacity because of the cracking and higher moisture tension in the soil. In general, the higher the moisture content the lower the infiltration rate.

The method of determining infiltration using a double cylinder infiltrometer is described by the USDA/ARS and SCS (1956) and outlined in Appendix B.2. The method is not well suited to strongly cracking soils which should be studied in basins or furrows . During soil surveys tests may have to be made at different moisture contents though the soil must not be saturated, of course. Both the initial intake rate on dry soil and the initial and basic rates on soil, at a moisture level near to that at which an irrigation would be given, are useful for irrigation design purposes.

Infiltration rates vary seasonally and from place to place and many tests are needed to obtain a reliable average figure. However, carefully chosen sites, each with 3-5 replicates, provide sufficiently reliable data for use in estimating irrigation efficiency, application rates and the length of time water must be applied, together with other factors such as depth of wetting, root zone, etc.

If the infiltration rate after six hours remains in excess of 12.5 cm/h, gravity irrigation may not be practicable except in small basins because of difficulties with water distribution and excessive percolation losses. With rates from 0.1 to 0.2 cm/h, surface waste may be excessive or ponding may reduce yields, crops may be damaged by scalding in hot weather, and leaching may be difficult. Below 0.1 cm/h the soils are generally considered non-arable (except for rice). Optimum infiltration rates for gravity irrigation are between 0.7 and 3.5 cm/h. On cracking clays the infiltration rate is very rapid at first but soon decreases to about zero. Such soils are more favourable than impermeable non-cracking clays but irrigation may be hazardous with poor quality water.

Infiltration studies should be regarded as an essential part of soil investigations for irrigation development. They provide information for estimating irrigation efficiencies, required farm turnout capacities and deep percolation losses, and as a guide to desirable irrigation practices. They may also be used as a help in distinguishing land suitability classes, though often high or low infiltration rates will be associated with other undesirable properties that cause lower productivity or higher irrigation labour requirements.

2.5.2 Permeability (Hydraulic Conductivity)

Permeability has been defined qualitatively by Parr and Bertrand (1960) as "the quality or state of a porous medium relating to the readiness with which such a medium conducts or transmits fluids." When defined quantitatively the term hydraulic conductivity is used. This has been defined by Commission I (Soil Physics) of the ISSS (1976) as the constant of proportionality between the flux and the total driving force in Darcy's law (expressed as m^2 per Pa per s or m^2 per mbar per s), or as the flux caused by a unit driving force.

The average hydraulic conductivity of a soil profile is used to determine subsurface drainage and to evaluate the possibility of perched water table conditions developing which may injure crop roots. No universally acceptable minimum values for hydraulic conductivity can be established. Such values depend on the depth at which the slowly permeable zone occurs, on the frequency of heavy rainfall during the cropping season, and on the crops to be grown. To obtain high yields, the upper rooting zone should not be saturated more than 48 hours during most of the crop growth period (less with a susceptible crop like sesame and rather longer with a tolerant crop, such as sorghum, after the seedling stage). Thus the minimum hydraulic conductivity should be adequate to ensure that a saturated condition, whether from rainfall, irrigation, or both, is unlikely to occur for more than 48 hours in the upper root zone.

For drainage design, the unsaturated as well as saturated flow may need to be taken into consideration, but this information is not usually available and is not collected during soil survey work though it may be studied by national soil institutes.

There are many factors that affect permeability: they include temperature, water quality and other factors, such as land use and standard of management, which strongly influence soil characteristics but are not inherent to the soil itself. Some factors, such as the presence of soil cracks or holes created by roots, worms or larger animals can exert a very important and sometimes extremely localized influence on permeability. Consequently, it is not always easy to obtain truly representative values of hydraulic conductivity that can be used with confidence in evaluating soils for irrigation, particularly when measurements must be made in dry soil rather than in saturated soil below the water table. In view of the critical nature of these values, it is especially desirable that descriptions of soil and unconsolidated strata should place special emphasis on morphological features that influence or reflect permeability. These include texture, structure and structure stability, consistency, colour and mottling, layering, the presence or absence of insoluble carbonates, cleavage planes, visible pores, and depth to impermeable strata such as bedrock or a hardpan. Good soil descriptions provide a check upon actual measurements of hydraulic conductivity - a basis for deciding whether or not such measurements are likely to be representative.

The measurement of hydraulic conductivity is discussed further in the context of soil drainability and internal drainage in sections 4.2.2 and 4.2.3. Table 4 includes average values for permeability for various grades of soil texture and substratum materials. Treatment of the data is described in Annex 6 of the publication on drainage testing (FAO 1976b).

Table 4

REPRESENTATIVE PHYSICAL PROPERTIES OF SOILS

Soil Texture	Infiltration 1/ and Permeability cm/h P_f	Total Pore Space % N	Apparent Specific Gravity A_s	Field Capacity % FC	Permanent Wilting % PWP	Total Available Moisture 2/		
						Weight % $P_w = FC - PW$	Volume % $P_v = P_w A_s$	cm/m $d = \frac{P_w}{100} A_s D$
Sand	5 (2.5-25)	38 (32-42)	1.65 (1.55-1.80)	9 (6-12)	4 (2-6)	5 (4-6)	8 (6-10)	8 (6-10)
Sandy Loam	2.5 (1.3-7.6)	43 (40-47)	1.50 (1.40-1.60)	14 (10-18)	6 (4-8)	8 (6-10)	12 (9-15)	12 (9-15)
Loam	1.3 (0.8-2.0)	47 (43-49)	1.40 (1.35-1.50)	22 (18-26)	10 (8-12)	12 (10-14)	17 (14-20)	17 (14-20)
Clay Loam	0.8 (0.25-1.5)	49 (47-51)	1.35 (1.30-1.40)	27 (23-31)	13 (11-15)	14 (12-16)	19 (16-22)	19 (17-22)
Silty Clay	0.25 (0.03-0.5)	51 (49-53)	1.30 (1.30-1.40)	31 (27-35)	15 (13-17)	16 (14-18)	21 (18-23)	21 (18-23)
Clay	0.05 (0.01-1.0)	53 (51-55)	1.25 (1.20-1.30)	35 (31-39)	17 (15-19)	18 (16-20)	23 (20-25)	23 (20-25)

Note: Normal ranges are shown in parentheses.

1/ Intake rates vary greatly with soil structure and structural stability, even beyond the normal ranges shown above.

2/ Readily available moisture is approximately 75% of the total available moisture.

The information in this Table is taken from Israelson and Hanson (1962) with the permission of the publishers J. Wiley and Sons, New York.

2.5.3 Soil-Water Availability

The capacity of a soil to retain water available to plants has a direct bearing on required depth and frequency of irrigation and is important therefore, in judging the suitability of a soil for irrigation.

Readily available water is that portion of the water in the soil that can be readily absorbed by plant roots (about 50-75% of the total available moisture). The "total available moisture" has customarily been regarded as the difference between the soil moisture contents at "field capacity" and "wilting point".

The earlier concept of field capacity as a specific amount for a given soil is not correct but in spite of its lack of precision the term is useful in practice to indicate in a qualitative way the wetter limit of water availability to plants. A measurement can be made by sampling the soil one or more days after saturation. In well-drained soils, water in excess of field capacity drains away more or less rapidly whereas in slowly drained soils lack of oxygen may limit water uptake. For many studies of soil-water, reproducible measurements of moisture content at specific pressures or tensions are preferable, though determinations, commonly carried out on disturbed samples, may deviate considerably from values under field conditions. The permanent wilting point can be satisfactorily represented by the moisture content at 15 bars tension for most plants.

There have been wide differences of opinion as to the availability of water between field capacity (FC) and the permanent wilting percentage (PWP). Viehmeyer (1972) and his colleagues presented experimental evidence supporting the "equal availability" theory which states that plants can obtain water with equal facility between FC and PWP. Other workers maintained that plant growth diminishes progressively as the moisture content falls. Neither theory has much support now. The third theory, originally presented by Wadleigh (1955) and others, that plant growth is a function of soil moisture stress is now generally favoured, although the application of this concept is difficult.

This difference in thinking has affected recommendations for irrigation practice. Those in favour of the equal availability theory recommend delaying irrigation till most of the available water has been consumed and the moisture content has dropped very close to the PWP, which implies infrequent irrigation with heavy applications. The 'more water, more growth' idea requires frequent irrigation to keep the moisture content close to field capacity. The concept relating plant growth to soil moisture stress means scheduling irrigation whenever the moisture tension increases to the level that affects plant growth (Hagan 1955).

Considerable experimental support can be found for the application of each of these concepts, and Hagan (1955) suggests that overgeneralization has been the major factor creating the controversy. In practice, irrigation is applied well before wilting point is reached and the different practices are related to different crops, soils and water control. Depletion levels at which irrigation is best applied have been determined for most crops (see for example Table 30.1 in Saise and Hagan 1967, and Table 39 in FAO 1977).

These considerations point the need for understanding the pattern of water availability in the soil throughout the range from near-saturation to wilting point. Laboratory methods have been developed for determining soil water holding capacity in weight percentage at specific tensions covering this range, possibly at 0.1, 0.2, 0.33, 0.5, 2.5 and 16 bars. Usually, in fact, the water content is determined at equilibrium under pressures in the pressure plate (up to 1 bar) and pressure membrane apparatus (above 1 bar it is commonly related to pF which is the logarithm of the numerical value of the negative pressure of the soil moisture expressed in centimetres of water). The values obtained are converted to volume percentages by multiplying by the measured bulk density of the soil and can be plotted against the corresponding tensions to obtain a soil moisture characteristic curve. Representative values for field capacity, permanent wilting percentage and available soil water for soils of different texture are given in Table 4.

The depth and the contrast in textures of separate horizons also affect moisture holding capacity in the field. For example, an horizon of fine textured soil overlying a coarse soil horizon will include a zone immediately above the coarser horizon having a higher capacity than if the soil were uniform throughout. A shallow soil profile of less than 60 cm depth will hold more water per unit depth at field capacity than a deeper soil of the same nature. Soil-water characteristic curves based on laboratory measurements cannot allow for these effects and may be unreliable for this reason. Wherever possible, determinations of field capacity should be carried out in situ. A tensiometer can be used in the field to measure increasing tension (up to about 0.85 bar) as a soil dries out following heavy irrigation. Corresponding measurements of moisture content can be made with a neutron-probe. Alternatively samples can be taken from several depths for moisture determinations against time. Levelling out of the moisture content curve indicates the field capacity. It may be convenient to start carrying out field investigation of moisture retention immediately after measurements of infiltration rate.

Data on soil water holding characteristics are interpreted, in particular, to determine the depth and frequency of irrigation required. The level of depletion appropriate for planned crops must be taken into account, together with other soil moisture **characteristics** such as infiltration rates, hydraulic conductivity and groundwater levels. In the case of saline soils, adjustments need to be made to account for the osmotic pressure of the saline soil solution. Additional considerations include the specific soil water requirements during the different stages of crop growth and the rather higher soil-water levels to be maintained during very hot dry periods.

The depth of soil which must be examined to determine available soil-water depends on the nature of the crops to be grown but, as a general rule, it is desirable that data be collected on all horizons to a depth of about 120 cm (deeper if tree crops are envisaged). The total available moisture is determined by summing the contributions of the separate horizons within the total depth considered.

The following examples, illustrate the way in which data on available water can be set out and developed:

a. for a single horizon:

texture : loamy sand
horizon depth (0-30 cm) : 30 cm
field capacity : 8.8 % by weight
water content at wilting point (15 bar) : 3.2 % by weight
bulk density : 1.55 g.cm^{3}
available water : $\frac{(8.8-3.2)\times30\times1.55}{100}=2.6$ cm

b. for a soil comprising four horizons:

Depth	Texture	Available water (cm)
0-30	Loamy sand	2.6
30-55	Loamy sand	2.2
55-90	Loamy fine sand	3.1
90-120	Medium sand	1.1
	Total available water	9.0 cm

c. to determine irrigation frequency:

To provide a simple example a crop, possibly potato, with a rooting depth of 55 cm is assumed to require irrigation when soil water tension reaches 0.5 bar under an evapotranspiration rate of 5 mm/day. From the following additional data the depth and frequency of irrigation can be calculated:

Horizon	Depth of Horizon (a)	Field Capacity (b)	0.5 bar percentage (c)	Bulk density (d)	Depth of water to be applied $\frac{(b-c) \times d \times a}{100}$
Horizon 1	30 cm	8.8 %	5.8 %	1.55 g/cm^3	1.4 cm
Horizon 2	25 cm	8.5 %	5.5 %	1.50 g/cm^3	1.1 cm
				Depth of water to be applied	2.5 cm

$$\text{irrigation interval in days} = \frac{\text{depth of irrigation}}{\text{evapotranspiration rate}} = \frac{2.5}{0.5} = 5 \text{ days.}$$

In this simplified example the depth calculated relates only to consumptive use. In practice the total depth of irrigation will have to take account of such factors as irrigation efficiency and leaching requirement. Moreover the evapotranspiration rate will have to be adjusted, using crop coefficients which indicate the crop water requirements at different stages of growth (see FAO 1977).

The required depth and frequency of irrigation has an obvious bearing on the suitability of a given soil for irrigation. In very sandy soils the soil water holding capacity may be too small for irrigation by normal surface methods to be practical. In general, profiles with less than 50 mm of total available water per 100 cm soil depth are difficult to irrigate successfully. Most class 1 soils contain at least 120 mm of total available water per 100 cm of soil depth, with a minimum of about 30 mm in the first 30 cm. These values are given merely to provide a general indication of requirements, for it must be stressed that minimum acceptable levels of soil water retention depend very much on local circumstances and, in particular, on the method of irrigation to be employed.

CHAPTER 3

TOPOGRAPHY AND LAND DEVELOPMENT CONSIDERATIONS

3.1 INTRODUCTION

This chapter mainly concerns the slope, shape and cover of the soil surface and their relationship to the cost and feasibility of irrigation development.

A moderate amount of training is required to develop proficiency in distinguishing and assessing lands of varying degrees of suitability for irrigation. For the purpose of land classification, considerable experience is needed to estimate adequately the costs of levelling and other development work from field observations. In this, an experienced agricultural engineer engaged in detailed layout studies for costing on various types of topography can be of help to the soil scientist.

One of the main purposes of surveys of low and medium intensity is to outline areas of high development potential for closer study later, and it is specially important to establish sound criteria for distinguishing unsuitable land. In drawing the broad conclusions required, considerations of topography are likely to be more important than those of soils, and serious mistakes can occur when estimates of development cost are unreliable, for instance because accurate topographic maps are unavailable. Such maps are essential for detailed appraisal of areas for surface irrigation and desirable, but less essential, when sprinkler irrigation is contemplated. They may not be sufficient by themselves, however, since they rarely indicate microtopography.

3.2 TOPOGRAPHICAL CONSIDERATIONS

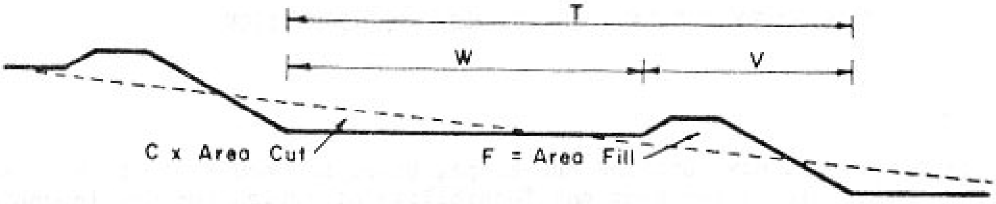
Topography is extremely important in irrigated agriculture for it influences choice of irrigation method, the labour requirements, irrigation efficiency, drainage, erosion, range of possible crops, costs of land development and size and shape of fields. In the sections which follow, topography is discussed in terms of four of its aspects which have a special bearing on irrigation suitability: slope, micro-relief, macro-relief and position.

3.2.1 Slope

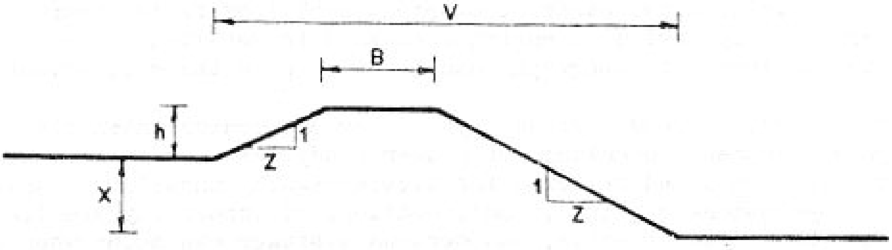
The acceptable degree of slope depends on factors such as: intended method of irrigation, rainfall intensity, risk of erosion and planned cropping pattern.

It is the experience of the U.S. Bureau of Reclamation that gravity irrigation is rarely suited to slopes exceeding 17%. Sprinkler irrigation of arable crops is acceptable in western U.S.A. on slopes not exceeding 20%, but tree crops are commonly grown on slopes of 35 and occasionally 45%. Elsewhere, allowance must be made for the erosive effect of heavy rainstorms of short duration by reducing the permissible slope (to 8 or even 2%) or growing more erosion resistant crops, e.g. grass.

Observation of cultivated slopes early in the soil survey should indicate the limit of slope for rainfed crops which is the same for sprinkler irrigation, the latter being adaptable to the infiltration capacity of the soil. The safe limit for gravity irrigation is usually about half that for rainfed farming; in some regions erosion by rainfall may dictate the limit of slope. In general, erosion is less under irrigation than it is under rainfed farming because land smoothing and grading minimizes local contributory causes of erosion, but poor water management can cause needless erosion. The maximum allowable stream flow is related to slope. In



CROSS SECTION OF BENCH



CROSS SECTION OF DIKE

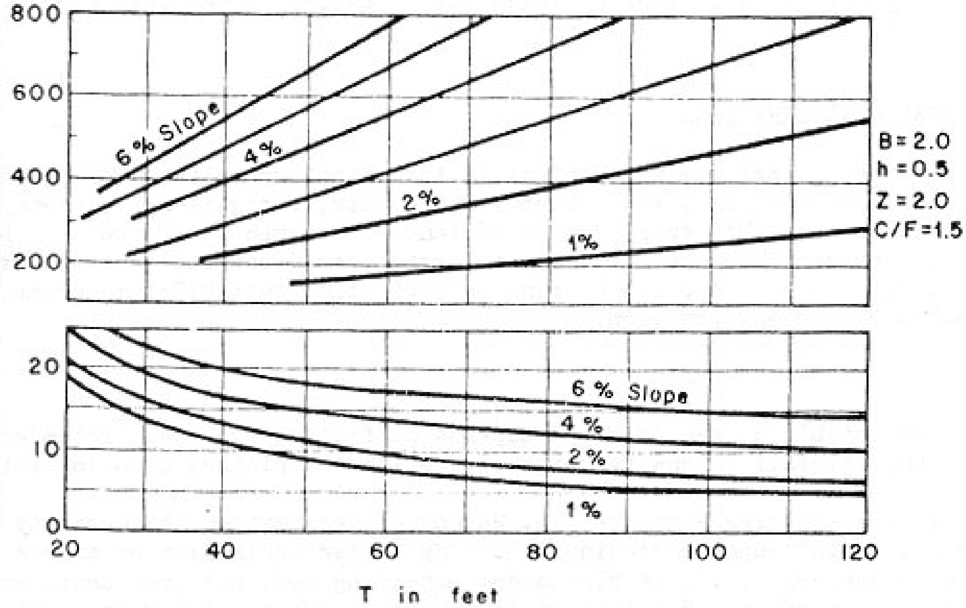


Figure 2: Contour bench relationships

Note: 1 yd^3 is equivalent to 0.765 m^3
1 acre is equivalent to 0.405 ha
100 yd^3/acre is equivalent to 189 m^3/ha

furrow irrigation, for example, Criddle (1956) suggested that this value (Q_{max}) can be roughly estimated in gallons per minute by dividing 10 by the percentage slope. Thus:

$$Q_{max} = \frac{10}{\text{Slope }\%} \text{ gallons per minute}$$

or alternatively

$$Q_{max} = \frac{0.63}{\text{Slope }\%} \text{ litres per second}$$

This formula applies to soil of average erodibility. Actual field tests should give more accurate estimates, even if variable because of the degree of soil compaction and type of land use at the time of the test.

Irrigation of extremely gentle slopes (0–0.5%), where the soil is slowly permeable and heavy rain is frequent, may lead to scalding by ponded water and waterlogging, particularly in a hot climate. However, if infiltration rates are moderately good and large flows of water are available to push the water across the field, such slopes are conducive to high irrigation efficiency. The uniform distribution of water on almost flat land requires very precise levelling, and productivity is often lower than on gently sloping land. To create a slope of 0.1% on flat land requires the movement of 280–330 m³ of soil per hectare. With very permeable soils, sprinkler irrigation may give the most uniform water distribution over flat land.

Smooth slopes of 0.1 to 2% are usually regarded as ideal for gravity irrigation under average topographic conditions. In contrast to steeper land, such slopes reduce costs for ditches, torrent structures and labour to a minimum and do not restrict the choice of climatically adapted crops. Progressively lower crop yields on gravity irrigated land of increasing steepness (range 2 to 7%) have been attributed to poorer water penetration, partially remediable by the use of low yield nozzles in sprinkler irrigation systems.

Contour bench terraces can be used for slope modification and erosion control. They are excellent for slopes up to 3% but less useful on steeper slopes because of loss of productive land to berms. Figure 2 shows a cross section of a bench terrace and associated dike area. It also shows, for slopes of up to 6%, the required excavation for bench construction and the relationship between productive and non-productive areas. Excavation requirements apply to a uniform smooth slope only.

Table 5 relates topography to the most appropriate irrigation method, type of crop and other features.

Table 5 GUIDE FOR SELECTING A METHOD OF IRRIGATION

Irrigation method	Topography	Crops	Remarks
Widely spaced borders	Land slopes capable of being graded to less than 1% slope and preferably 0.2%	Alfalfa and other deep rooted close-growing crops and orchards	The most desirable surface method for irrigating close-growing crops where topographical conditions are favourable. Even grade in the direction of irrigation is required on flat land and is desirable but not essential on slopes of more than 0.5%. Grade changes should be slight and reverse grades must be avoided. Cross slope is permissible when confined to differences in elevation between border strips of 6–9 cm.

Table 5 (cont.)

Irrigation method	Topography	Crops	Remarks
Closely spaced borders	Land slopes capable of being graded to 4% slope or less and preferably less than 1%	Pastures	Especially adapted to shallow soils underlain by clay pan or soils that have a low water intake rate. Even grade in the direction of irrigation is desirable but not essential. Sharp grade changes and reverse grades should be smoothed out. Cross slope is permissible when confined to differences in elevation between borders of 6-9 cm. Since the border strips may have less width, a greater total cross slope is permissible than for border irrigated alfalfa.
Check back and cross furrows	Land slopes capable of being graded to 0.2% slope or less	Fruit	This method is especially designed to obtain adequate distribution and penetration of moisture in soils with low water intake rates.
Corrugations	Land slopes capable of being graded to slopes between 0.5% and 12%	Alfalfa pasture and grain	This method is especially adapted to steep land and small irrigation streams. An even grade in the direction of irrigation is desirable but not essential. Sharp grade changes and reverse grades should at least be smoothed out. Due to the tendency of corrugations to clog and overflow and cause serious erosion, cross slopes should be avoided as much as possible.
Graded contour furrows	Variable land slopes of 2-25% but preferably less	Row crops and fruit	Especially adapted to row crops on steep land, though hazardous due to possible erosion from heavy rainfall. Unsuitable for rodent-infested fields or soils that crack excessively. Actual grade in the direction of irrigation 0.5-1.5%. No grading required beyond filling gullies and removal of abrupt ridges.
Rectangular checks	Land slopes capable of being graded so single or multiple tree basins will be level within 6 cm	Orchards	Especially adapted to soils that have either a relatively high or low water intake rate. May require considerably grading.

Table 5 (cont.)

Irrigation method	Topography	Crops	Remarks
Countour checks	Slightly irregular land slopes of less than 1%	Fruit, rice, grain and forage crops	Reduces the need to grade land. Frequently employed to avoid altogether the necessity of grading. Adapted best to soils that have either a high or low water intake rate.
Contour ditches	Irregular slopes up to 12%	Hay, pasture and grain	Especially adapted to foothill conditions. Requires little or no surface grading.
Portable pipes	Irregular land surface	Hay, pasture on small scale	Minimum preparation of land surface required.
Subirrigation	Smooth-flat	Shallow rooted crops such as potatoes or grass	Requires a water table, very permeable subsoil conditions and precise levelling. Very few areas adapted to this method.
Sprinkler	Undulating 1- > 35% slope	All crops	High operation and maintenance costs. Good for rough or very sandy lands in areas of high production and good markets. Good method where power costs are low. May be the only practical method in areas of steep or rough topography. Good for high rainfall areas where only a small supplemental water supply is needed.
Contour bench terraces	Sloping land - best for slopes under 3% but useful to 6%	Any crop, but particularly well suited to cultivated crops	Considerable loss of productive land due to berms. Require expensive drop structures for water erosion control.
Subirrigation (installed pipes)	Flat to uniform slopes up to 1% surface should be smooth	Any crop, row crops or high value crops usually used	Requires installation of perforated plastic pipe in root zone at narrow spacings. Some difficulties in roots plugging the perforations. Also a problem as to correct spacing. Field trials on different soils are needed. This is still in the development stage.
Drip	Any topographic condition suitable for row crop farming	Row crops or fruit	Perforated pipe on the soil surface drips water at base of individual vegetable plants or around fruit trees. Has been successfully used in Israel with saline irrigation water. Still in development stage.

3.2.2 Micro-relief

The term micro-relief applies to minor surface undulations and irregularities of the surface, with differences in height between crest and trough of 4-5 cm in flat lake plain areas or 4-5 m in areas of windblown sand.

Evaluation of irrigation suitability requires an estimate of levelling requirements. Gravity and subsurface irrigation methods are the most, and sprinkler the least, sensitive to micro-relief. The amount of levelling and total cost of land development justified for areas of each land class is usually based on economic analysis of the anticipated net values attributed to irrigation for crops expected to be grown. A rough guide is that the cost of undeveloped land plus land development costs should not exceed the cost of fully developed irrigated land in the area. In schemes wholly financed by government, prior agreement to maximum land development costs should be obtained, and if possible the land with most expensive costs should be avoided.

The maximum land development costs, as calculated or agreed, may be expressed in terms of amount of work (e.g. cubic metres of soil to be moved) that could be done for the agreed sum, assuming it to be the sole item for development. Clearly, however, it is the cost of correcting all deficiencies that is the criterion for land classification.

Land grading is the most common development requirement. It is often expressed in terms of cut and fill, assuming that an average half the area is cut and half is fill. The total volume of earth so moved is not the sole determinant of cost. Other factors include depth of cut, distance of land, soil conditions, desired precision of the final grading and type of equipment available.

Table 6 shows the amount of earth to be moved at various depths of cut and fill which together with local unit costs can be used to calculate grading costs.

Table 6 GRADING ESTIMATES IN TERMS OF CUT AND FILL

Type of grading	Light	Medium	Heavy
Average cut and fill (cm)	7.5	15	30
Earth moving (m^3/ha)	375	750	1500
Earth moving (yd^3/ac)	200	400	800

Note: 100 yd^3/ac equivalent to 189 m^3/ha.

Subsoil quality must always be evaluated by the soil surveyor since it may limit the amount of grading advisable or greatly increase the cost if it is possible to conserve and later respread the topsoil. Although most subsoils are unproductive when first exposed, they gradually recover with the addition of fertilizers and organic matter. In contrast, coarse sands, gravels or layers rich in lime or gypsum or exchangeable aluminium may never respond to irrigation after severe cutting.

Where levelling for gravity irrigation is likely to be a permanent threat to productivity on shallow soils, sprinkler irrigation should be considered. Alternatively, very short runs and small fields may have to be accepted.

Additional information on the estimation of land levelling costs from topographic data was given by Marr (1957) and USDA Soil Conservation Service (1959).

3.2.3 Macro-relief and Field Size

In contrast to the correctable deficiencies of land with a smooth, uniform slope are the noncorrectable deficiencies of complex topography where slopes change frequently in gradient and direction. The more complex the topography the less desirable is gravity irrigation. Sprinkler irrigation is better suited to this type of terrain, but suffers from relatively high annual operation, maintenance and replacement requirements.

For maximum production with a minimum labour requirement, irrigated fields should be large and the irrigation runs long and straight. When topographic or man-made features prevent development of large, smooth, rectangular fields, the land is less suitable for irrigation. Disadvantages inherent to small, irregularly shaped fields include a disproportionate amount of land taken up by head ditches, drains and headlands for turning machinery, a possibly reduced range of economically possible crops and increased labour costs for all operations including irrigation. Land grading costs per cubic metre are also higher.

Field size and shape need to be considered as criteria in evaluating land for gravity irrigation. Sprinkler irrigation is less exacting in its requirements but large fields are generally still needed for efficiency and economy. For additional information on this topic see Vader (1967), Haldeman and Frost (1965), Maletic (1968) and Langley (1969).

Table 7 shows an evaluation of field size and shape in relation to suitability for mechanized farming. Field size and shape are less important when machinery is not used.

Table 7 EVALUATION OF IRRIGATED FIELD SIZE

	Very favourable	Favourable	Moderately favourable	Unfavourable
Field size, minimum (ha)	8.0	3.6	2	1
Length of run, minimum (m) 1/	390	120	100	50
Dimensions (m)	390 x 200	120 x 300	100 x 200	50 x 200

1/ Consideration must be given to intake rates when assessing the length appropriate for a given soil.

3.2.4 Position and Accessibility

Small tracts of land, regardless of quality, are frequently found uneconomic to include in an irrigation scheme if they are remote from the source of water or suitable drainage outlet. They are usually excluded after completion of the initial land classification.

Areas of land rising several metres above adjacent land should be delineated on the map for ease of identification and location. Any decision to exclude them from the project would be made by the engineers and economists in consultation with the soil surveyor. Normally, areas under 0.5 ha would be disregarded.

Any very low land likely to present drainage problems or to become too wet for certain crops should be assessed with the help of the drainage engineer. In pumping schemes, well drained lands at a lower level than the water source can sometimes be served advantageously by a gravity diversion.

3.3 CONSIDERATIONS OF LAND COVER

Unfarmed land has some vegetative cover and possibly also stones scattered on the surface. Clearing costs must enter into the evaluation of land.

3.3.1 Removal of Vegetation

Removal costs depend on size and type of vegetation, local labour costs, equipment available and area involved. Costs rise steeply as the size of individual bushes and trees and density of stand increases. Using modern equipment and in comparison with clearing costs of light brush (sage), a thick stand of pine 30-45 cm in trunk diameter could cost 40 times as much and dense jungle 120 times as much. For large tracts of land (over 2000 ha) very heavy machinery now available could halve the cost of jungle clearing by conventional methods (large bulldozers).

Sandy soils tend to cost less to clear than fine textured soils. Clearing large trees with bulldozers tends to leave large holes where the tree stood, and soil clinging to the roots is carried to the windrows in preparation for burning. Land grading is therefore usually necessary. Ground cover that is salable reduces the net clearing costs.

3.3.2 Removal of Rocks and Stones

Rock outcrops are difficult and expensive to remove and blasting is the usual method if their removal is essential. They are, however, seldom troublesome in irrigable areas since land with bedrock near or at the surface would not meet the conditions for arable land. When soil and drainage conditions are favourable occasional outcrops may be disregarded unless they restrict the productive area or field size and shape. In the latter event, the land suitability class should be downgraded.

Stones (20-40 cm in diameter) and cobbles (7-20 cm in diameter) are usually removed from the tillage zone although some crops, e.g. pasture and orchard, suffer little loss of production. Removal costs should be a consideration in assigning land classes.

A method of estimating the cost of stone removal used by the U.S. Bureau of Reclamation is to remove and pile all stones or cobbles from the surface and upper 8 inch (20 cm) depth from a 21 ft x 21 ft area (0.01 acre) and then to measure or estimate the volume of the stone heap. Thus, each 10 inch diameter stone from this area is equivalent to 1 yd^3/ac in the area as a whole. A metric equivalent of this method might use an area of 10 m x 10 m (0.01 ha) for excavation. Each 26.7 cm stone found within this area would then be approximately equivalent to 1.0 m^3 of stones per hectare.

Mechanical equipment will pick up superficial stones and cobbles at a cost of about $6.50 and $2.25 per cubic metre respectively. Special equipment or manual labour is required for larger stones. Some 2-3 manhours per cubic metre are required for manual picking of stones, plus the cost of stone transport.

3.4 OTHER LAND DEVELOPMENT CONSIDERATIONS

3.4.1 'Usual' Land Development Costs

'Usual' land development costs include expenditure on farm ditches, lining of ditches, headgates, water control structures, farm waste water ditches, erosion control structures, etc. These 'usual' costs vary little between farms, particularly between farms sited on lands of the same subclass designation. Because of their small variability within areas of similar terrain, such costs are rarely taken into account in determining land suitability class, but must be quoted in estimates of total land development costs.

3.4.2 Soil Profile Modification

With the advent of deep ploughing equipment capable of modifying soil profile characteristics to a depth of 120 cm or more at reasonable cost, profile modification becomes a practical means of improving the production capacity of some types of soil. For example, in the State of Idaho, USA, deep ploughing to a depth of about 100 cm is being extensively used on solonetz soils as a means of increasing productivity. In these soils the deep ploughing completely obliterates the normal dense "B" horizon, and mixes this horizon throughout the 100 cm depth. Production increases of 500% or greater are commonly associated with deep ploughing solonetz soils in this area. This level of increase leads to production equal to the best lands in the area. Infiltration rates are increased from less than 0.15 cm per hour to about 2.0 cm per hour, and become stable at the latter value. Evaluation of irrigation potential based on the premise of deep ploughing is being used by the U.S. Bureau of Reclamation in some areas. Deep ploughing costs under the conditions cited above range from $86 - 111 per hectare.

Apart from its success in alleviating the problems of solonetz soils, profile modification appears to be a potential means of improving several other kinds of unfavourable soil morphology including soils with very sandy topsoil overlying medium textured material or soils with clayey surface layers overlying coarser subsoil. Local field trials should be made to verify that productivity can be improved by this technique before it is used for land classification purposes.

3.4.3 Flood Protection

Overflow hazards from rivers or drainage ways often influence the use, management, and development costs of affected portions of an irrigation project. Any lands located in areas susceptible to such damage should be evaluated for possible flood problems and possible protective measures. Evidence of frequent flooding is often provided by surface debris and observable injuries to trees. Important information to collect in flood hazard areas include (1) location and extent of flooding; (2) frequency of flooding; (3) depth and duration of flooding; (4) the time of year of flooding in relation to crop planting dates and growing season; (5) type of flood damage (i.e.: erosion, sediment, other); (6) local evidence of the influence of the flood hazard on irrigation farming operations, and (7) on the choice and yield of crops.

Very often flood damage observable at the time of soil survey will not recur because of upstream dam construction for the irrigation project. Reduction or elimination of flooding is frequently a benefit of large-scale projects. Thus, before conclusions are drawn relating to land suitability classification, the flooding evidence should be discussed with the project hydrologist and engineer who will be able to estimate the effect of proposed project works on future flooding.

Lands subject to severe and frequent, damaging floods should usually be excluded from an irrigation project. Care should be taken, however, in assessing damage caused by flooding. For example, winter flooding of lowlying pasture lands in the State of Oregon, USA, has been observed to do very little damage because the flood water has low velocity, no sediment, and rises slowly. In parts of the Far East a floating rice crop is grown during the flood season. Although not as productive or as convenient as the normal wet rice crop, floating rice affords some income and is a means of making the most of a bad situation.

Sound evaluation of flood hazards and the associated effects on irrigation suitability is difficult because no two situations are exactly alike. In some places small protective dikes or channel cleaning may be an adequate preventive measure. Elsewhere a change of crops or of crop sequence is the best solution.

In other instances the floods are so infrequent that the average annual production is adequate to make farming worthwhile. In this last situation the suitability classification should reflect the average anticipated productivity.

Runoff from adjacent hillsides is a common problem on lands lying at the base of hills. The problem is particularly serious in erosive areas subject to torrential and damaging rainfall during parts of the year. Under such conditions soil, stones, and vegetative debris from the hillside may overflow crop land located at the base. The potential runoff and flood damage in these areas needs to be assessed. Stones and cobble on the surface of the soil and observable severe erosion on the hillside will be indications of existing or potential flood problems. Lands subject to such damage are less suitable for irrigation development than lands otherwise similar. If the condition is very severe, lands subject to this type of runoff should be excluded from the irrigable area.

3.4.4 Farm Drainage

Farm drainage is that drainage undertaken by the water user on his own farm at his own expense (USBR 1953). Policies vary considerably in different parts of the world regarding responsibility for drainage construction associated with irrigation development. In some areas, including projects undertaken by the U.S. Federal Government in the western United States, subsurface drainage requirements may be considered a part of the total project costs. In other areas, responsibility for on-farm drainage is left to the individual farmer, only the outlet facilities being included in the project development plans. The latter approach is usually less desirable for, if some farmers fail to construct their portion of the planned drainage, their neighbours will be adversely affected.

If the individual farmer is to be responsible for subsurface drainage, the costs involved must be regarded as land development costs and added to other development cost estimates in evaluating arability. As a consequence, lands are frequently rated as unsuitable for irrigation development on the grounds of high drainage costs.

In irrigation development, throughout the world, it is usual to regard provision of surface drainage for farm wastes as a farm cost. Unless expensive erosion control structures or outlets for very lowlying areas are required, such costs are usually nominal and are considered as part of the 'usual' land development costs (see 3.4.1).

The assessment of drainage requirements is discussed in the next chapter.

CHAPTER 4

DRAINAGE AND RECLAMATION

4.1 INTRODUCTION

The control of water table levels must be economically possible for successful irrigated farming. This chapter describes the criteria used for assessing the quality of soil drainage and planning a system to maintain or improve it. The closely related problems of reclaiming saline and sodic soils are also considered.

Symptoms of rising groundwater and salinization may not become apparent for several years. It is essential from the beginning to recognize the need for drainage works in almost every irrigation scheme and commonly of some subsurface drainage. Secondly it is necessary to predict drainage requirements accurately, despite the difficulties caused by variability in underground strata, for without this the economic success of the project is in jeopardy.

The soil surveyor should assume initial responsibility for the preliminary appraisal of soil drainability and record data on observable water tables, variations in geomorphic units, areas with markedly different texture, structure, bulk density, salinity etc. for discussion with the drainage engineer. The soil surveyor will also be working with the agronomist and economist when deciding what combination of crops and irrigation practices would best suit the anticipated internal drainage conditions. The importance of surface and subsurface drainage is such that the soil surveyor must clearly understand the basic principles and procedures used in estimating drainage requirements.

Some conventional drainage terms used in this bulletin are defined as follows:

Surface drainage is the removal of water from the surface of the land.

Subsurface drainage is the removal or control of groundwater to maintain it at desired depth for successful crop production.

Drainage is the removal of excess surface and subsurface water.

Soil drainage refers to the flow of water through the soil, and the frequency and duration of periods when the solum is free of saturation under natural conditions.

Soil drainability refers to the ability of soil and substrata to respond to subsurface drains. It is a useful term since it enables predictions to be made of soil drainage under projected irrigation conditions.

Internal soil drainage is defined in the U.S. Soil Survey Manual (1951) as "that quality of a soil that permits the downward flow of excess water through it." It is determined by the texture, structure, and other characteristics of the soil profile and underlying layers and by the height of the water table, either permanent or perched, in relation to water added to the soil.

4.2 SOIL DRAINAGE STUDIES

4.2.1 Critical Depth to Groundwater

Crop production is limited by an inadequate rooting system and increasing salinity resulting from shallow groundwater. The water table may rise very rapidly if natural drainage is slow. For example, a deep percolation of 30 cm per year, a not unusual amount, can cause a rise of 150-450 cm under unfavourable conditions.

The following may provide clues to the likely magnitude of the rise in the water table that might result from irrigation:

- present fluctuations in the level of the water table due to rainfall;
- the elevation of the land surface with respect to possible drainage outlets;
- the distance to natural drainage outlets;
- the depth to any drainage barrier;
- the infiltration rate;
- groundwater pumping data;
- factors relating to the planned irrigation project including the anticipated irrigation efficiency, the anticipated distribution losses in the canal and lateral system, the consumptive use of the planned cropping system, and finally but not least, the anticipated level of irrigation management.

The highest level to which the water table should be permitted to rise during an irrigation season is an important factor in developing cost estimates for a subsurface drainage system. The permissible depth depends on such factors as the capillary conductivity characteristics of the soil; the prevailing evaporative conditions; the depth of rooting needed for optimal production; soil aeration; the intensity, amount, and frequency of rainfall; the quality of irrigation water; the quality of groundwater; crop water table tolerances; crop salt tolerance; the capability of the drainage system to provide the desired rooting environment. Tovey (1969) has shown in lysimeter studies that a high water table is not necessarily detrimental provided it is relatively stable.

As a general rule, a higher level of water table is tolerable in a cool area than in a hot, dry area, particularly if the water in the hot area is saline.

Although it may be desirable to maintain a water table at depths below 300 cm (10 feet), practical considerations of cost may make this goal unrealistic. However, except in very unusual circumstances, the water table for crops other than paddy rice should seldom be closer to the surface than 90 - 120 cm (36 - 48 inches) for over 24 hours. The decision on the design depth for water table control facilities, which has an important bearing upon drainage costs, should be jointly shared by the soil scientist, the drainage engineer, the economist and the agronomist.

Where an aquifer is sufficiently permeable as to produce large volumes of water from shallow wells, drainage costs by pumping are usually less than with open or tile drains. With pumped drainage it is usually advisable to hold the water table below a depth of 300 to 400 cm (10 or 12 feet) as a safety precaution in the event of a well failure. The quality of groundwater (see Chapter 5) tends to deteriorate over time. So it should be monitored if the pumped water is used for irrigation.

On peat soils it is usually necessary to maintain a high water table to prevent oxidation and subsidence. Roe (1936) found that maximum yields on peat soils were associated with a water table depth of 75 cm. If salinity problems are likely to develop, peat soils should be avoided for irrigation. However, under most conditions favouring the formation of peat, the water quality is excellent and soils with high water tables can be successfully irrigated - particularly for vegetable production.

Subirrigation is a special irrigation method requiring specific conditions. It involves large flows of water into the soil from surface ditches or blocked drainage channels which rapidly raise the water table enough to wet the surface by capillarity. Between main irrigations the water table is held at 45-60 cm depth by flows from widely spaced ditches. Surface irrigations may be needed for salt leaching where the rainfall is low. The soil should have a perfectly level surface and very permeable coarse textured or peaty subsoil for precise control of the water table depth. The water quality must be excellent. Irrigation efficiency is low because of deep percolation losses on coarse textured soil though losses may be small on peat. Shallow rooted crops do best, such as onions, carrots, potatoes melons and grasses, but even alfalfa, a deep rooted plant, produces moderately well if the water table is precisely controlled.

4.2.2 Soil Drainability and Internal Drainage

Soil permeability and depth to a drainage barrier stratum are important in predicting drainability. A barrier zone is a slowly permeable stratum such as impermeable clay layers, indurated or cemented hardpans, shale, rock or similar material. By definition (U.S. Bureau of Reclamation 1964) the drainage barrier has a permeability value less than one fifth the average of the horizons above it.

A drainage barrier usually causes a saturated zone to develop above it and sets a limit to the depth of permeable material through which water can move laterally to a natural or man-made outlet. In uniform permeable material most of the flow may be below the drains so a barrier stratum means that the drains must be more closely spaced.

Construction costs for open ditch or tile drainage become very high when the barrier stratum is less than 275 cm from the surface. Therefore an accurate knowledge regarding depth to barrier is important to drainage cost estimates. The soil scientist should expect to help in locating drainage barriers within 3 metres (10 feet) of the surface while the drainage engineer will be mainly responsible for studying deeper materials and in characterizing the barriers for design purposes.

Thus, in studying soil profile characteristics the soil scientist should give particular attention to such factors as soil structure, observable pore size distribution, cemented or indurated horizons, and evidence of burrowing by insects, worms and larger animals, all of which have a direct bearing on drainage characteristics. Further clues to drainage conditions in different horizons are provided by soil colour (presence or absence of gley colours or mottling) and by the degree of development and distribution of the root system. Laboratory data, in particular information relating to the type of clay minerals, the bulk density and the content of exchangeable sodium, will assist reliable appraisal.

In drainage investigations the soil scientist has a supporting role to the drainage specialists who decide the need and design of drainage works. Soil survey does not normally provide sufficiently precise information on substrata conditions for a drainability map, which requires detailed studies by a network of observation wells and numerous permeability tests. The soil drainage characteristics observed by the soil surveyor are not necessarily definitive, since conditions may change when large amounts of water are applied, particularly in arid lands, though poor internal drainage is likely to remain poor unless it is remedied.

Satisfactory internal drainage implies a soil and substratum able to transmit water before saturation harms plants. Problems are unlikely with homogeneous soils, even clays unless they have high bulk density or exchangeable sodium, or with clay over sand, since the downward movement of water is only slightly retarded by the differing moisture tensions. Underlying clay or dense or indurated layers are warning signals.

Infiltration and percolation measurements help to assess the possibility of draining away the leaching requirement (see section 4.2.2) and of ponding or a perched water table occurring for longer than about 48 hours which is normal. Infiltration rates of 0.15 cm/hr may be excessive for a good rice soil, but are about the minimum for most other crops.

Table 8 lists some permeability values for common soil and substratum materials as developed by Ralph M. Parsons Company. They do not represent all soil conditions and local site-specific measurements are always needed. Some well aggregated clays in the western USA have permeabilities up to 25 cm/hr, whereas medium sands occur with very low permeability due to their high exchangeable sodium and a little montmorillonitic clay, and cemented gravels often have poor drainability.

4.2.3 Some Principles Guiding Drainage Investigations

Drainage investigations are directed toward determining the prevailing depths, slopes and fluctuations in level of the groundwater surface; the presence or absence of confined water tables (i.e. water under pressure below a slowly permeable strata); and the thickness and permeability of soil and substrata layers which may act to retard or transmit water. These investigations and the subsequent preparation of drainage recommendations are usually undertaken by drainage specialists and only the general approach to such work is described here.

Soundly conducted drainage investigations require a network of cased observation wells of known elevation; piezometer installations to detect confined water tables; numerous deep borings to determine the variability of substrata materials; and field tests for permeability. Three methods for obtaining in-place horizontal permeability data are commonly used. These are the auger-hole (or shallow well pump-out) test, the piezometer test, and the shallow well pump-in test. The 'permeameter' test is used to determine the vertical permeability of a narrow zone. Since soil scientists assist in conducting these tests, they are outlined in the following paragraphs and are described in more detail in the Appendix of this document.

The auger-hole test (Maasland and Haskew 1957; Van Beers 1963, Winger 1965) is a simple but reliable method for determining in-place permeability below a water table. A large auger hole (about 10 cm diameter) is bailed out and the rate at which the water returns towards the static level provides a basis for calculating the permeability. The test measures the average horizontal permeability from the static water table to the bottom of the hole when an impermeable layer is at the bottom of the hole, or a few inches below the bottom of the hole when the impermeable layer is some distance below the bottom of the hole. It has the advantage of simulating conditions in a drainage ditch (see Appendix B.1.1).

The piezometer test (Luthin and Kirkham 1949; Winger 1965) is similar but employs a narrow impermeable tube which is driven into the ground to a selected depth below the water table. Bailing or pumping followed by recording of the rise of water within the tube provides a measure of permeability within a thin layer adjacent to the bottom of the piezometer tube. The primary application of the test is to compare permeability in different layers and so detect the effective barrier layer (see Appendix B.1.2).

Winger (1965) described the shallow well pump-in test (see Appendix B.1.3). This procedure is also called the well permeameter test and is used when the water table is below the zone to be tested. Essentially, the test consists of measuring the volume of water flowing laterally from a well in which a constant head of water is maintained. The permeability rate is a composite rate for the full depth of hole being tested, but reflects primarily the permeability of the more permeable layers.

In most drainage studies knowledge of the horizontal permeability obtained by one of these three methods is considered to be sufficient, it being assumed that vertical permeability will be adequate for water to reach the saturated zone from which it will be drained horizontally. If there is cause to suspect the presence of slowly permeable layers above the saturated zone, the 'ring-permeameter' test described by Winger (1965) provides a method of determining the vertical permeability of these layers, which, although complex and rather slow, gives uniformly dependable results at a reasonable cost. It consists of measuring the rate at which water permeates through the test layer from a carefully positioned cylinder maintained at a constant head. Pairs of tensiometers and of piezometers are used to confirm the absence of a perched water table, the attainment of saturated conditions and fulfillment of the requirements of Darcy's law for the movement of liquids through saturated material, on which the subsequent calculation of permeability is based (see Appendix B.1.4).

The various forces acting upon groundwater are intricately involved and their separate influence may vary markedly within short distances. Several formulae have been developed to estimate required drain spacings from data on permeability and depth to barrier. Here it must suffice to say that the method used by the U.S. Bureau of Reclamation and widely elsewhere throughout the world (Dumm 1968) takes account of crop water requirements, irrigation efficiency, leaching requirements, desired water table depth, rainfall characteristics and specific yield.

Drain spacings have sometimes been determined by empirical methods based on depth to barrier and average permeabilities associated with various materials. Because of the importance of drainage to the success of an irrigation project, short cut methods for estimation of drainage requirements should be avoided unless their validity in the particular area has been proved.

A developed surface drainage system is necessary before irrigation can start and must include a surface drainage outlet to each farm. The soil scientist during the soil survey should locate all existing drainageways and areas which will require outlet surface drains for the drainage engineer to ensure that necessary facilities are made a part of the development plan.

4.2.4 Drainability Surveys - Field Operations

Some steps in drainability survey have been described already but the following paragraphs summarise the overall procedure. It is assumed that the soil survey will have already identified the major soils and their broad distribution in the landscape and it is highly desirable that the soil scientists responsible should discuss their findings with the drainage specialists.

i. The area is first covered in a reconnaissance manner for the purpose of noting the character of the vegetation, the presence of salts or sodic conditions, indications of water table problems, and in general

Table 8 COMPARISON AND CLASSIFICATION OF PERMEABILITY FOR DIFFERENT SOIL AND SUBSTRATUM MATERIALS

(Table prepared by Ralph M. Parsons Co.) (Permeabilities expressed in $cm/cm^2/h$)

Textural Grades and/or 1/ Substratum Materials	Maximum	Minimum	Normal	Soil Survey Index No.	Classification of Normal rates 2/ (Indices and Descriptive Classes)		
					Key Class	Drainability Index No.	Survey Key Class
Heavy clays	2.00	<0.005	0.03	1	Very slow	1	Very poor
Medium clays	2.50	0.01	0.10	1	" "	1	" "
Silty clay	2.50	0.01	0.15	2	Slow	2	Poor
Sandy clay	2.50	0.03	0.2	2	"	2	"
Silty clay loam	3.00	0.02	0.50	2	"	3	Fair
Clay loam	5.00	0.10	0.60	2	"	3	"
Silts	2.50	0.02	0.40	2	"	3	"
Silt loam	12.70	0.05	1.27	3	Mod. slow	3	"
Sandy clay loam	12.70	0.10	1.90	3	"	3	"
Loam	15.00	0.25	2.50	3	"	4	Good
Fine sandy loam	15.25	0.50	3.75	4	Mod. rapid	4	"
Sandy loam	16.00	0.50	4.50	4	" "	4	"
Coarse sandy loam	20.00	1.25	7.60	5	Rapid	5	Very good
Loamy fine sand	16.00	1.25	7.60	5	"	5	" "
Loamy sand	20.50	1.50	10.20	5	"	5	" "
Loamy coarse sand	25.40	7.60	12.70	5	"	5	" "
Fine sand and very fine sand	50.00	0.50	7.60	5	"	5	" "
Medium sand	250.0	7.60	15.25	6	Very rapid	5	" "
Coarse sand	500.0	25.40	50.80	7	Excessive	5	" "
Gravelly clays to gravelly clay loams	5.0	<0.005	0.5	2	Slow	3	Fair
Gravelly silts to loams	15.0	0.02	3.75	4	Mod. rapid	4	Good
Gravelly fine sandy loams to fine sands	250	7.60	25.4	6	Very rapid	5	Very good
Very gravelly clays to very gravelly sandy loams	50.8	5.10	12.7	5	Rapid	5	" "
Very gravelly silts to loams	250	12.7	25.4	6	Very rapid	5	" "
Very gravelly fine sandy loams to fine sands	500	25.4	50.8	7	Excessive	5	" "
Mixed pea gravels and sands	250	6.4	50.8	7	"	5	" "
Pea gravels clean	1000	100	200.0	7	"	5	" "

1/ 2/ see notes on page

Textural Grades and/or 1/ Substratum Materials	Maximum	Minimum	Normal	Soil Survey Index No.	Classification of Normal rates 2/ (Indices and Descriptive Classes)		
					Key Class	Drainability Index No.	Survey Key Class
Gravel, cobble and sands (mixed)	500	7.70	150.0	7	Excessive	5	Very good
Clean gravels	5000	150	320.0	7	"	5	" "
Cobble and gravel	7500	300	500.0	7	"	5	" "
Cobble	10000	500	1000.0	7	"	5	" "
"S" loose gravelly, "Gypsy" etc. 3/	100	2.5	50.0	7	"	5	" "
"S" marly or limey, soft to semi-hard	15	0.25	1.25	4	Moderate	3	Fair
"S" marly or limey, semi-hard to hard	0.25	<0.02	0.13	2	Slow	2	Poor
"S" clayey to limey, compact to very hard	0.15	<0.02	0.05	1	Very slow	1	Very poor
Lightly cemented gravels	320	0.5	50.0	7	Excessive	5	Very good
Any creviced or fractured rock	320	0.02	25.4	6	Very rapid	5	" "
Porous rocks including semi-hard and hard caliche	320	0.02	25.4	6	" "	5	" "
Uniform bedrock few or no fractures or crevices	0.02	<0.001	>0.002	1	Very slow	1	Very poor
Gypsum beds	5000	100	200	7	Excessive	5	Very good

1/ Textural grades are classified on the basis of normal structures and do not include highly dispersed soils containing excess exchangeable sodium ions. Data are from all known sources.

2/ These indices compare rates of water transmittal only. Drainability of an area is influenced also by depth to impervious layers, stratification, thickness and position of aquifers, slope and the rate of water intake and storage capacity of soils.

3/ Includes a wide variety of commonly unconsolidated substratum and subsoil materials (sand, silts, clays and gravels) with various degrees of weathering, illuviation and cementation.

areas requiring drainage relief before irrigation can begin. The soil scientists should be able to give great assistance to the drainage specialists in this preliminary stage of their studies and should accompany them in the field.

ii. Once the general location of project lands is established a grid of drainage observation pits is laid out. In general the rows of pits will be located along lines normal to the land contour, flow of the river, or major outlet. For the initial study of large project areas, deep pits at one to two kilometre intervals in lines two to five kilometres apart will suffice. If the variation in soil and substrata characteristics is considerable, additional pits will probably be needed. Drainage observation pits should be excavated to depths of 3 to 5 metres, if possible, and logged carefully by experienced soil scientists. These pit descriptions will doubtless contribute to characterizing the soils of the area. In relation to drainability, the profile logs should include information on the following for each horizon:

- textural character of each horizon and state of weathering;
- drainability, or permeability, as judged from structure, pore size characteristics, bulk density, root channels, root distribution, depth of lime, type and extent of mottling, and stratification;
- evidence of any differences between vertical or lateral permeability from soil structure characteristics;
- degree of hardness or cementation;
- indications of a drainage barrier layer.

Additional observations should be made for general soil characterization purposes and samples taken from each horizon for appropriate laboratory studies.

iii. Field tests of horizontal permeability are made by approved methods (see 4.2.3) at representative sites as needed.

iv. Following the logging of the pits appropriate soil borings are made between the line of pits to evaluate uniformity of materials and to estimate the areal extent of soil and substrata materials observed in the pits.

v. Observation wells should be installed in areas where soil or other surveys indicate shallow groundwater, and in a few other representative areas regardless of these indications. Wells may be hand dug, bored by hand augers, or drilled with well drilling equipment. Village and farm wells may be useful sources of data, but are not as reliable as cased observation wells. Approximately one third of the observation wells should be drilled to a depth of at least 9 metres unless an impenetrable barrier is encountered.

vi. Initially, where water table problems are apparent, observation wells should be sited in about the same locations and frequency as the observation pits; less where no drainage problems are foreseen. Once some information on groundwater fluctuation is available the need to site additional wells to fill obvious gaps in the data may become apparent.

vii. If artesian pressure is suspected it may be necessary to install piezometers, using hand augers or a jetty rig, to measure the hydrostatic pressure at the bottom of the pipe. Their use is to study groundwater flow patterns and to define areas having water under hydrostatic pressure in permeable zones under impervious strata. Details of techniques for piezometer installation are shown in the USBR Drainage Manual (1964).

viii. The precise elevations and locations of wells and piezometers should be obtained by engineering surveys.

ix. Over a period of 1 year, or preferably longer, readings of groundwater elevations should be made at intervals frequent enough to establish the complete range of fluctuations. Periods of heavy rainfall should be followed by especially frequent groundwater readings.

x. If substrata conditions are fairly uniform, flow measurements should be made on existing drains and springs to determine rate of movement of underground water. If the lands on which existing drainage facilities are located are not representative of the main areas of interest, flow measurements are unlikely to be worthwhile.

xi. Laboratory analyses should be made of the water quality in observation wells, springs, community wells, and in any natural or constructed drains.

xii. Appropriate drawings should be made showing water table contours, depth to water, water-table profiles, piezometer profiles, hydrographs, and depth to barrier.

xiii. Depth to barrier, anticipated deep percolation, desired control of water table, behaviour of present water table, subsoil lateral permeability, and other data collected are used to design the project drainage system.

It is obvious from this description of activities that the primary responsibility for collecting relevant data and for appraising the need, nature and location of drains rests with the drainage specialists. Soil scientists materially assist the drainage engineers by helping to log observation pits, and by drawing attention to such observations as differences in soil drainage characteristics, areas shallow to barrier, with different infiltration rates or having shallow tables.

4.3 RECLAMATION OF SALINE AND SODIC SOILS

The development of the unfavourable properties of saline and sodic soils, outlined in Chapter 2, is a continuing hazard in irrigation which can be prevented by adequate drainage and good irrigation and soil management practices. These practices include (1) adequate irrigation to leach soluble salts below the root zone combined with (2) efficient distribution of water to prevent excessive deep percolation; (3) construction of a good surface drainage system to remove runoff water from each field; and (4) addition of gypsum where necessary to prevent or correct unfavourable sodic conditions.

Excessive salinity or sodic conditions encountered during soil survey should be considered as correctable when evaluating lands for irrigation development. In difficult circumstances the costs for reclamation may exceed the anticipated benefits so they must be estimated before including affected land within the projected irrigation area. Some of the factors which need to be considered are briefly described in the following sections. For a more comprehensive summary of the subject the reader is referred to FAO/Unesco (1973), FAO (1973) and FAO (1976c).

4.3.1 Reclamation of Saline Soils

Reclamation of saline soils requires leaching and is rarely possible unless conditions of internal drainage are satisfactory. Leaching without drainage requires exceptional circumstances (FAO/Unesco 1973), and normally proves futile because the salts leached downwards return to the surface by saturated or unsaturated flow depending on the level of the water table. For sustained irrigation the excess salts must be leached below the root zone and underdrainage must convey the leachate out of the irrigated area.

All irrigation waters contain some soluble salts and many contain an appreciable quantity. If irrigation applications could be limited to the amount required for consumptive use, salts would accumulate unless leached by rainfall. In fact, the efficiency of irrigation by gravity methods rarely exceeds 75% with present technology and is usually less than 50% because of deep percolation losses. Even with sprinkler irrigation, deep percolation losses normally exceed 15–20%. Consequently, in practice, few farmers salinize their soils by applying too little water, although the risk of doing so is greater on slowly permeable, fine textured soils and in areas where the irrigation water is saline. On soils with moderate to low salinity levels, on which some crop production is possible, a systematic leaching programme may not be necessary because normal irrigation practices, with provision for a larger than normal deep percolation loss, will generally reclaim the soils in a few years with little additional expense for leaching.

Where the salinity problem is more severe leaching is an essential prelude to successful irrigation. Land levelling to create basins in which water can be impounded to equal depth is a customary means for preparing lands for leaching. However, Biggar (1964) has shown that sprinkler irrigation is more effective for leaching than impoundment of surface water. In fact, any type of leaching which is intermittent like sprinkling, and which permits more time for water to move through the small pores, will be more efficient than ponding in terms of water use although it will require more time. Where salinity levels are very high, leaching of salt deposits may result in uneven settlement of land which necessitates additional subsequent land grading.

The total quantity of water required for leaching depends on the method of leaching, pore size distribution, degree and type of salinity, and the desired level of salinity after leaching. Reeve and Fireman (1967) state that, in general, about 50% of the salt is removed from the soil when the ratio of the depth of water applied per unit depth of soil equals 0.5 and about 80% when this ratio equals 1.0. That is, 30 cm of leaching water would be expected to remove approximately 80% of the soluble salt from the surface 30 cm of soil or 50% of the soluble salt from the surface 60 cm of soil. For sandy soils the required quantity of water for this amount of leaching is generally somewhat less, and for fine textured soils, somewhat more.

The minimum deep percolation needed to prevent an increase in the desired soil salinity level has been called the "leaching requirement". The term is defined by the following equation:

$$LR = \frac{EC_{iw}}{EC_{dw}} \times 100$$

where LR = leaching requirement or the percent of applied water which must pass the root zone;

EC_{iw} = electrical conductivity of the irrigation water;

EC_{dw} = the projected or tolerable electrical conductivity at bottom of the root zone.

The value for the conductivity of the irrigation water (EC_{iw}) which is used in calculating leaching requirements should take account of the diluting influence of effective rainfall. In these calculations the projected value of the electrical conductivity of the drainage water (EC_{dw}) is commonly equated with the electrical conductivity tolerance of the crop, or crops, which will be grown (see Table 3, section 2.3.3).

Care must be taken in leaching programmes to prevent soil dispersion and associated reduction of infiltration and permeability rates. McNeal (1968) and Muhammad et al. (1969) have shown that improved permeability is obtained by the use of saline rather than low salinity water for leaching. Thus drainage water or other saline waters can often be used successfully. A gradual reduction of the salinity level in the leaching water by dilution may be needed in the transition period. Field leaching studies to explore the use of saline water for leaching should also explore the best means for preventing soil dispersion in shifting from the saline water to the ultimate irrigation water. Soils containing significant amounts of gypsum are unlikely to cause dispersion problems.

Figure 3 shows a typical salt leaching curve and, at the same time, illustrates a useful way to plot the results of field leaching studies.

Reclamation involves expenditure and in order to plan and estimate the cost of a realistic and useful reclamation programme a variety of data are required. The date required to deal with a salinity problem of any significant magnitude include:

- extent, type and distribution of salinity;
- quantity and distribution of gypsum in the soil;
- water table depth and fluctuations;
- quality of irrigation water;
- quality of ground water;
- possible source of saline water for initial leaching;
- anticipated cropping system and salinity tolerances;
- anticipated crop production level after leaching;
- infiltration and permeability rates with saline water source;
- infiltration and permeability rates with irrigation water;
- results of field leaching tests;
- a comparison of impoundment and intermittent leaching water requirements if water supply is short;
- an estimate of possible soil subsidence with reclamation.

4.3.2 Reclamation of Saline-Sodic and Sodic Soils

Various chemical, physical and biological approaches to the reclamation of saline-sodic and sodic soils need to be considered. While the optimum approach depends on local circumstances, a combination of methods will often prove most rapid and effective. Any treatment, whether chemical, physical or biological which provides soluble calcium to replace sodium in the exchange complex, will help. Leaching and drainage are essential once the exchange reactions have begun and any improvement in permeability by physical and biological means will assist the reclamation process (FAO/Unesco 1973).

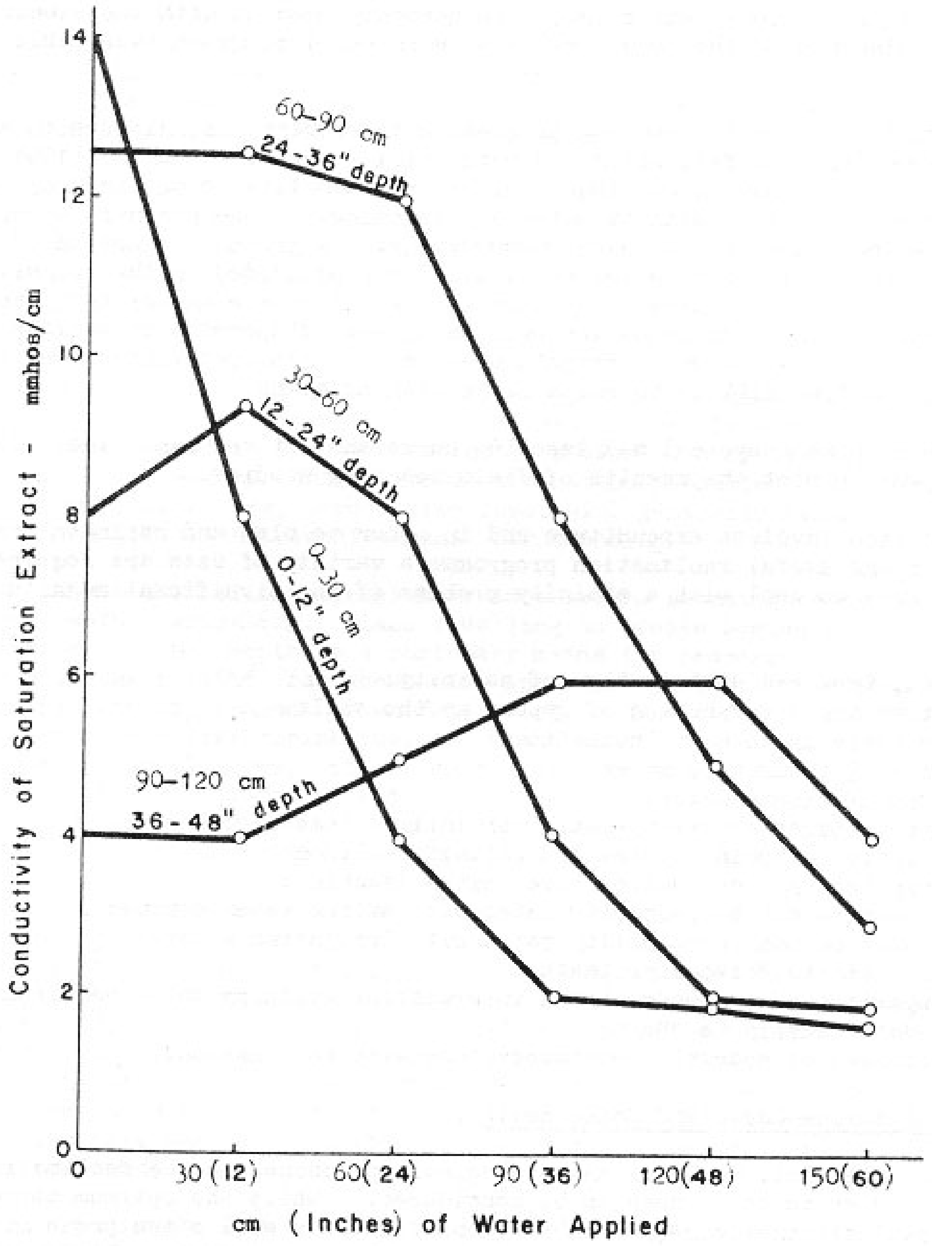


Figure 3: Typical salt leaching curve

Physical aids to reclamation include:

- deep ploughing, especially on stratifield soils with permeable and impermeable layers, or on soils with gypsum layers within reach of the plough;
- subsoiling, especially to break an indurated B-horizon or lime layer;
- profile inversion, where the upper subsoil has undesirable properties (lower and upper subsoils are inverted and then the top soil is replaced);
- sanding, involving the spreading and mixing of sand into the upper horizons of fine textured soils (not effective on heavy clay soils).

Both living and dead organic matter affect biological amelioration principally by improving soil permeability and by releasing carbon dioxide. Thus large dressings of manure serve to improve surface structure and to increase carbon dioxide evolution, the latter effect being of greatest benefit in stimulating the solution of calcium in calcareous alkaline soils.

Chemical amendments are very often necessary in the reclamation of saline-sodic and sodic soils to neutralize free sodium and to supply a cation that will replace sodium in the exchange complex. Gypsum is, by far, the most commonly used amendment. Table 9 shows other amendments which are used locally. Those which do not supply calcium directly work by acidifying the soil, thus releasing calcium from lime and other compounds.

Table 9 CHEMICAL AMENDMENTS FOR SALINE-SODIC AND SODIC SOILS (FAO/Unesco 1973)

Amendments	Effective equivalent to one ton of pure gypsum (in tons)
Gypsum ($CaSO_4 - 2H_2O$)	1.0
Calcium Chloride ($CaCl_2 - 2H_2O$)	0.85
Limestone ($CaCO_3$)	0.58
Sulphur	0.19
Sulphuric Acid	0.57
Iron Sulphate ($FeSO_4 \cdot 7H_2O$)	1.62
Aluminium Sulphate ($Al_2(SO_4)_3 \cdot 10H_2O$)	1.29
Calcium polysulphide (CaS_5) 24% sulphur	0.77

The amount of amendment required is related to the quantity of sodium to be removed. Thus, in theory:

$$\text{Gypsum requirement (in meq/100 g of soil)} = \frac{\text{C.E.C. (initial ESP - final ESP)}}{100}$$

'Initial ESP' is the measured value before reclamation. 'Final ESP' is the desired value which is often taken as 10, a level of exchangeable sodium at which no noticeable peptization results. For example, if initial ESP = 30; final ESP = 10 and C.E.C. = 24:-

$$\text{Gypsum requirement (meq/100 g soil)} = 24 \times \left(\frac{30 - 10}{100}\right) = 4.8$$

Since 1 meq of gypsum/100 g of soil is equivalent to 860 ppm of gypsum, and since one hectare of soil to a depth of 20 cm may be taken to weigh 3 100 000 kg, the amount of gypsum theoretically required to treat this depth of soil will be:

$$\text{Gypsum requirement/ha/20 cm} = 860 \times 10^{-6} \times 3.10^{6} \times 4.8 = 12\ 400 \text{ kg}$$

In practice, the gypsum is likely to be impure and a correction factor for percentage purity must be used. Furthermore, the efficiency of replacement of sodium by calcium is not 100%, partly because of the presence of free sodium in the soil. Therefore, it is recommended that the amount of gypsum to be applied be increased in accordance with the equivalents of free sodium carbonate and bicarbonate (FAO/Unesco 1973). U.S. Bureau of Reclamation studies in Idaho (unpublished) have shown that, in general, gypsum is only 60-75% efficient in replacing exchangeable sodium; a finding which can be used to adjust the calculated requirement. Table 9 shows the amount of other amendments that would be as effective as one ton of pure gypsum, if they were locally more economic.

Saline-sodic soils are generally flocculated and permeable at the start of reclamation whereas sodic soils are not. The problem is to improve and maintain permeability which is usually more difficult on sodic soils. Although physical treatments and additions of gypsum are useful, reclamation can usually be accelerated under adverse conditions by increasing the electrolyte content of the leaching water (McNeal 1968; Muhammed et al. 1969).

In addition to increasing the electrolyte content, care must be taken to maintain the sodium adsorption ratio (SAR, see Table 12) of the applied water below a certain limit depending on the type of clay minerals. This value will generally be less than 10 for 2:1 type minerals and somewhat higher for 1:1 type minerals. Saline water (8 000 - 12 000 ppm) with additions of gypsum or calcium chloride to lower the SAR below the appropriate limiting value would usually be appropriate for the initial leaching of saline-sodic or sodic soils. A depth of two or more metres of the saline water following by a metre of good quality water may be required for successful leaching of these soils.

Apart from identifying and mapping the saline and sodic soils, the soil scientist must assess the way in which they will respond to reclamation measures. In doing so he will need to take particular account of the content of gypsum and of the exact nature, severity and distribution within the profile of salinity, sodicity and permeability problems. He must also note the quality of available irrigation and leaching waters (notably their sodium adsorption ratio) and the availability of chemical amendments. In co-operation with the drainage specialist he should undertake measurements of infiltration and permeability rates using leaching water at various levels of salinity.

These problems should be throughly investigated before any conclusions are formed on the reclamation measures required or the suitability of the land for irrigation development. Some quick tests exist which can serve as useful diagnostic aids. For example, a pH measurement in a 1-5 soil/water suspension that is 1.1 or more units greater than that in the saturated paste is indicative of a sodic soil in some areas. Schroo (1967) showed that for soils in Pakistan several valuable conclusions could be drawn from a study of the concentration of calcium and magnesium ions in the saturation extract. Values greater than 15 meq/l of $Ca^{++} + Mg^{++}$ indicated the presence of gypsum. In these soils, pH was typically over 8.5 if the concentration of these divalent cations was less than 5 meq/l and over 8.8 if their concentration was below 1.5 meq/l. These useful indicators in Pakistan may not be valid elsewhere. In general, no great reliance should be placed on quick tests until sufficient laboratory data have been obtained to prove their validity.

4.4 TEAM RESPONSIBILITIES IN DRAINAGE/RECLAMATION INVESTIGATIONS

In a team which is studying irrigation development, the usual responsibilities of the soil scientist, the drainage engineer and the economist in relation to drainage and reclamation investigations are as follows:

4.4.1 Responsibilities of the Soil Scientist

i. Locate and delineate areas with high water table and associated salinity and sodic problems;

ii. log observation pits and observation well borings for drainage engineer;

iii. obtain soil samples and arrange for appropriate laboratory analyses;

iv. evaluate need for gypsum additions;

v. run field infiltration permeability and leaching tests;

vi. evaluate quality of irrigation water and determine if saline leaching water required;

vii. identify any significant geomorphological distinctions within the project area and advise on the physical differences of the areas concerned;

viii. evaluate present internal drainage characteristics of all soils;

ix. provide an estimate of maximum water table level which should be permitted for each soil and projected cropping programme;

x. provide the drainage engineer with profile descriptions of the upper 270 cm of all soils likely to be irrigated with appraisal of possible drainage barriers.

4.4.2 Responsibilities of the Drainage Engineer

i. Select sites for observation pits and arrange for excavation;

ii. select sites for observation wells and piezometers and arrange for their installation;

iii. evaluate available substrata data and determine depth to barrier in various parts of the project;

iv. determine horizontal permeability at drainage depths by in-place methods;

v. measure observation wells and evaluate data;

vi. prepare maps showing water table contours, depth to water, depth to barrier, water table profiles, piezometer profiles, and hydrographs showing elevation of water table over time for single observation holes;

vii. estimate drainage requirements and costs.

4.4.3 Responsibilities of the Agricultural Economist

i. Determine maximum acceptable expenditure for drainage and reclamation in relation to anticipated cropping systems and crop yields;

ii. determine cropping system consistent with soils, salinity, climate, farmer's abilities, and marketing opportunities (in consultation with other team members).

CHAPTER 5

WATER QUALITY AND CLIMATE

5.1 INTRODUCTION

The quality of available water or the rigours of the climate may be more significant than soil characteristics in determining the suitability of some lands for irrigation. Excellent soils may be unusable, for example if water available would quickly render them saline or toxic or if the frost-free period is too short. Less extreme deficiencies require careful appraisal, and this must commonly be made by the soil scientist, who because of his background knowledge will be called upon to predict the effects of the water quality on soil physical and chemical properties and crop production.

Although good water quality has always been assumed to be necessary for the success of an irrigation project, examples can be cited where poor quality irrigation waters have been successfully used for many years. Thus the successful long-term use of any irrigation water depends on a anumber of factors including water quality and it must be duly considered - neither over-emphasized nor under-emphasized.

5.2 WATER QUALITY

5.2.1 Water Quality Evaluation

Schemes of water quality evaluation and classification have been devised by several investigators. These are reviewed in the FAO/Unesco International Source Book on Irrigation and Drainage of Arid Land (1973). None of these schemes can be considered applicable over all ranges of conditions but the most widely used system of classification was published by the U.S. Salinity Laboratory (1954).

These schemes have classified the water within certain limits but the response obtained from water having a given set of characteristics may vary widely depending on the soils, tolerance of various crops, rainfall patterns, drainage conditions, irrigation methods, availability of water, and climate. Each of these factors may affect the utility of a given water supply for irrigation. Therefore it is desirable to review the characteristics of the available water supply and determine its usefulness for irrigation purposes in relation to the localized conditions of the project by determining the problems this water may cause and the management level necessary to overcome these problems.

The problems created by irrigation water quality are farm management problems and must be solved at that level; therefore water quality evaluation must be in terms of its specific use and potential hazard to crop production. A farm management approach is taken here to evaluate the usefulness of a water supply for irrigation. The factors that must be considered are:

- the type and severity of the problem that can be expected following an extended period of use;

- the constituents and quantity of each in the water that are expected to cause the problem; and

- the management alternatives that may be available to prevent, correct or delay the onset of the problem.

Management problems of water quality are of four kinds: salinity, permeability, toxicity and miscellaneous. Even though these generally occur in combination, the evaluation and solution is more easily understood and treated if they are considered one at a time. This approach is presented in FAO Irrigation and Drainage Paper No. 29 (1976) and will be used here.

5.2.2 Laboratory Determinations Needed

To evaluate a water for agricultural use, certain laboratory determinations are needed. Analytical procedures for these determinations are discussed in USDA Handbook 60 (1954), FAO Soils Bulletin 10 (1970) and Standard Methods of the American Water Works Association (1971). These and other recognized procedures should be consulted. The determinations of importance to irrigation water quality are given in Table 10.

Table 10 LABORATORY DETERMINATIONS NEEDED TO EVALUATE WATER QUALITY

Laboratory Determination	Reporting Symbol	Reporting Units	Equivalent Weight
Electrical conductivity	ECw	mmhos/cm	–
Calcium	Ca	meq/1	20
Magnesium	Mg	meq/1	12.2
Sodium	Na	meq/1	23
Carbonate	CO_3	meq/1	30
Bicarbonate	HCO_3	meq/1	61
Chloride	Cl	meq/1	35.4
Sulphate	SO_4	meq/1	48
Boron	B	mg/1	–
Nitrate-Nitrogen	NO_3-N	mg/1	14
Acidity-Alkalinity	pH	pH	–
Adjusted Sodium Adsorption Ratio	adj. SAR 1/	–	–
Potassium 2/	K	meq/1	39.1
Lithium 2/	Li	mg/1	7
Iron 2/	Fe	mg/1	–
Ammonium-Nitrogen 2/	NH_4-N	mg/1	14
Phosphate Phosphorous 2/	PO_4-P	mg/1	31

1/ Calculation procedures given in Table 12.
2/ Special situations only.

5.2.3 Guidelines for Interpretation of Water Quality for Irrigation

Guidelines to evaluate water quality for irrigation are presented in Table 11. Emphasis in the guidelines is on the long term dominating influence of the water's quality on the soil-water-plant relationships that affect production and management. They are practical and usable in general irrigated agriculture for evaluation of the usual constituents in all waters. They are not intended, however, to evaluate the more unusual or special constituents found in wastewaters including such things as pesticides and trace elements.

Table 11 GUIDELINES FOR EVALUATING IRRIGATION WATER QUALITY

TYPE OF PROBLEM	Units	WATER QUALITY GUIDELINES		
		No Problem	Increasing Problem	Severe Problem
SALINITY (affects crop water availability)				
ECw	mmhos/cm	<0.7	0.7 - 3.0	>3.0
PERMEABILITY (affects infiltration rate into soil)				
EC_w	mmhos/cm	>0.5	0.5 - 0.2	<0.2
adj SAR [1]				
Montmorillonite - Smectites (2:1 crystal lattice)		<6	6 - 9 [2]	>9
Illite - Vermiculite (2:1 crystal lattice)		<8	8 - 16 [2]	>16
Kaolinite - sesquioxides (1:1 crystal lattice)		<16	16 - 24 [2]	>24
SPECIFIC ION TOXICITY (affects sensitive crops) [3]				
Sodium (Na)				
Surface Irrigation	adj SAR [1]	<3	3 - 9	>9
Sprinkler Irrigation	meq/l	<3	>3	
Chloride (Cl)				
Surface Irrigation	meq/l	<4	4 - 10	>10
Sprinkler Irrigation	meq/l	<3	>3	
Boron (B)	mg/l	<0.7	0.7 - 2.0	>2.0
MISCELLANEOUS EFFECTS (affect susceptible crops)				
Nitrogen (NO_3-N or NH_4-N) [4]	mg/l	<5	5 - 30	>30
Bicarbonate (HCO_3) with sprinklers	meq/l	<1.5	1.5 - 8.5	>8.5
pH		Normal range 6.5 - 8.4		

[1] For calculation procedure see Table 12. Evaluation should be based on the dominant type of clay mineral in the soil (Rallings 1966, and Rhoades 1975).

[2] Use the lower range if ECw <0.4 mmhos/cm; the intermediate range if ECw = 0.4 - 1.6 mmhos/cm; the upper range if ECw > 1.6 mmhos/cm.

[3] Most tree crops and other woody plants are sensitive to sodium and chloride (use values shown). Most annual crops are not sensitive (use the crop tolerance tables, Table 14).

[4] NO_3-N means nitrogen in the form of NO_3 while NH_4-N means nitrogen in the form of NH_4. Both reported as N in mg/l.

Table 12

CALCULATION OF adj. SAR

The adjusted Sodium Adsorption Ratio (adj. SAR) is calculated from the following equation 1/:

$$\text{adj. SAR} = \frac{\text{Na}}{\sqrt{\frac{\text{Ca} + \text{Mg}}{2}}} \left[1 + (8.4 - \text{pHc})\right]$$

where Na, Ca and Mg are in meq/l from the water analysis and pHc is calculated using the tables given below which relate to the concentration values from the water analysis. The table values are then substituted in the pHc equation:

$$\text{pHc} = (\text{p}K_2' - \text{p}K_c') + \text{p}\,(\text{Ca+Mg}) + \text{p}\,(\text{Alk})$$

Tables for calculating pHc

$(\text{p}K_2' - \text{p}K_c')$ is obtained from using the sum of Ca+Mg+Na in meq/l
p(Ca+Mg) is obtained from using the sum of Ca+Mg in meq/l
p(Alk) is obtained from using the sum of CO_3+HCO_3 in meq/l

Obtained from water analysis

Sum of Concentration (meq/l)	$\text{p}K_2' - \text{p}K_c'$	p(Ca + Mg)	p(Alk)
.05	2.0	4.6	4.3
.10	2.0	4.3	4.0
.15	2.0	4.1	3.8
.20	2.0	4.0	3.7
.25	2.0	3.9	3.6
.30	2.0	3.8	3.5
.40	2.0	3.7	3.4
.50	2.1	3.6	3.3
.75	2.1	3.4	3.1
1.00	2.1	3.3	3.0
1.25	2.1	3.2	2.9
1.5	2.1	3.1	2.8
2.0	2.2	3.0	2.7
2.5	2.2	2.9	2.6
3.0	2.2	2.8	2.5
4.0	2.2	2.7	2.4
5.0	2.2	2.6	2.3
6.0	2.2	2.5	2.2
8.0	2.3	2.4	2.1
10.0	2.3	2.3	2.0
12.5	2.3	2.2	1.9
15.0	2.3	2.1	1.8
20.0	2.4	2.0	1.7
30.0	2.4	1.8	1.5
50.0	2.5	1.6	1.3
80.0	2.5	1.4	1.1

Example pHc calculation:

Given:
Ca = 2.32 meq/l
Mg = 1.44 "
Na = 7.73 "
Sum = 11.49 meq/l

CO_3 = 0.42 meq/l
HCO_3 = 3.66 meq/l
Sum = 4.08 meq/l

From Tables and using the equation for pHc:

$\text{p}K_2' - \text{p}K_c' = 2.3$
p(Ca+Mg) = 2.7
p(Alk) = 2.4
pHc = 7.4

Substituting

$$\text{adj. SAR} = \frac{7.73}{\sqrt{\frac{3.76}{2}}}\left[1 + (8.4 - 7.4)\right]$$

$$\text{adj. SAR} = 5.64\ (2.0) = 11.3$$

Note: Values of pHc above 8.4 indicate a tendency to dissolve lime from the soil through which the water moves; values below 8.4 indicate a tendency to precipitate lime from the water applied.

(Ref. L.V. Wilcox, U.S. Salinity Laboratory, Mimeo Dec. 30, 1966; and Rhoades 1972).

A suggested table of maximum concentrations of the trace elements for irrigation waters is shown in Table 13. These are believed to be the best listing now available (National Academy of Sciences 1972, and Pratt 1972). Again these suggested maximum concentrations are based on the protection of soils for plant production under long continued use of the water. Criteria for short term use are also suggested for soils that have high capacities to inactivate these trace elements. The criteria should be adjusted when more reliable estimates become available.

In the preceding general discussion and Guidelines of Tables 11 and 13 the basic information needed for an evaluation has been presented. This should allow the soil scientist to conclude that water "A" having constituents "X, Y and Z" in concentrations shown by laboratory analysis does or does not have an important potential for causing a management problem. The use and interpretation of these Guidelines will be discussed here in more detail by considering each of the four management problems presented in Table 11.

5.2.4 Salinity Problem

A salinity problem related to water quality occurs if the total quantity of salts in the irrigation water is high enough to affect yields or if these salts accumulate in the crop root zone to the extent that yields are affected. In either case the salts originate from the irrigation water used.

The electrical conductivity in millimhos/cm ($EC \times 10^3$) is commonly used as a means of indicating the salt content or salinity of a water (ECw). The ECw is taken from the water analysis and this ECw by itself is usually an adequate measure of the total salinity of the water. However, there are certain unusual situations for which the ECw value as reported may need to be modified such as with waters containing slightly soluble lime and gypsum.

Since ECw is a single value, a heavy reliance is placed on its accuracy. There are several useful relationships to cross check the accuracy of the chemical analysis data which should be routinely done:

- For waters having a conductivity in the range of 0.1 to 5.0 mmhos/cm the electrical conductivity in mmhos/cm multiplied by 640 is approximately equal to the Total Dissolved Solids (TDS) in milligrams per litre (or ppm).
- The total soluble anion concentration and the total soluble cation concentration expressed in meq/l are nearly equal.
- The ECw expressed in mmhos/cm multiplied by 10 is approximately equal to the total soluble cation concentration in meq/l when the ECw is in the range of 0.1 to 5.0 mmhos/cm.

Table 13 RECOMMENDED MAXIMUM CONCENTRATIONS OF TRACE ELEMENTS IN IRRIGATION WATERS

Element (symbol)	For waters used continuously on all soils mg/l	For use up to 20 years on fine textured soils of pH 6.0 to 8.5 mg/l
Aluminium (Al)	5.0	20.0
Arsenic (As)	0.1	2.0
Beryllium (Be)	0.1	0.5
Boron (B)	1/	2.0
Cadmium (Cd)	0.01	0.05
Chromium (Cr)	0.1	1.0
Cobalt (Co)	0.05	5.0
Copper (Cu)	0.2	5.0
Fluoride (F)	1.0	15.0
Iron (Fe)	5.0	20.0
Lead (Pb)	5.0	10.0
Lithium (Li) 2/	2.5	2.5
Manganese (Mn)	0.2	10.0
Molybdenum (Mo)	0.01	0.05 3/
Nickel (Ni)	0.2	2.0
Selenium (Se)	0.02	0.02
Vanadium (V)	0.1	1.0
Zinc (Zn)	2.0	10.0

These levels will normally not adversely affect plants or soils. No data available for Mercury (Hg), Silver (Ag), Tin (Sn), Titanium (Ti), Tungsten (W).

1/ See Table 11.

2/ Recommended maximum concentration for irrigating citrus is 0.075 mg/l.

3/ For only acid fine textured soils or acid soils with relatively high iron oxide contents.

Source: Environmental Studies Board, Nat. Acad. of Sci., Nat. Acad. of Engineering, Water Quality Criteria 1972.

The following laboratory analysis of a typical river water illustrates this relationship:

	ION	Milliequivalents per litre
	Calcium (Ca^{++})	4.16
	Magnesium (Mg^{++})	1.42
	Sodium (Na^{+})	5.96
	Potassium (K^{+})	–
(1)	Sum of Cations	11.54
	Carbonate (CO_3^{--})	0.5
	Bicarbonate (HCO_3^{-})	3.59
	Sulphate (SO_4^{--})	5.00
	Chloride (Cl^{-})	3.10
(2)	Sum of Anions	12.19 compare with (1) above
(3)	TDS	750 mg/l
	adj. SAR	7.92
	EC_w at 25°C	1.16 mmhos/cm
(4)	$(EC_w) \cdot 10$	11.6 compare with (1) above
(5)	$(EC_w) \cdot 640$	742 mg/l compare with (3) above

If the ECw is less than 0.75 mmhos/cm, the water user should experience no problem with salinity for any crop provided adequate leaching takes place. The use of electrical conductivity values in determining the leaching requirements associated with a given source of water has been described in Chapter 4 (Section 4.3.1).

Waters with an ECw greater than 3 mmhos/cm will cause rather severe salinity problems with some crops. Certain salt sensitive crops cannot be grown successfully at all but this need not cause alarm. Certain salt sensitive crops such as beans, tree crops and some vegetable crops are not adapted while many forage and field crops are very well suited to irrigation water of poor quality. When using poorer quality water, care must be taken to select crops that are tolerant and in addition, water management that controls salt becomes more imperative.

Crop tolerance tables for representative crops are given in Table 14, which also indicates approximate yield potentials, these being limited either by soil salinity (ECe) or equivalent irrigation water salinity (ECw). The tables show that a decrease in yield is directly proportional to the mean salinity of the soil saturation extract (ECe) or the salinity of the irrigation water (ECw). It is recognized though, that many factors other than water quality can affect production and must be considered. Crop tolerance is also not a fixed value as shown in the tables, but changes with stage of growth, rootstocks, varieties and climate; therefore conditions of local use should be considered.

Table 14

CROP TOLERANCE TABLE
Yield Potentials expected when Common Surface Irrigation Methods are Used

FIELD CROPS

CROP	100%		90%		75%		50%		No Yield
	ECe[1]	ECw[2]	ECe	ECw	ECe	ECw	ECe	ECw	ECe
Barley[3] (Hordeum vulgare)	8.0	5.3	10	6.7	13	8.7	18	12	28
Cotton (Gossypium hirsutum)	7.7	5.1	9.6	6.4	13	8.4	17	12	27
Sugarbeet[4] (Beta vulgaris)	7.0	4.7	8.7	5.8	11	7.5	15	10	24
Wheat[2] [2] (Triticum aestivum)	6.0	4.0	7.4	4.9	9.5	6.4	13	8.7	20
Safflower (Cartnamus tinctorius)	5.3	3.5	6.2	4.1	7.6	5.0	9.9	6.6	14.5
Soybean (Glycine max)	5.0	3.3	5.5	3.7	6.2	4.2	7.5	5.0	10
Sorghum (Sorghum bicolor)	4.0	2.7	5.1	3.4	7.2	4.8	11	7.2	18
Groundnut (Arachis hypogaea)	3.2	2.1	3.5	2.4	4.1	2.7	4.9	3.3	6.5
Rice (paddy) (Oryza sativa)	3.0	2.0	3.8	2.6	5.1	3.4	7.2	4.8	11.5
Sesbania (Sesbania exaltata)	2.3	1.5	3.7	2.5	5.9	3.9	9.4	6.3	16.5
Corn (Zea mays)	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10
Flax (Linum usitatissimum)	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10
Broadbean (Vicia faba)	1.6	1.1	2.6	1.8	4.2	2.0	6.8	4.5	12
Cowpea (Vigna unguiculata)	1.3	0.9	2.0	1.3	3.1	2.1	4.9	3.2	8.5
Beans (Phaseolus vulgaris)	1.0	0.7	1.5	1.0	2.3	1.5	3.6	2.4	6.5
FRUIT CROPS									
Date palm (Phoenix dactylifera)	4.0	2.7	6.8	4.5	10.9	7.3	17.9	12	32
Fig (Ficus carica) Olive (Olea europaea) Pomegranate (Punica granatum)	2.7	1.8	3.8	2.6	5.5	3.7	8.4	5.6	14
Grapefruit (Citrus paradisi)	1.8	1.2	2.4	1.6	3.4	2.2	4.9	3.3	8
Orange (Citrus sinensis)	1.7	1.1	2.3	1.6	3.2	2.2	4.8	3.2	8

Table 14 (cont.)

CROP	100%		90%		75%		50%		No Yield
	ECe	ECw	ECe	ECw	ECe	ECw	ECe	ECw	ECe
Lemon (Citrus limon)	1.7	1.1	2.3	1.6	3.3	2.2	4.8	3.2	8
Apple (Malus sylvestris) Pear (Pyrus communis)	1.7	1.0	2.3	1.6	3.3	2.2	4.8	3.2	8
Walnut (Juglans regia)	1.7	1.1	2.3	1.6	3.3	2.2	4.8	3.2	8
Peach (Prunus persica)	1.7	1.1	2.2	1.4	2.9	1.9	4.1	2.7	6.5
Apricot (Prunus armeniaca)	1.6	1.1	2.0	1.3	2.6	1.8	3.7	2.5	6
Grape (Vitis spp.)	1.5	1.0	2.5	1.7	4.1	2.7	6.7	4.5	12
Almond (Prunus dulcis)	1.5	1.0	2.0	1.4	2.8	1.9	4.1	2.7	7
Plum (Prunus domestica)	1.5	1.0	2.1	1.4	2.9	1.9	4.3	2.8	7
Blackberry (Rubus spp.)	1.5	1.0	2.0	1.3	2.6	1.8	3.8	2.5	6
Boysenberry (Rubus ursinus)	1.5	1.0	2.0	1.3	2.6	1.8	3.8	2.5	6
Avocado (Persea americana)	1.3	0.9	1.8	1.2	2.5	1.7	3.7	2.4	6
Raspberry (Rubus idaeus)	1.0	0.7	1.4	1.0	2.1	1.4	3.2	2.1	5.5
Strawberry (Fragaria spp.)	1.0	0.7	1.3	0.9	1.8	1.2	2.5	1.7	4
VEGETABLE CROPS									
Beets[4] (Beta vulgaris)	4.0	2.7	5.1	3.4	6.8	4.5	9.6	6.4	15
Broccoli (Brassica oleracea italica)	2.8	1.9	3.9	2.6	5.5	3.7	8.2	5.5	13.5
Tomato (Lycopersicon esculentum)	2.5	1.7	3.5	2.3	5.0	3.4	7.6	5.0	12.5
Cucumber (Cucumis sativus)	2.5	1.7	3.3	2.2	4.4	2.9	6.3	4.2	10
Cantaloupe (Cucumis melo)	2.2	1.5	3.6	2.4	5.7	3.8	9.1	6.1	16
Spinach (Spinacia oleracea)	2.0	1.3	3.3	2.2	5.3	3.5	8.6	5.7	15
Cabbage (Brassica oleracea capitata)	1.8	1.2	2.8	1.9	4.4	2.9	7.0	4.6	12
Potato (Solanum tuberosum)	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10

Table 14 (cont.)

CROP	100%		90%		75%		50%		No Yield
	ECe	ECw	ECe	ECw	ECe	ECw	ECe	Ecw	ECe
Sweet corn (Zea mays)	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10
Sweet potato (Ipomea batatas)	1.5	1.0	2.4	1.6	3.8	2.5	6.0	4.0	10.5
Pepper (Capsicum annuum)	1.5	1.0	2.2	1.5	3.3	2.2	5.1	3.4	8.5
Lettuce (Lactuca sativa)	1.3	0.9	2.1	1.4	3.2	2.1	5.2	3.4	9
Radish (Raphanus sativus)	1.2	0.8	2.0	1.3	3.1	2.1	5.0	3.4	9
Onion (Allium cepa)	1.2	0.8	1.8	1.2	2.8	1.8	4.3	2.9	7.5
Carrot (Daucus carota)	1.0	0.7	1.7	1.1	2.8	1.9	4.6	3.1	8
Beans (Phaseolus vulgaris)	1.0	0.7	1.5	1.0	2.3	1.5	3.6	2.4	6.5
FORAGE CROPS									
Tall wheat grass (Agropyron elongatum)	7.5	5.0	9.9	6.6	13.3	9.0	19.4	13	31.5
Wheat grass (fairway) (Agropyron cristatum)	7.5	5.0	9.0	6.0	11	7.4	15	9.8	22
Bermuda grass 6/ (Cynodon dactylon)	6.9	4.6	8.5	5.7	10.8	7.2	14.7	9.8	22.5
Barley (hay) 3/ (Hordeum vulgare)	6.0	4.0	7.4	4.9	9.5	6.3	13.0	8.7	20
Perennial rye grass (Lolium perenne)	5.6	3.7	6.9	4.6	8.9	5.9	12.2	8.1	19
Trefoil, birdsfoot narrow leaf 8/ (L. corniculatus tenuifolium)	5.0	3.3	6.0	4.0	7.5	5.0	10	6.7	15
Harding grass (Phalaris tuberosa)	4.6	3.1	5.9	3.9	7.9	5.3	11.1	7.4	18
Tall fescue (Festuca elatior)	3.9	2.6	5.8	3.9	8.6	5.7	13.3	8.9	23
Crested Wheat grass (Agropyron desertorum)	3.5	2.3	6.0	4.0	9.8	6.5	16	11	28.5
Vetch (Vicia sativa)	3.0	2.0	3.9	2.6	5.3	3.5	7.6	5.0	12
Sudan grass (Sorghum sudanense)	2.8	1.9	5.1	3.4	8.6	5.7	14.4	9.6	26
Wildrye, beardless (Elymus triticoides)	2.7	1.8	4.4	2.9	6.9	4.6	11.0	7.4	19.5
Trefoil, big (Lotus uliginosus)	2.3	1.5	2.8	1.9	3.6	2.4	4.9	3.3	7.5
Alfalfa (Medicago sativa)	2.0	1.3	3.4	2.2	5.4	3.6	8.8	5.9	15.5
Lovegrass 7/ (Eragrostis spp.)	2.0	1.3	3.2	2.1	5.0	3.3	8.0	5.3	14

Table 14 (cont.)

CROP	100%		90%		75%		50%		No Yield
	ECe	ECw	ECe	ECw	ECe	ECw	ECe	ECw	ECe
Corn (forage) (Zea mays)	1.8	1.2	3.2	2.1	5.2	3.5	8.6	5.7	15.5
Clover, berseem (Trifolium alexandrinum)	1.5	1.0	3.2	2.1	5.9	3.9	10.3	6.8	19
Orchard grass (Dactylis glomerata)	1.5	1.0	3.1	2.1	5.5	3.7	9.6	6.4	17.5
Meadow foxtail (Alopecurus pratensis)	1.5	1.0	2.5	1.7	4.1	2.7	6.7	4.5	12
Clover, alsike, ladino, red, strawberry (Trifolium spp.)	1.5	1.0	2.3	1.6	3.6	2.4	5.7	3.8	10

Notes:

1/ ECe means electrical conductivity of the saturation extract of the soil reported in mmhos/cm at 25°C.

2/ ECw means electrical conductivity of the irrigation water in mmhos/cm at 25°C. This assumes about a 15–20% leaching fraction and an average salinity of soil water taken up by the crop about three times that of the irrigation water applied (ECsw = 3 ECw) and about twice that of the soil saturation extract (ECsw = 2ECe). From the above, ECe = 3/2 ECw. New crop tolerance tables for ECw can be prepared for conditions which differ greatly from those assumed. The following are estimated relationships between ECe and ECw for various leaching fractions : LF = 10% (ECe = 2 ECw), LF = 30% (ECe = 1.1 ECw), and LF = 40% (ECe = .9 ECw).

3/ Barley and wheat are less tolerant during germination and seedling stage. ECe should not exceed 4 or 5 mmhos/cm.

4/ Sensitive during germination. ECe should not exceed 3 mmhos/cm for garden beets and sugar beets.

5/ Tolerance data may not apply to new semi-dwarf varieties of wheat.

6/ An average for Bermuda grass varieties. Suwannee and Coastal are about 20% more tolerant; Common and Greenfield are about 20% less tolerant.

7/ Average for Boer, Wilman, Sand, and Weeping varieties. Lehman appears about 50% more tolerant.

8/ Brood-leaf birdsfoot trefoil appears to be less tolerant than narrow-leaf.

Source: Data as reported by Maas and Hoffman (1977); Bernstein (1964) and University of California Committee of Consultants (1974).

Choosing a crop which is tolerant to the existing of potential salinity problems is only one of the management steps that can be applied to overcome water quality related problems. There are still other management steps which can further aid in control of a salinity problem. These include:

a. irrigating more frequently to maintain a high soil moisture,

b. routinely using extra water to satisfy a leaching requirement,

c. changing irrigation methods, and

d. changing cultural practices.

These and other more drastic practices are discussed in FAO Irrigation and Drainage Paper No. 29 (1976).

5.2.5 Permeability Problem

A permeability problem related to water quality occurs when the rate of infiltration of water into and through the soil is reduced by certain salts or lack of salts in the water. It is evaluated from two points: first from total salts, since low salt water can result in poor soil permeability and, secondly, from a comparison of the ratio of sodium to calcium and magnesium in the water. Carbonates and bicarbonates can also affect soil permeability and must be evaluated.

Low salinity waters are corrosive and tend to deplete surface soils of readily soluble minerals. Very low salinity waters (ECw $<$ 0.2 mmhos/cm) often result in soil permeability problems whereas higher salinity waters (ECw $>$ 0.5 mmhos/cm) seldom do, provided there is a good ratio of sodium to calcium. Since the permeability problem acts to reduce the volume of water placed into storage for recovery and use by the crop, there seems little need to take corrective action until either the crop water demand or the leaching requirement can no longer be satisfied. The permeability problem due to low salt water usually occurs in the upper few centimetres of soil and managing this zone can be helpful in overcoming the problem. High sodium bicarbonate and carbonate in the irrigation water can cause soil permeability problems. The adjusted SAR value in the Guidelines of Table 11 evaluates the sodium to calcium and magnesium ratio, the effect of concentration, the tendency of the water to dissolve lime from the soil which may add calcium and reduce the sodium effect and the tendency of lime to precipitate from the water which reduces the calcium and increases the sodium effect.

This permeability problem must be evaluated in relation to the type of clay mineralogy and soil type since, as stated in Chapter 2 (Section 2.4.2), the type of clay mineralogy strongly influences soil dispersion and structural degradation. Swindale and El-Swaify (1968) in studies of water quality effects on tropical soils have found that usual irrigation water quality standards can be exceeded on low humic latosols and tropical andosols. They attribute the high resistance of these soils to the virtual absence of swelling clay minerals, the abundance of free iron oxides, and their highly developed structural characteristics.

There are physical and chemical practices that can be used to increase the infiltration rate of the soil or allow more time for infiltration. These include: (a) irrigation more frequently; (b) cultivation and deep tillage; (c) increasing the time allotted (duration) for an irrigation; (d) changing the direction of irrigation to reduce slope; (e) collecting and recirculating run-off water; (f) with sprinklers, matching water application rate of soil infiltration rate; (g) using organic residues; (h) using soil or water amendments (gypsum, etc.); and (i) blending or changing irrigation water supply.

Too high a reliance is often placed on chemical amendments which can be costly or unavailable. Use of amendments is only recommended when the demonstrated results justify their use and other cultural practices have proved ineffective; they should not be used just in the hope that they will do some good.

The use of amendments and various cultural practices to overcome a permeability problem are discussed in detail in FAO Irrigation and Drainage Paper No. 29 (1976).

5.2.6 Toxicity Problem

A toxicity problem occurs when the uptake and accumulation within the plant of certain salts results in a reduced yield. This is usually related to one or more specific ions of certain salts. The toxic constituents that are commonly of concern are sodium, chloride and boron.

Not all crops are equally sensitive to toxic constituents but most tree crops and woody perennial plants are sensitive. Sprinkler irrigation offers special problems with toxicity.

i. Sodium

Most annual crops are not sensitive at low concentrations but may be affected by much higher concentrations, while most tree crops and woody-type perennial crops are sensitive at low concentrations. The symptoms of sodium toxicity occur first on the oldest leaves since a period of time is required before accumulation reaches toxic levels. Symptoms are leaf burn or dying of tissue at the outer edges, progressing towards the leaf centre as the severity increases.

Uptake of sodium depends greatly on the amount of calcium present relative to the sodium. Sodium toxicity is reduced or eliminated by the presence of adequate calcium. Often, however, the reduction in yield found with certain high sodium waters is the result of a deterioration in soil physical condition rather than from direct toxicity. This is reflected in Table 15 which shows the tolerance of certain crops to Exchangeable Sodium.

Table 15 TOLERANCE OF VARIOUS CROPS TO EXCHANGEABLE SODIUM (ESP) UNDER NON-SALINE CONDITIONS (Pearson 1960)

Tolerance to ESP and range at which affected	Crop	Growth response under field conditions
Extremely sensitive (ESP = 2-10)	Deciduous fruits Nuts Citrus (Citrus spp.) Avocado (Persea americana Mill.)	Sodium toxicity symptoms even at low ESP values
Sensitive (ESP = 10-20)	Beans (Phaseolus vulgaris L.)	Stunted growth at these ESP values even though the physical condition of the soil may be good
Moderately tolerant (ESP = 20-40)	Clover (Trifolium spp.) Oats (Avena sativa L.) Tall fescue (Festuca arundinacea Schreb.) Rice (Oryza sativa L.) Dallisgrass (Paspalum dilatum Poir.)	Stunted growth due to both nutritional factors and adverse soil conditions

Table 15 (cont.)

Tolerance to ESP and range at which affected	Crop	Growth response under field conditions
Tolerant (ESP = 40-60)	Wheat (Triticum aestivum L.) Cotton (Gossypium birsutum L.) Alfalfa (Medicago sativa L.) Barley (Hordeum vulgare L.) Tomatoes (Lycopersicon esc. Mill.) Beets (Beta vulgaris L.)	Stunted growth usually due to adverse physical conditions of soil
Most tolerant (ESP = more than 60)	Crested and Fairway wheatgrass (Agropyron spp.) Tall wheatgrass (Agropyron elongatum (Host) Beau.) Rhodes grass (Chloris gayana Kunth)	Stunted growth usually due to adverse physical conditions of soil

Note: Estimates of the equilibrium ESP can be made from the irrigation water or more preferably from the SAR of the soil saturation extract using the nomogram in Appendix B to FAO 1976 d. This estimation method is not applicable where soil gypsum is present. Effectiveness of any planned corrective action should be field tested before being applied on a large scale. Soils at ESP = 20-40 and above will usually have too poor physical structure for good crop production. The research results given above were obtained with soils whose structure was stabilized with Krilium.

ii. Chloride

As with sodium, most tree crops and woody perennial plants are sensitive, and most annual crops are not, at low concentrations of chloride. Damage may also be more severe with sprinklers. Harding and Mahler (1966) have shown that chloride damage is worse under conditions of high temperature and rapid evaporation than in cool, moist climates. Table 16 shows the tolerance of various crops to chloride concentration in the soil as listed by Bernstein (1965) and tolerances to chloride in the irrigation water. It should be noted that the values in Table 16 can be greatly affected by soil moisture conditions, varieties and climate. This is shown in Table 17 from data by Elgabaly and Madkour (1965) and also in data from Nir (1965), who showed that crop reductions became evident when the chloride concentration of the saturation extract exceeded 10 meq/l. Nir found that, in order to maintain the chloride concentration below 10 meq/l, the product of the ppm of the chloride ion in the irrigation water times the saturation percentage of the soil divided by the annual rainfall in millimetres should be less than 50.

With sprinkler irrigation under high evaporative conditions, water containing as low as 3 meq/l has been known to cause tip burn and with higher concentrations, plant defoliation can take place. Crops known to be sensitive to damage by leaf absorption are most of the stone fruits, almonds, citrus, walnuts, and some woody ornamentals (Doneen 1975).

iii. Boron

Although small amounts of boron are essential for plant growth, the element is extremely toxic to many plants if present in the soil solution in concentration above a few parts per million (see Section 2.3.4 ii).

Table 16 CHLORIDE TOLERANCES IN THE SATURATION EXTRACT OF SOIL FOR FRUIT CROP ROOTSTOCKS AND VARIETIES TO AVOID LEAF INJURY

(Bernstein 1965)

Crop	Rootstock or variety	Maximum permissible Cl in saturation extract meq/l	Limit of tolerance to Cl in irrigation water meq/l 1/
	Rootstocks		
Citrus	Rangpur lime, Cleopatra mandarin	25	16.0
(Citrus spp.)	Rough lemon, tangelo, sour orange	15	10.0
	Sweet orange, citrange	10	6.6
Stone fruit	Marianna	25	16.0
(Prunus spp.)	Lovell, Shalil	10	6.6
	Yunnan	7	4.6
Avocado	West Indian	8	5.3
(Persea americana Mill.)	Mexican		3.3
Grape	Salt Creek, 1613-3	40	
(Vitis spp.)	Dog Ridge	30	
	Varieties		
Grape	Thompson Seedless, Perlette	25	16.0
(Vitis spp.)	Cardinal, Black rose	10	6.6
Berries 2/	Boysenberry	10	6.6
(Rubus spp.)	Olallie blackberry	10	6.6
	Indian Summer raspberry	5	3.3
Strawberry	Lassen	8	5.3
(Fragaria spp.)	Shasta	5	3.3

1/ Tolerance limits in irrigation water assume ECe = 1.5 ECw as used in the Guidelines of Table 11 and Crop Tolerance Table 14.

2/ Data available for single variety of each crop only.

Table 17 INFLUENCE OF CHLORIDE ION CONCENTRATION ON YIELDS OF MAIZE AND COTTON IN UAR

(Elgabaly and Madkour 1965)

Crop	Yield	Chloride in saturation extract (meq/l)
Maize	2 471 kg/ha	12.3
	1 730 kg/ha	19.7
	233 kg/ha	47.0
Cotton	1 297 kg/ha	11.3
	793 kg/ha	38.7
	465 kh/ha	92.7

The content of boron is thus an important consideration in judging the suitability of water for irrigation. Boron problems seem to be more prevalent in well waters and springs from thermal areas and earthquake faults. Few streams have boron problems.

Eaton (1935) states that plants have a tendency to concentrate boron in their leaves, and that these organs are first to exhibit injurious effects. Usually the apical margins of the leaves turn yellow, and the yellowing then extends between the lateral veins toward the midveins. Leaf symptoms, however, differ on different species. A gummosis or exudate is also sometimes very noticeable on seriously affected trees, especially almonds. Hanson (1958) found high concentrations of boron weakened many fruit trees and little or no fruit was produced.

Reeves et al. (1955) has found that boron can be leached from a soil but requires considerably more water than ordinary salt removal. He found that under conditions in which 80% of the initially high salts were leached by an application of one foot of water for each foot depth of soil, equal leaching of boron required three times as much water. Coarse-textured soils are normally more readily leached of excess boron than fine-textured soils. However, Eaton (1935) states that some soils have remarkable boron-fixing power. He cites an example of a soil near Hollister, California, where crops have not shown conspicuous injury even when irrigated with waters containing up to 10 ppm of boron for a number of years, while drill row applications of only 10 pounds of anhydrous borax per acre greatly reduced cotton yields on light soils in the southeastern states. The effect of boron is less severe where rainfall occurs in sufficient quantity to dilute the soil solution.

In Table 18 crops are listed in descending order of their tolerance to boron in irrigation waters. The boron content shown at the top of each column may be expected to cause some injury to the more tolerant crops and serious injury to the more sensitive crops in the group. In most circumstances all of the crops listed in the first column could be irrigated with water containing 2.0 ppm of boron without risk of serious injury.

The values in Table 18 reflect the best available information on the tolerance of certain crops to boron in irrigation waters. This tolerance can change appreciably under adverse soil conditions such as poor drainage. The existing boron content of the soil must also be taken into account since the values in this table reflect the equilibrium irrigation conditions after residual soil boron has been leached.

Should the potential water source contain boron and the appraisal studies indicate equilibrium boron levels exceeding the tolerance of the anticipated crops, there are several planning alternatives. They involve considerations for (a) modifying the composition of the water supply; (b) ensuring that the arable lands have adequate drainage and leaching characteristics and providing for the essential drainage facilities; (c) predicating the project on a high level of soil and water management. Consideration should be given to reservoir and system design and operations that would provide water of suitable quality for the lands at hand. When the equilibrium levels under normal irrigation are only slightly in excess of the crop tolerance, the leaching requirements, with respect to boron, might be met by scheduling additional irrigation water.

Table 18

RELATIVE TOLERANCE OF CROPS AND ORNAMENTALS TO BORON 1/
Tolerance Decreases in Descending Order in each Column
(Wilcox 1960)

Tolerant	Semitolerant	Sensitive
4.0 mg/l of boron	2.0 mg/l of boron	1.0 mg/l of boron
Athel (Tamarix aphylla)	Sunflower, native (Helianthus annuus L.)	Pecan (Carya illinoensis (Wang.) K. Koch)
Asparagus (Asparagus officinalis L.)	Potato (Solanum tuberosum L.)	Walnut, black and Persian or English (Juglans spp.)
Palm (Phoenix canariensis)	Cotton, Acala and Pima (Gossypium sp.)	Jerusalem artichoke (Helianthus tuberosus L.)
Date palm (P. dactylifera L.)	Tomato (Lycopersicon esculentum Mill.)	Navy bean (Phaseolus vulgaris L.)
Sugarbeet (Beta vulgaris L.)	Sweetpea (Lathyrus odoratus L.)	American elm (Ulmus americana L.)
Mangel (Beta vulgaris L.)	Radish (Raphanus sativus L.)	Plum (Prunus domestica L.)
Garden beet (Beta vulgaris L.)	Field pea (Pisum sativum L.)	Pear (Pyrus communis L.)
Alfalfa (Medicago sativa L.)	Ragged-robin rose (Rosa sp.)	Apple (Malus sylvestris Mill.)
Gladiolus (Gladiolus sp.)	Olive (Olea europaea L.)	Grape (Sultanina and Malaga) (Vitis sp.)
Broadbean (Vicia faba L.)	Barley (Hordeum vulgare L.)	Kadota fig (ficus carica L.)
Onion (Allium cepa L.)	Wheat (Triticum aestivum L.)	Persimmon (Diospyros virginiana L.)
Turnip (Brassica rapa L.)	Corn (Zea mays L.)	Cherry (Prunus sp.)
Cabbage (Brassica oleracea var. capitata L.)	Milo (Sorghum bicolor (L.)Moench)	Peach (Prunus persica (L.)Batsch)
Lettuce (Lactuca sativa L.)	Oat (Avena sativa L.)	Apricot (Prunus armeniaca L.)
Carrot (Daucus carota L.)	Zinnia (Zinnia elegans Jacq.)	Thornless black berry (Rubus sp.)
	Pumpkin (Cucurbita spp.)	Orange (Citrus sinensis (L.) Osbeck)
	Bell pepper (Capsicum annuum L.)	Avocado (Persea americana Mill.)
	Sweetpotato (Ipomoea batatas (L.) Lam.)	Grapefruit (Citrus paradisi Macfad.)
	Lima bean (Phaseolus lunatus L.)	Lemon (Citrus limon (L.) Burm.f.)
2.0 mg/l of boron	1.0 mg/l of boron	0.3 mg/l of boron

1/ Relative tolerance is based on boron in irrigation water at which boron toxicity symptoms were observed when plants were grown in sand culture. Does not necessarily indicate a reduction in yield.

5.2.7 Miscellaneous Problems

In most cases, the three previously discussed subjects encompass the majority of problems associated with water quality. However, occasionally certain other problems do affect crop production in special ways and will be discussed here. These are problems due to nitrogen, bicarbonate, pH and lithium. Guideline values are given for all these except lithium which will be discussed although it is felt that additional research data are needed on other plant species prior to establishing general Guideline values; however, tolerance limits are suggested in Table 13.

i. Nitrogen

Nitrogen problems concern nitrate and ammonia nitrogen (NO_3-N and NH_4N) which are nutrients and stimulate crop growth. At nitrogen concentrations above 5 ppm (5 kg N/1 000 m^3 of water) from either nitrate or ammonia, production of certain nitrogen sensitive crops may be affected, but other crops not sensitive may find the nitrogen to be beneficial. However, this level of nitrogen may result in excessive algae growth which plugs pipelines, emitters, sprinklers and valves to the point that either mechanical controls (screens and filters) or chemical controls (copper sulphate) may be necessary.

Some of the nitrogen sensitive crops are sugar beets, sugar cane, apricots, citrus and cotton. At certain periods of their growth, nitrogen in the environment may cause excessive vegetative growth and low or delayed fruit production. In the case of sugar beets, it may cause low sugar content.

Management alternatives to counteract this problem are blending or alternate water supplies during critical growth periods and growing of crops that can effectively utilize the nitrogen in the water.

ii. Bicarbonate

The permeability problem due to bicarbonate has been previously mentioned and here the problem of white deposits on fruit will be discussed. During periods of high evaporation and the use of sprinklers, a white deposit of $CaCO_3$ is formed on the leaves and fruit which is not washed off by later irrigation. Although toxicity is not involved, it may reduce the marketability of the fruit or plant parts.

There are various management alternatives to correct this problem when sprinklers are planned, such as: (a) irrigate at night during critical periods; (b) increase the speed of the sprinklers; (c) do not use sprinklers which break the droplets into finer particles; (d) avoid sprinkling during low humidity periods; (e) change irrigation methods; and (f) use sprinklers only during the cooler part of the year.

iii. pH

The normal range for use is pH 6.5–8.4. A pH value above or below this is a warning that an abnormal situation exists and needs further evaluation. A problem from the pH alone on crop production would only exist under extreme conditions since the soil is such a strong buffer. However, long-term use of this type of water may cause soil or cropping problems as a result of the constituent that is affecting the pH.

iv. Lithium

Bradford (1963) detected lithium in some California irrigation waters in concentrations ranging from 0.05 to 0.5 ppm. On the basis that these concentrations could result in lithium accumulations in the soil, Bingham et al. (1964) studied the lithium tolerance of 11 plant species. Tests were made in the greenhouse by addition of lithium sulphate to soil. A summary of their results is shown in Table 19.

Table 19 TOLERANCE OF PLANTS TO SOIL ADDITIONS OF Li_2SO_4 (Bingham et al. 1964)

Plant tested	Lithium rates (ppm lithium) producing:	
	25% growth depression	Leaf injury symptom
Avocado (Persea americana Mill.)	6	3
Soybean (Glycine max.)	7	7
Sour orange (Citrus aurantium L.)	8	4.5
Grape (Vitis sp.)	12	12
Tomato (Lycopersicon esculentum Mill.)	12	30
Red kidney bean (Phaseolus vulgaris L.)	12	10
Cotton (Gossypium sp.)	25	30
Dallis grass (Paspalum dilatatum Poir.)	25	30
Red beet (Beta vulgaris L.)	35	80
Rhodes grass (Chloris gayana kunth)	65	65
Sweet corn (Zea mais)	70	120

Additional research data will be needed to test other plant species and to evaluate lithium properly as an undersirable ion in the water. However, observations in California show that lithium at concentrations of only 0.1 ppm in irrigation water can cause tip and marginal burn and defoliation of citrus leaves (FAO/Unesco 1973).

5.3 CLIMATE AND MICROCLIMATE

5.3.1 General Climatic Considerations

The definition of 'land' given in Chapter 1 embraces characteristics of the atmosphere above the soil surface, including the more stable, or cyclic, aspects of climate. These then are factors which must be considered in determining the suitability of land for irrigation.

Several climatic factors exert an influence on crop performance which is virtually independent of soil or other factors. Common observation certifies the existence of climates that are too cold, too hot or too dry for certain crops. For many crops there is fairly precise knowledge of the ranges and fluctuations of temperature and moisture that are acceptable or optimum. Other climatic factors, or other effects of the same factors may be less direct in their influence on crop production, but have to be taken into account in assessing the significance of different aspects of soil/moisture relations or of salinity, for example.

Maletic and Bartholomew (1967) studied the relationship between selected climatic factors and crop production under conditions prevailing in the irrigated land of western USA. They recognized that the influence of weather factors on crop distribution and yield was highly complex and not well understood but believed that more rapid progress towards understanding could be achieved by developing hypotheses and then testing the variables involved in a selected mathematical model. In a part of their study they used gross crop value as an index of the range of crop adaptation and yield level as conditioned by the market and social environment. They assumed that under optimum land conditions (i.e.: Class 1 lands) and with good management, the gross crop value from an appropriate agricultural programme would be functionally related to climate. The gross crop value, on lands meeting these requirements, was used, therefore, as the dependent variable in a mathematical model and various climatic elements were tested as independent variables. Three of the readily available climatic measures showed the highest correlation with the gross crop value index in these studies, namely:

- length of the growing season (frost free days);
- number of days with greater than 90° F (33° C) temperature;
- amount of summer rainfall (June, July, August in the study area).

In the study area these three factors were shown to explain 80% of the variation in gross crop value. These criteria have not been tested in the same fashion in other parts of the world but it seems likely that they would have similar importance in other temperate zones. A long growing season permits multiple cropping and a wide range of high value crops. The influence of high temperature is complex and varies from one crop to another but the form of the equation developed by Maletic and Bartholomew (loc. cit.) serves to average the combined effects of this factor. Summer rainfall has been found to be detrimental to irrigation for several reasons: (1) it may come at an inopportune time and prevent or delay harvests; (2) cloudy days reduce radiation needed for vigorous growth; (3) wet, rainy periods reduce soil aeration; (4) rainy periods prevent cultivation and weed control may be ineffective; and (5) with certain crops rain at specific stages of growth can reduce total production and quality.

Other climatic factors that may be important in forecasting adaptable crops and possible yield levels include annual temperature minima, average and maximum wind velocities, total rainfall, hail hazard, and intensity of rainfall. Minimum temperatures may place important limitations on the range of crops which can safely be grown. Many fruit and nut crops are particularly susceptible. Low temperatures that such trees will survive when young and healthy may prove fatal when the trees are older or diseased. Low temperatures in late spring or autumn when the trees are not dormant are particularly risky.

Data on average and maximum wind velocities may be important in appraising wind erosion hazards, problems in harvesting crops, consumptive use requirements and selection of irrigation methods. They may also indicate the need for shelter belts.

The total annual rainfall is important when appraising existing water table conditions, soil pH, depth of lime, and the water requirements. However, distribution of rainfall may be more important than the total amount. Intensity of rainfall is an important criteria in determining maximum water erosion hazards and acceptable slopes. Surface drainage requirements for relief from heavy rainfall are often greater than those required for irrigation wastes.

Where it exists, the hazard of hail, even at infrequent intervals, can be very detrimental to farm operations, and frequent damaging hailstorms could necessitate major changes in cropping pattern projections.

5.3.2 Microclimate

Variations in climatic conditions within a project area can influence the choice of cropping pattern and the yield. Air drainage is one of the more critical variants, particularly in areas having appreciable relief. Cold air tends to settle in low areas such as valleys, or depressed upland locations and will cause frost damage although surrounding areas are frost-free. The effects can be particularly severe in the early spring when fruit trees are in bloom. In winter the differences in temperature may be sufficient to cause selective killing of trees in the areas of unfavourable air drainage. Considerable differences exist in the air drainage between low gradient and steeply sloping valleys and between valleys with and without trees and brush to inhibit air flow. For general cropping purposes differences in air drainage may not be significant, but for areas which are otherwise considered suitable for fruit or nut production, air drainage is extremely important.

Another difference in microclimate significant to irrigation occurs in projects encompassing long valleys having substantial gradient. For example, the extreme ends of a valley and adjacent terrace uplands 50 to 100 km long may have substantially different climatic conditions of economic significance. If so, an evaluation of irrigation suitability in the valley would require either two sets of specifications or a single set of specifications which reflected climatic variations. Examples of specifications which reflect differences in climate are given in Appendix A.1).

CHAPTER 6

SOIL SURVEY METHODS

6.1 INTRODUCTION

An outline of the various stages of a systematic soil survey leading to land classification for irrigation has been given in Chapter 1. This chapter is concerned with specific aspects of method which are advocated for the actual conduct of survey operations. The choice of survey intensity is first considered before discussing basic survey operations and the nature of the soil observations which have to be made. Finally, consideration is given to methods of soil classification and to the preparation of a soil mapping legend. Discussion is largely confined to methods of high and very high intensity soil survey undertaken for the purpose of estimating the economic feasibility of and/or implementing irrigated agriculture.

6.2 SOIL SURVEY INTENSITY AND MAPPING SCALE

The paragraphs which follow are concerned with the choice of survey intensity and mapping scale for basic soil survey. It is assumed, however, that the mapping scale employed for most interpretative maps, including land classification maps, will be the same as that of the basic soil maps from which they are derived.

6.2.1 Terminology of Soil Survey Intensity

Terms such as 'reconnaissance', 'semi-detailed' and 'detailed', which are widely used to describe soil survey intensity elsewhere, have been avoided in this publication. These terms convey very different meanings to soil surveyors working for different organizations and in different countries. In many countries they carry strong, yet differing implications of mapping scale which could be misleading in the discussion on required survey intensity which follows. The terms employed, 'high intensity', 'low intensity' etc., are no more meaningful in themselves, but they carry fewer established connotations. Misunderstanding of terminology of survey intensity can have serious consequences, especially when it arises between the planners of a project and the surveyors who carry out the work.

Table 20 defines the terminology of survey intensity used in this publication in terms of the nature of mapping units recognized and of final mapping scale. Table 21 provides additional information on the characteristics of surveys at each level of intensity. Study of both tables is required to obtain a true impression of the intended meaning of the intensity terminology, although it must be recognized that the exact density of observation required and the rate of progress at each intensity of survey will vary from one environment to another. Wherever the intensity terms are used in the publication they are intended to embrace the concepts expressed in both Tables 20 and 21.

6.2.2 Advance Estimates of Required Survey Scale

An advance estimate of survey scale is usually required for budgeting purposes and as a guide for the surveyors who will carry out the work. It is especially necessary when a contract has to be prepared for the work to be carried out by a commercial firm. Minimum requirements for the density of soil observations can be stipulated on the basis of existing experience once a desirable scale of mapping has been established, although the exact density of observation required can only be decided on the basis of experience on the site itself.

The desirability of a staged approach to soil resource evaluation, in which successive soil surveys of increasing intensity serve to focus attention on areas

Table 20

TERMINOLOGY OF SOIL SURVEY INTENSITY IN RELATION TO FINAL MAPPING SCALE AND KIND OF MAPPING UNIT

Kind of Survey	Range of Scales	Kind of Mapping Unit
Very High Intensity (Detailed)	Larger than 1 : 10 000	Phases of soil series; soil series; occasionally soil complexes
High Intensity (Detailed)	1 : 10 000 to 1 : 25 000	Phases of soil series: soil complexes
Medium Intensity (Reconnaissance)	1 : 25 000 to 1 : 100 000	Associations of soil series; physiographic units (enclosing identified soil series)
Low Intensity (Reconnaissance)	1 : 100 000 to 1 : 250 000	Associations of Great Soil Groups or Subgroups; occasionally individual Great Groups; phases of Great Groups. Alternatively, land units of various kinds enclosing identified Great Soil Groups
Exploratory	1 : 250 000 to 1 :1 000 000	Land units of various kinds (preferably enclosing identified Great Soil Groups)
Syntheses	Smaller than 1 :1 000 000	Great Soil Groups and phases of Great Groups (having essentially taxonomic significance)

Table 21

GENERAL INDICATIONS OF SAMPLING DENSITY AND RATE OF PROGRESS ASSOCIATED WITH DIFFERENT INTENSITIES OF SOIL SURVEY

(Systematic Soil Survey - with some use of Air-photo Interpretation)

Kinds of Survey	Scale	Area Represented by 1 cm^2 of map	Density of 1/ Observations (0.5 obs/cm^2 of map)	Approx.Average 2/ Rate of Progress per 20-day month)	Accuracy of Boundaries
Very High Intensity	1: 5 000	0.25 ha	1/0.5 ha	500 ha	Position of all boundaries checked throughout length on the ground
	1: 10 000	1.0 ha	1/2 ha	800 ha	
High Intensity	1: 20 000	4.0 ha	1/8 ha	1 250 ha	Position of almost all boundaries checked throughout length on the ground
	1: 25 000	6.25 ha	1/12.5 ha	1 500 ha	
Medium Intensity	1: 50 000	25.0 ha	1/50 ha	75 km^2	Some boundary checking - most inferred
Low Intensity	1: 100 000	1 km^2	1/2 km^2	200 km^2	Almost all boundaries inferred

1/ Density of observations: figures represent the density of all soil observations averaged over the entire area of the map; (acceptable density usually ranges between 0.25 and 1.0 observation/cm^2 of map on this basis).

2/ Rate of Progress: figures given represent an approximate average from the wide range of progress rates experienced in actual surveys.

of promise for particular development purposes, has been stressed in Chapter 1. Recommendations on the areas deserving further investigation and on the intensity of survey work required should appear in the reports prepared at each successive stage. If this is done, a substantial volume of environmental data will be available when the need arises to plan high intensity survey for irrigation development.

Further guidance in the advance selection of soil survey mapping scale must come from the planned availability of topographical maps, aerial photography and the scale of mapping required for general irrigation and drainage design purposes. New photography and specially prepared base maps are usually required for the planning of irrigation implementation. All the purposes for which these materials will be used must be considered in selecting suitable scales. Topographical maps, soil maps and engineering designs need not be at identical scales but they must be compatible, for they will be used jointly in overall planning.

A survey in excessive detail is not only needlessly expensive but may lead to the accumulation of an embarassing volume of data within which the essential elements are obscured by information of little interpretative value. Thus the first considerations in making an advance choice of scale for soil maps are:

a. the reliability of existing environmental data;

b. the apparent feasibility of irrigation in the area.

If these considerations lead to unfavourable conclusions it would obviously be unwise to proceed immediately to very high intensity soil survey. Less intense survey leading to maps at a scale of about 1:25 000 or possibly 1:50 000 will serve to check existing data or to provide information which justifies abandoning the project. If the early findings are favourable the intensity of survey can be increased without significant loss of time or effort, provided this decision is taken before the survey teams leave the area.

If high or very high intensity survey appears justified, an advance choice of final mapping scale requires consideration of:

(i) the nature of the soil problems likely to be encountered in the area and thus the required precision of boundary placement;

(ii) the likely minimum area of planning interest.

The recognition of subtle differences in soil by very high intensity survey is only justified to the extent that these differences will have practical significance in planning the layout of irrigation and drainage systems and in planning management practices and cropping patterns within the irrigation network. The desirability of a large soil mapping scale in irrigation studies is more closely related to the need for precision in boundary placement than to a need to recognize very subtle distinctions in the nature of soils. The design of canals and drains, in which factors other than soil have to be considered, places limitations on the extent to which it is feasible to adapt management practices to minor soil differences. Nevertheless, marked contrasts in the hydraulic characteristics of soils, or the presence of saline, alkali or poorly drained soils, have an important bearing on irrigation practice and design. Boundaries between such soils must be precisely located in relation to topographic detail on large scale soil maps.

The minimum area of planning interest is, in effect, the area within which practical considerations of management dictate that farming practice must be uniform. In general, this is the smallest area of land that can be usefully differentiated on a soil map.

It is obvious that precise information on many of the factors which determine the minimum area of planning interest will not be available in advance of the survey. An estimate can be made, however, by considering the overall development aims of the project. This entails joint consideration not only of environmental factors such as landform, the general nature of the soils and the availability of water of a given quality, which determine the kind of irrigation to be employed, but also of factors which determine the kind of land holding and the sophistication of management practice. The latter include the farmer training schemes, supervision and extension assistance envisaged; the proposed system of land tenure; and the general level of capital investment foreseen with particular reference to the use to be made of mechanization in land shaping, cultivation and harvesting. In general, the greater the level of sophistication or the level of skilled supervision foreseen the greater the extent to which management can be adapted to soil differences and, therefore, the smaller is the minimum area likely to be of interest to planners.

If the map is to be used conveniently, the minimum area of planning interest should occupy not less than 1 to 2 square centimetres of the map (c.f. Table 21). Smaller units of very special significance, such as rock outcrops, can still be shown, but if there are likely to be many such units, a larger scale of final mapping should be chosen.

If very little environmental information is available, a need for preliminary survey of low or medium intensity is indicated and a different approach to the advance choice of survey intensity is unavoidable. Development possibilities and environmental problems will be largely unknown and the scale of presentation of most value to planners must be determined during the course of the survey. Within the limitations imposed by available base maps and/or suitable air photography, existing experience of survey work in comparable environments provides the only guide to an advance decision on required survey intensity.

In relation to the planning of irrigated agriculture the general applications of soil survey of differing intensity are as follows:

i. <u>Low intensity soil survey (final mapping scale 1:250 000 to 1:100 000)</u>

To identify the forms of development, including irrigation, that are physically possible within large regions of a country. The level and nature of national effort required to implement such development are assessed in general terms, providing a basis for establishing priorities and a timetable for the use of limited specialized staff and facilities in development.

ii. <u>Medium intensity soil survey (final mapping scale often 1:50 000)</u>

To identify specific areas apparently suited to specific forms of agricultural development. A reliable interpretation is obtained of the overall proportion and general distribution of soils (and related physical characteristics of the land) of differing potential for the development purpose(s) in view. Such information may be sufficient to assess the economic feasibility, and even permit implementation, of the less intense forms of agricultural development In relation to irrigation however, these surveys usually serve only a 'pre-investment' purpose - to identify 'project areas' within which expenditure on more intense studies for investment feasibility assessment and implementation appears to be justified.

iii. <u>High intensity soil survey (final mapping scale 1:25 000 to 1:10 000)</u>

To contribute to investment feasibility studies of fairly large irrigation projects (15 000 to 50 000 ha) and to plan the implementation of simple irrigation schemes. The accuracy of economic studies required to attract capital from international investment agencies necessitates fairly detailed knowledge of the distribution of different kinds of soil in all parts of the project but does not require the degree of precision in boundary placement needed for sophisticated irrigation planning.

Soil maps at about 1:20 000 may provide an adequate basis for planning irrigation implementation in certain circumstances. These circumstances include:

a. large areas of very uniform slope within which the nature of the soil differences and the nature of the planned irrigated farming practices do not demand very precise location of soil boundaries;

b. areas in which, for topographical or other reasons, only sprinkler irrigation and very simple drainage measures are foreseen;

c. areas in which irrigation improvement is required but in which the presence of existing structures (main canals and drains, bunded paddy fields, terraces etc.) places severe limitations on the possibilities of layout changes in the light of soil information.

i. Very high intensity soil survey (final mapping scale larger than 1:10 000)

To plan the implementation of irrigated agriculture in a sophisticated, or closely supervised, community and in areas where complex soil problems require precise definition. It may be economic in small projects (up to about 15 000 ha), where prospects of irrigation are promising, to proceed directly to very high intensity soil survey for both feasibility assessment and implementation purposes.

6.2.3 The Choice of Working Scale and Observation Density

Choice of a working scale for field sheets which is larger than that intended for final soil mapping is often desirable for two reasons:

i. to ensure that the positioning of soil boundaries in relation to topographical detail has a high standard of reliability on the final maps at reduced scale;

ii. to ensure that adequate space is available on the working sheets for field data to be clearly recorded, bearing in mind that such data will be handwritten - often in difficult circumstances. Errors in the interpretation and fair copying of field data are inevitable if the symbols recorded are cramped, distorted or displaced from their point of reference.

Ideally, working sheets should be at about twice the scale intended for final maps. This is not always possible since the preparation of separate base maps, or the enlargement of air photographs to provide a working base may not be economically justified. If working maps are prepared by photographic or mechanical enlargement of existing maps, it is generally undesirable to present final maps at scales larger than the original base.

A general indication of the density of soil observations required to justify publication of soil maps at various scales is given in Table 21. It should be noted that the figures given relate to soil observations of all kinds, including soil pits, deep borings and rapid auger inspections. It will also be noted that the required density of observations per unit area of map remains about the same at all scales of mapping. This implies, however, that the number of observations per unit area on the ground increases according to the square of the ratio between final mapping scales (i.e. if the scale is five times larger, about twenty five times as many observations per unit area are required).

The exact density of observations of different kinds required can only be determined by field inspection and will clearly depend on the complexity of the soil pattern that has to be mapped. This in turn depends not only on the natural variability of the soils but also on the nature of the criteria chosen to distinguish soil units. Therefore, the soil surveyor, in consultation with specialists in other fields, must first decide what soil characteristics are significant in relation to the different interpretative problems and then, by field inspection, determine what significant expressions, or levels, of each of these characteristics provide practical criteria for distinguishing soils in the particular project area. If soil units are to have interpretative value their nature must be determined in this way.

Once the required distinguishing criteria have been decided, the number of observations needed to characterize and map the various soil units depends only on the natural variability of the soils. Early field work will provide an indication of the density of observations required sufficient to prepare a Work Plan and a reasonably reliable time schedule for the whole survey. Of course, as work proceeds, a need to recognize further diagnostic criteria and to modify the density of observations may arise. As soon as possible, preliminary attempts to group the soil units for the various interpretative purposes should be made, to check that the density of observations is neither insufficient nor excessive.

6.2.4 The Choice of a Reporting Scale for Soil Maps

As a soil survey nears completion careful consideration must be given to the scale of mapping which will most effectively illustrate the data gathered. The scale estimated in advance for survey planning purposes is the most likely choice but it should not be assumed that this will be most suitable. Much has been learnt about the project area in the meanwhile.

The expense of printing and publishing basic soil maps is often justified since they have a continuing value as a basis for a variety of interpretations. If publication is intended, the possibilities of photographic reduction provide greater latitude in the choice of final mapping scale, which otherwise may be severely restricted by the availability of suitable base maps.

As stated in the previous section, a reduction in scale from the field sheets is usually foreseen and is desirable. In modern soil surveys, however, in which the use of air photographs permits very accurate location of observations in relation to surface features, reporting at the scale of the field sheets is often acceptable.

Particularly in irrigation projects a need for soil maps at scales larger than the field sheets may arise; for example, as a base on which to illustrate details of irrigation or drainage design. If this is unavoidable, the danger of misinterpreting the precision of the soil data can be minimized by clearly indicating the scale of the original soil mapping on the enlarged map and, where possible, by enlarging the soils data together with its original topographic base (thereby preserving the relationship of soil boundaries with topographic detail). This practice should only be permitted when the precision of soil boundaries is not critical for the purpose in view and when the expense or time needed for a more intensive soil survey to produce maps of the required scale is not justified.

In considering an optimum publication scale, all the factors relating to the aims of the project which were considered in planning the survey need to be reviewed again in the light of the information obtained by the soil surveyor and other specialists. In particular, the minimum area of planning interest has to be reassessed.

Other considerations include the aesthetic appearance of the map and convenience both in use and publication. The importance of aesthetic considerations should not be underestimated, for an attractive, easily readable map is more likely to draw and hold attention. A large publication scale should not be chosen merely to accommodate very complex mapping symbols, particularly if such a scale is not justified by the precision of the survey. Instead the symbols should be simplified.

Considerations of convenience in use and publication usually favour choice of a small mapping scale. Large maps, or large numbers of smaller maps, are expensive to publish and inconvenient to fold or use in the field. The minimum scale is dictated by the nature of the information which has to be shown; the required precision of boundary placement and the minimum area of planning interest.

6.3 BASIC SURVEY PROCEDURES

Soil surveys are very rarely undertaken today without the assistance of aerial photography. It can be assumed, therefore, that soil survey operations will involve air photo interpretation and ground control, either on traverses or by free ground survey methods. The value and limitations of each of these approaches are discussed in subsequent paragraphs before considering how they should be phased in the survey programme.

6.3.1 Air Photo Interpretation

It is assumed that the reader is familiar with the basic principles and methods of stereoscopic air photo interpretation in soil survey, which are essentially the same regardless of the agricultural purpose for which the survey is intended. 1/

The reliance which can be placed on air photo interpretation, and thus the time and effort saved in ground survey, is relatively much less in high and very high intensity soil surveys for irrigation purposes than in most other kinds of soil survey, because:

i. the large mapping scale involved in itself demands a high density of ground sampling to ensure the required precision of boundary placement and the required homogeneity of soil units;

ii. it cannot be assumed that all physical differences in the soil, subsoil and substrata, of supreme significance in relation to irrigation, will be reflected in air photo tones, patterns and textures.

Nevertheless, air photo interpretation can be very helpful in these surveys, particularly in their early stages; in the study of land form and in obtaining a general appreciation of the probable distribution of the major soil differences. It is likely to be particularly useful in arid and semi-arid areas where vegetation is minimal, and especially in flood plains where meander patterns etc. can be readily interpreted. These are situations in which major irrigation schemes are commonly sited.

The features which can usually be readily identified by stereoscopic examination of paired air photographs include:

1/ For further information see: FAO (1967) Aerial Photo Interpretation in Soil Survey. Soils Bulletin No. 6 FAO, Rome; and USDA (1966) Aerial Photo Interpretation in Classifying and Mapping Soils. Agricultural Handbook No. 294, Soil Conservation Service, USDA, Washington.

a. land forms (flood plains, terraces, residual uplands, dunes, etc.),

b. surface drainage patterns and systems,

c. erosional forms and eroded areas,

d. land use patterns and land use boundaries (and other evidence of human activity - roads, railways, habitations, quarries, etc.),

e. major types of natural vegetation,

f. wet areas, including lakes, lagoons and swamps,

g. surface evidence of salt-affected soils,

h. rock outcrops,

i. tones (colour changes in colour photography) and patterns which may reflect soil differences and the probable position of many soil boundaries.

From this evidence, subject of course to ground checking, a broad understanding of the geomorphology, physiography, surface hydrology and, to some extent, geology of the survey area can be obtained, which is invaluable in developing a sound working legend for soil mapping.

In high and very high intensity soil survey work complete air photo coverage at two scales is very helpful. The first set, at a scale of about 1:40 000 is used for stereo-interpretation and for obtaining a general appreciation of the area (a photo mosaic at this, or smaller scales, can also be very helpful for the latter purpose). A second set of larger scale photographs, at the same scale as, or slightly larger than, the probable final scale of soil mapping (e.g. at about 1:5 000) is used for some detailed stereo-interpretation but mainly as maps on which soil observations and boundaries can be precisely located in the field. Single photographs can be used for the latter purpose but even in the field more reliable results can be achieved by the study of photo-pairs, using a pocket stereoscope.

A single set of photographs at the larger scale is less satisfactory for stereo-interpretation purposes, partly because of the large number of photographs involved and partly because it may prove more difficult to obtain a general impression of land form from large scale photographs. To avoid confusion in identifying ground location arising from changes in surface features, particularly vegetation, the large scale photographs should be of recent date. Recent photography is desirable but less essential for the smaller scale photographs.

It must be recognized that air photo interpretation in soil survey is a very skilled occupation, requiring experience, high visual and analytical acuity, and an exceptionally broad knowledge of the interrelationships between environmental factors. Scientific tests have shown wide variation in the ability of individuals to master the required skills, even with specialized training. In the hands of the incompetent, air photo interpretation can prove very misleading and can have serious consequences affecting the validity of the whole survey. Even in the hands of an expert, air photo interpretation must be checked by adequate ground control.

6.3.2 Traverse Survey

This implies the systematic location of soil observation points along accurately located traces. It does not necessarily imply that the traces are arranged in the form of a parallel grid, or even that they are necessarily straight throughout their length. The position of individual traverses likely to yield the most informative observations can often be determined by a preliminary study of air photographs.

The principal merit of traverse survey rests on the precise location of observations, particularly amongst dense vegetation or on featureless terrain. Systematic positioning of observations on a parallel grid of traverses offers the further important advantage of assisting a numerical assessment of the proportion of different kinds of soil in a survey area - of particular value in an investment feasibility study. To provide a realiable assessment, the parallel traverses should be arranged to run across the general trend of the topography.

Parallel grid sampling should be employed:

i. where the density of vegetation makes it difficult to locate observations by any other means;

ii. over large areas of apparently uniform soil as a check on homogeneity, particularly in terrain lacking topographical or other features that might provide guidance to the position of soil boundaries;

iii. over areas with sporadic salinity/alkalinity, to evaluate the extent and distribution of these phenomena;

iv. over areas in which the complexity of soils is such that their individual occurrence cannot be mapped using a feasible intensity of observation, but in which their proportional representation must be established (e.g. complex meander patterns).

An important disadvantage of systematic grid sampling is that it provides only limited information on the position of soil boundaries. Supplementary investigations to locate the position of boundaries between observation points must, therefore, be undertaken, certainly in surveys of very high intensity. In addition, there is always a danger that important localized variations between traverses, or even between observation points, will be ignored. This applies in particular, to rock outcrops, wet spots and localized occurrences of salinity; to localized changes in microtopography; and to the significance of traverse slopes which, in dense vegetation, may not be detected on the traverse.

Cost is sometimes stated to be a further disadvantage of traverse survey but the cost of laying out traverses is only high in dense vegetation, when it is often unavoidable. In irrigation surveys, costs can often be minimized by timing soil surveys to make use of traces prepared for topographical survey.

6.3.3 Free Survey

Free survey, in which the soil surveyor uses his judgement in siting soil observations in relation to land form and other environmental features, is only convenient in open country where both access and visibility are almost unrestricted and is only possible when high quality air photographs or excellent topographical maps solve the problem of location. If the surveyor is sufficiently experienced and the preparation of maps rather than proportional assessment is the primary aim, free survey is the most efficient and most economic method of ground survey, because observations are sited only where they are likely to be most informative. For the inexperienced, however, it offers precisely the same dangers of misinterpretation and inadequate sampling which attend undue reliance on air photo interpretation.

In siting his observations under free survey, the surveyor must pay particular attention to both major and minor variations of topography. Considerable guidance in selection of promising observation sites will be derived from systematic air photo interpretation, but sites so chosen must be supplemented by additional observations to check the homogeneity and exact boundaries of soil units postulated from the air photographs. At the same time, the possibility of significant soil change which is unrelated to topography should be checked by making occasional borings in equivalent slope positions.

6.3.4 The Phasing of Survey Operations

Whether or not the survey team includes specialist photo-interpreters the sequence of air photo interpretation and ground survey should be systematically phased.

In surveys of medium intensity the sequence of studies is often as follows:

i. Layout of photos (or mosaics) and preliminary photo interpretation

To obtain a general appreciation of landscapes and terrain conditions and a preliminary assessment of the main physiographic units requiring recognition.

ii. Rapid field reconnaissance

To relate features distinguished on photographs in the first stage with actual ground conditions. Sufficient soil observations are made to identify the major diagnostic criteria to be recognized; to establish the general level of sampling density required; and to develop a preliminary working legend for soil mapping.

iii. Selection and systematic photo-interpretation of sample areas

Sample areas which, from the findings of stages i and ii, appear to be collectively representative of the survey area are selected and systematic photo-interpretation of their physiography is carried out.

iv. Field work in sample areas

Mapping units identified in the sample areas by air photo-interpetation are correlated with actual soil characteristics on the ground. This work is carried out at a higher level of intensity than that required for the overall survey but traverse survey is only used if no other form of access is possible. The working soil map legend and the air photo-interpretation criteria are further refined.

v. Photo-interpretation of the whole area

Boundaries established by photo-interpretation and field work in the sample areas are extrapolated or interpolated, as far as possible, by systematic interpretation of the remaining photographs of the area. Particular note is made of any areas which appear to present differing characteristics from those already recognized in the sample areas - these will be the subject of special field checks.

vi. Field checks outside the sample area

The density of field checking outside the sample areas varies according to the required scale and precision of the final map, the degree of change between sample areas and the degree of correlation between soil and photo-interpretation boundaries observed in the survey of the sample areas. The density is naturally increased in areas where discrepancies are found and anywhere else where the photo-interpretation is for any reason in doubt. Photo-interpreted boundaries are corrected where necessary and the soil map legend is finalized.

It is apparent that systematic ground survey can commence as soon as the photo-interpretation of one sample area has been completed. Indeed, any of the later phases can commence as soon as a certain amount of work in the previous phase has been done. These phases will overlap, therefore, especially if photo-interpretation and ground survey are the primary responsibility of different specialists. Complete separation of these responsibilities must not be permitted if the essential very close co-ordination of photo-interpretation and ground survey is to be achieved.

In high intensity soil survey the phasing of photo-interpretation and ground survey is basically similar. The phases are less clearly separated, however, since intense ground control is required over the whole area and less reliance can be placed on inferences drawn from air photo patterns and tones. The preliminary phases are followed by systematic air photo-interpretation of the entire area, preferably using photographs at a smaller scale than that of the final survey. Usually the total area involved is relatively small and this phase can be rapidly accomplished. It provides guidance on:

a. the probable distribution of major soil units,

b. the selection of areas best surveyed by free survey or traverse methods,

c. primary soil observation points for free survey and/or the best direction and position of traverses,

d. areas where more detailed stereo-interpretation of larger scale photographs is likely to be valuable.

The emphasis is on ground methods for the remainder of the survey although major assistance in positioning sample points and in checking the likely positioning of boundaries can be obtained by the study of large scale air photographs in the field.

The phasing of soil survey operations should be planned with careful reference to the activities of other specialists in the irrigation survey team. Apart from the obvious advantage of joint use of cut traverses, the timing of soil survey operations in different parts of the survey area should ensure that soil information is made available as quickly as possible in those parts where it is most urgently needed by other specialists. Thus, on completion of the reconnaissance phase, team consultation should decide in which part of the area detailed ground studies should be concentrated at first.

6.4 SOIL OBSERVATION AND SAMPLING

Soil observations are made for different purposes and the method and intensity of study required to meet these purposes differ. In the following paragraphs the requirements of observations made to characterize soil units, to check on their homogeneity (routine soil observations) and to establish their boundaries are discussed separately. Further consideration is given to deep boring, sampling for laboratory analysis and to field tests. Finally, the nature of field tools best suited to different purposes under different conditions of soil and environment are discussed.

6.4.1 Observations Intended to Characterize Soil Units

Purpose: To obtain detailed information on the morphology, physical and chemical characteristics considered to be representative of each soil unit occupying a significant area of the project.

Technique: Observations should be made in pits specially dug for the purpose. As far as possible, two sides of the pit should be kept free of spoil and untrampled. Morphological observations are made first, the pit may then be sampled for laboratory analysis and stepped for physical determinations, if required.

Depth: 2 metres or to an impenetrable layer.

Siting and Density: The preparation and detailed examination of pits is time consuming and the precision of laboratory data is not meaningful unless the samples analysed have representative significance. Therefore, to ensure that pit observations will be representative of the model characteristics and range of variation of the soil units concerned, pit sites should be individually chosen with reference to previous routine soil observations and other environmental factors. Pits should normally be sited at least 50 m from roads, quarries, housing and other features likely to disturb or contaminate the soil profile. Both cultivated and virgin sites should be examined if both are extensively represented on an individual kind of soil within the project area. The number of pit observations required in a given project depends on the degree of soil variation in the project area and the amount and quality of information available from previous surveys. It should be the *minimum* number required to *adequately* define all major differences in the internal characteristics of the soils in the project area. Normally, at least two pits in each major kind of soil should be examined.

Records: Complete descriptions of soil profile morphology and of site characteristics should be made at each pit (see FAO 1977 b).
Fair copies of these descriptions should be carefully preserved, together with any laboratory or field test data relating to the same pit. The exact site of each pit must be precisely identified on the working map sheets or air photographs.

6.4.2 Routine Soil Observation

Purpose: To identify the kinds of soil present in the area and, once provisional soil boundaries have been recognized, to check on the homogeneity of the soil units enclosed.

Technique: Observation and description of samples obtained by auger or spade.

Depth: About 1.5 m.

Siting and Density: Initial observation points may be spaced at regular intervals on a traverse grid or, in free survey, may be sited by judgement of environmental features guided by preliminary air photo-interpretation. General indications of required initial observation density in traverse surveys of high and very high intensity are given in Table 21. Initial observation density requirements in free survey are essentially similar. The degree of variability between adjacent soil observations, preliminary attempts to draw soil boundaries, and the observation of minor variations in topography which may be associated with soil changes, will point to the need for additional auger or spade examinations. Particular attention should be given to areas where soils can be expected to be heterogeneous, notably in bottom lands bordering rivers or streams.

Records: All routine observations must be precisely located on working sheets or air photographs and identified by a number (relating to the observation description) and by a symbol reflecting the characteristics of the soil to assist mapping.

Complete morphological description of all routine samples is not practical but all the major characteristics of each natural horizon should be observed and recorded in a field log. The observations should include:

Observation Identification:

- Identification No.
- Classification (added later if need be)
- Name of observer
- Date

Site Characteristics:

- Slope: percent, length, regularity, etc.
- Microtopography: gilgai, rills and gullies, sand hummocks, etc.
- Surface: stoniness, rockiness, evidence of salinity, cracking, leaf litter, etc.
- Vegetation or land use

Soil Characteristics: (for each natural horizon or stratification)

- Depth of top and bottom of layer
- Moist colour (Munsell system)
- Colour mottling, if any
- Texture
- Structure
- Consistence (i) wet (ii) moist (iii) dry
- Cementation or pans, if any
- Pores (frequency and size only)
- Content of large particles (stones, gravel, concretions etc.)
- Evidence of soluble salts, carbonate, gypsum
- pH (field test kit)
- Depth to groundwater table.

The recording of routine soil data is greatly facilitated by the provision of standard cards on which soil profile data is recorded in abbreviated form. The design of the standard card should be adapted to meet the special needs of particular countries.

6.4.3 Soil Observation to Locate Soil Boundaries

Purpose: To provide a rapid check on the exact position of boundaries between soil units.

Technique: Observations of samples obtained by auger boring (screw auger is adequate in medium and fine textured, gravel-free soils).

Depth: 1 to 1.5 m.

Siting and Density: As required.

Records: Normally no permanent records are made of boundary observation checks except that boundaries are aligned or adjusted in accordance with their evidence. However, should a boundary check reveal an unexpected change in soil characteristics it should assume the status of a routine soil observation (previous section) and additional routine soil observations should be made to establish the extent of the different kind of soil.

6.4.4 Deep Boring

Purpose: To check characteristics of subsoil and substrata layers with particular reference to permeability and salinity and to locate any impermeable layers and the depth and quality of groundwater.

Technique: Observation (and laboratory analysis if required) of samples obtained by auger with extension rods.

Depth: 3 - 5 m.

Siting and Density: Decided in consultation with drainage engineers and hydrogeologists. Depends on the complexity of underlying strata, the presence of impermeable, saline, or unstable (e.g. gypsic) layers at depth and the degree of hazard of waterlogging.

A need for one or two deep borings on average in every km^2 is to be expected in very high intensity surveys (1:5 000 scale); about one to every 2 km^2 are usually needed in high intensity surveys (1:10 000 scale); and about one to every 5 or 6 km^2 are required in medium or low intensity surveys (1:50 000 - 1:100 000 scale) carried out to obtain general information on the extent and location of arable lands.

Records: All soil horizons in deep borings should be completely described and retained as permanent records. Sampling at appropriate depths for salinity analysis is usally desirable. Groundwater should be sampled or its electrical conductivity determined on the spot.

(Note: As indicated in Chapter 4, section 4.2.4, the soil scientist should assist the drainage engineer in logging the deep borings undertaken as part of the drainage studies; frequently this information will meet the need for soil data from depth without additional borings).

6.4.5 Sampling for Laboratory Purposes

In terms of obtaining a representative measure of soil physical and chemical characteristics the possibility of error due to sampling is far greater than that due to laboratory procedure. Special attention must be given, therefore, to the careful selection of sites for laboratory sampling and to the collection of the samples themselves to ensure that they are both representative and uncontaminated. Sampling precautions depend on the nature of the analyses contemplated but the following general precautions should be observed:

i. samples should be taken from pits specially dug for the purpose or from pits dug for general morphological characterization and selected as being especially representative;

ii. samples should not be taken at arbitrary depths but should represent natural soil horizons or stratifications. Normally all soil horizons over 10 cm thickness should be sampled;

iii. in sampling for chemical analysis, special care should be taken to avoid mixing samples from different horizons. Thus, once the whole vertical profile has been carefully cleaned, samples from the lowest horizon should be taken first followed in sequence by the horizons above. Samples of the uppermost horizons, likely to have been disturbed in the process of pit digging, should be taken from undisturbed sites as close as possible to the pit;

iv. samples for chemical analysis should weigh about 1 kg or, in gravelly soils, should be of sufficient size to obtain at least 100 g of fine earth (smaller than 2 mm diameter). Stones and large pieces of organic material (in surface samples) should be removed from the sample;

v. samples should be placed directly in stout plastic bags, or in canvas bags with plastic liners, and securely tied. If samples are to be examined and compared before bagging they should be placed in discrete heaps on a sheet of plastic or close woven material to avoid contamination with each other and with manure, surface salts etc. on the soil surface;

vi. all samplebags should be securely labelled to correctly indicate the pit identification number, the depths of the horizon sampled and the date;

vii. the morphology of all pits sampled should be described in detail.

Exceptions to this general procedure arise in areas which include a scattered occurrence of soils having specific chemical limitations (e.g. salinity or alkalinity). In such areas relatively large numbers of auger samples will be taken, for limited laboratory analysis (e.g. pH, conductivity and ESP). The purpose of such sampling is to determine the extent and severity of the problems investigated. The number of samples involved precludes morphological description at each sample point and the samples usually relate to arbitrarily selected, fixed sampling depths. The position of sampling points must be accurately located on working sheets, however, and each sample must be accurately labelled by depth and location. It is usually useful to determine the field texture.

6.4.6 Field Tools

i. Basic field equipment

Basic equipment for a soil survey party working in potentially irrigated areas includes the following:

Soil sampling equipment: various augers (see separate note below), post-hole spade(s), shovel(s), pickaxe(s), geological hammer, large sampling knife, sample bags, labels etc. and bucket.

Soil description equipment: hand level (Abney type), prismatic compass, steel measuring tapes (2 m), hand lens, colour charts (Munsell), portable conductivity meter (see separate note below), colorimetric pH kit, plastic squeeze bottles for 10% hydrochloric acid and water, profile description forms and clipboard (or hardback notebook).

Field test equipment: (for details see Appendix B)

Survey and mapping equipment: mirror stereoscope (for use in office), pocket stereoscope (for use in field), aerosketchmaster (for transfer of information between maps and airphotos) or if feasible, optical pantograph (adjustable), plane table, measuring chain or surveyor's tape, storage cabinets for records, maps and air photographs, and drawing office equipment.

In addition the party will require a vehicle adapted to the terrain and capable of carrying the full party with its equipment and samples. For reconnaissance studies in desert terrain the vehicle should be equipped with two-way radio communication with a base capable of mounting rescue operations. In most countries the vehicle should be supplied with a full range of spare parts. The party may also require desert camping equipment, food, water, medical supplies etc., depending on the degree of isolation of the survey area.

The following additional notes have special relevance to the requirements of irrigation development studies and to the kinds of environment where such development is likely to be contemplated.

ii. Mechanically operated sampling equipment

Potentially irrigable terrain usually offers relatively free access to vehicle-mounted equipment. Careful consideration should be given to the feasibility of using a mechanically operated, tractor mounted, back-hoe for digging soil pits and a power operated auger for auger sampling. Such equipment can offer very substantial savings in time and effort and, perhaps more important, can permit a more intensive sampling pattern to be completed within a tight time schedule.

Suitable back-hoe equipment capable of digging to depths in excess of 3 m can be mounted on a fairly small agricultural tractor. The attached bucket can be of a general purpose type, or, if conditions require, a special rock bucket or a clay bucket incorporating an hydraulic ejector plate, can be fitted.

Power augers can be supplied on a self-contained trailer or mounted upon and driven from the tail of suitably equipped pick-up trucks or Land Rover-type vehicles. A single machine can be capable of screw-type or push-type core augering to meet requirements of individual sites.

iii. Choice of hand augers

A variety of different designs of hand auger exist. They are intended to serve different purposes. A geographically extensive enquiry into experience with various augers on FAO projects yielded the following findings:

Bucket (or 'Orchard') type auger: A cylindrical auger with specially designed cutting bits on the lower lip. In its standard form with a barrel about 15 cm (6 inches) long and 8 cm (3-1/4 inch) diameter this is probably the most useful general auger for soils of medium texture. The tool is light, penetrates most soils easily and is relatively easy to lift. The sample is disturbed but not unacceptably so for most descriptive purposes. The larger 10 cm (4 inch) diameter standard auger is especially appropriate for in situ permeability tests (see Appendix B). The standard auger is not effective on non-coherent sandy and gravelly soils and samples from clayey soils are difficult to remove (especially when moist). A modified 'mud auger' is manufactured with large 'windows' in the sides of the barrel; these facilitate the removal of clay textured samples. Another modification of the standar auger, in which the cutting bits are more sharply curved inwards, is designed to retain the sample in sandy textured soils (this is more successful if the sample is moistened as boring proceeds). The 'Durango' type auger is a modification with smaller, more numerous cutting bits. These reduce the disturbance of sampling and make it easier to study soil structure.

'Dutch' or 'Edelman' auger: This auger is particularly effective on coherent, rather wet soils of high clay content, including paddy soils, where many consider it superior to the bucket-type auger. It is not very effective, however, on sandy, gravelly or stony soils or on dry soils of any texture.

Jarret auger: Also an open bucket auger with side cutters of robust design. Very strong but heavy in use and requiring a strong operator. Will penetrate most soils and is particularly effective in gravelly soils but will not collect a sample in dry non-coherent soils, unless they are wetted during boring.

Screw auger: Of limited value for soil observation because of the severe disturbance of the sample. Can be useful for rapid examination to check map boundaries on medium textured soils. Not effective on sandy or gravelly soils and difficult to drive in tight clays.

Tube (or 'push') sampler: Useful for rapid sampling, especially of topsoils (e.g. for salinity or other analysis), in medium textured and organic soils. Various devices can be used to obtain deeper samples (lever, jack-screw, hammer-collar). Not effective on non-coherent soils, hard clays or stoney and gravelly soils.

iv. Portable conductivity meters

A special note on this subject is included since soil surveyors who are new to arid and semi-arid areas may have little practical experience in the determination of electrical conductivity of the soil solution, or of water samples, as a measure of salinity. Portable conductivity meters are particularly useful in exploratory surveys to outline areas of salinity hazard and for determining the required intensity of routine sampling and testing for salts. The actual routine determinations of salt content, of which there may need to be a very large number, are more conveniently and reliably carried out in a fully equipped laboratory.

A range of portable conductivity meters is available on the market. A typical portable kit weighs about 2 kg, is about 20 x 15 x 10 cm in size, and contains a conductivity meter, conductivity cell and simple equipment for preparing a saturated paste and for filtering off the soil solution. Such a kit can be used to make rapid determinations of salinity actually in the field or, better, in a temporary field laboratory.

Electrical conductivity (EC), also called specific conductance, is defined as the reciprocal resistance (at 25°C) measured across two inert 1 cm^2 nonpolarized plates placed 1 cm apart. The test solution is placed between the plates in a standard cell and current is carried by ions in the solution. Thus, the EC reflects the total concentration of ionized constituents of the solution. The standard unit of measurement is mhos/cm. Since this unit is large, however, it is convenient to express the EC of soils in units of millimhos/cm ($EC \times 10^3$) and of water in units of micromhos/cm ($EC \times 10^6$).

Conductivity measurement normally involves determination of resistance of the unknown electrolyte within a standard cell using an AC Wheatstone Bridge. In modern equipment the condition of balance (when no current flow is detected) is indicated by an electroray eye or a centre reading null meter. In older equipment passage of current may be detected with earphones, the null point corresponding to the minimum buzzing noise.

The most reproducible and reliably interpretable results are obtained with electrodes immersed in solution extracted from the saturated soil sample. Modern equipment incorporates temperature compensators and automatically provides readings corresponding to conductivity at 25°C regardless of the actual temperature of the test solution. If this correction is lacking, the temperature of the sample must be measured immediately after the conductivity reading and a correction made from tables supplied by the manufacturer.

Modern conductivity meters are usually designed to be operated from either mains electricity or a small dry battery source but it is important that AC voltage of suitable frequency be supplied to the electrodes to avoid polarization. The frequency of the conductivity meter current is commonly 60 and more rarely 1 000 hz, the former being suitable for measurements of solutions low in electrolytes and the latter for those of high electrolyte content. Coating the electrodes with a deposit of spongy black platinum, which increases greatly the effective surface, reduces the polarization effect of the passage of current between the electrodes. The electrodes should be cleaned after use and replatinized whenever the readings become erratic or when any inspection shows that any of the platinum black has flaked off. 1/ The cell should be kept filled with distilled water when not in use.

The conductivity cell used should have a cell constant (determined mainly by the geometry of the cell) appropriate for the range of EC to be measured. A relatively low cell constant (2/cm or less) is suitable for solutions with EC less than 4 000 micromhos/cm. For solution with higher salt content a cell with a high cell constant (20/cm) will give better results.

The reader is also referred to pages 343 - 353 of the Soil Survey Manual (US Soil Survey Staff 1951) for a detailed description of the measurement of conductivity in saturated soil paste in a special standard cup (the 'Bureau of Soils' cup). The method described is satisfactory for obtaining a preliminary indication of salinity hazards.

6.4.7 Field Tests of Soil/Moisture Relationships

Field tests are an essential supplement to laboratory measurements in obtaining the understanding of soil/moisture relationships required in irrigation and drainage projects.

Infiltration tests using single or double ring infiltrometers enable the soil surveyor to provide the agronomist and irrigation engineer with basic intake curves on which field design and irrigation practices can, in part, be based. The importance of infiltration rates has been discussed in section 2.5.1 and practical procedures of measurement are given in Appendix B2.

Permeability measurements are needed to establish drainability classes and to guide drainage design. Permeability has been discussed in section 2.5.2; methods of measurement are outlined in section 4.2.3 and practical procedures of measurement are given in Appendix B 1.1, 1.2, 1.3 and 1.4

A sufficient number of both infiltration and permeability tests should be undertaken to characterize fully all of the extensive soils identified in a survey area. In theory, this calls for at least three replicates of each test on each soil to confirm uniformity of results. In practice, shortage of time and particularly of water may render this ideal unattainable.

Basin leaching trials represent larger scale tests undertaken where doubt exists on the practicability of reclaiming saline or salin-alkali soils. Such tests are generally not necessary if all evidence from laboratory and field tests show reasonable permeability. Sometimes, however, these tests indicate low or very low permeability values that suggest that reclamation is impractical and that the land should be classed as non-arable. Where substantial tracts of such lands occur or the affected areas are interspersed with good lands, thus interfering with field irrigation layout, basin leaching trials should be undertaken.

1/ The technique of platinizing is described on p.89 of Agricultural Handbook 60 of the U.S. Dept. of Agriculture (Richards et al. 1954).

At least three Field Plots (10 x 10 m to 5 x 5 m) are laid out so that a small border-ridge with about 45 cm settled height is built with soil from outside each basin - the soil within basins is disturbed as little as possible. Water is hauled to the plots or brought in by field ditch or pipe. Three types of leaching trials are usually conducted:

(1) leaching tests with water as near as possible to the quality expected for future irrigation use;

(2) leaching tests using saline water, i.e., introducing salts into water initially and gradually reducing salt content back to normal water; and

(3) working gypsum into surface soil, equivalent to 30% of gypsum requirements as calculated by laboratory tests, and leaching with water (1).

The tests made include penetration depths, quantities of water percolated hourly or daily, changes in conductivity of soil solution, changes in percent exchangeable sodium and piezometric readings at 1, 2 and 3 m depths or in aquifer zones during and for several days following tests.

Such tests and observations will show whether such soils are reclaimable and if so by which methods. Highly dispersable sodium clays sometimes seal up and become impervious when leached with low salt water but may be kept permeable by methods 2 and 3 above.

If examination indicates drainage barriers interfere with tests, some temporary drains may be needed to complete the field basin trials. This coupled with drainability surveys of the affected tracts should provide a basis for land classification and for future reclamation and development planning.

6.5 SOIL CLASSIFICATION AND THE SOIL MAPPING LEGEND

6.5.1 The Role of Taxonomic Classification

The use of taxonomic soil classification in soil surveys carried out to meet specific development objectives, notably irrigation planning, is sometimes criticized on the grounds that such classifications are too academic and too concerned with the relationships between one kind of soil and another, rather than with the practical significance of the properties possessed by a particular area of soil. Soil surveyors have themselves to blame for this criticism in so far as they have been content to map soils in terms of an established taxonomic classification and have failed, either to take account of diagnostic criteria which are of purely practical significance (e.g. unfavourable microtopography) or to explain the significance of their classification in terms of value to other specialists (i.e. to interpret their survey).

The criteria selected for differentiating soils in modern systems of taxonomic classification almost invariably have important practical significance with regard to agriculture. It is their additional significance with regard to soil genesis, however, that makes them so valuable in mapping soils and in comparing soils in different localities.

In the early stages of a survey, time, effort and experience is needed to obtain a broad understanding of the genetic relationships between soils and parent material and topography; but, once established, these relationships provide a logical basis for recognizing units of soil having a defined range of associated characteristics and for mapping the boundaries between these units with greater confidence. The phrase "associated characteristics" deserves emphasis, for not all the significant differences in soil character induced by differences in genetic history may be obvious upon visual examination of the soil. The significance of more obscure differences may only be revealed by field tests or laboratory analysis, or indeed, may only be appreciated through actual farming experience. For example, in mature river basins, where irrigation projects are often sited, the most obvious soil difference is often a complex variation in texture. It may be extremely difficult to map such soils on the basis of texture alone and the results may not be very satisfactory because individual alluvial deposits are likely to possess other distinguishing characteristics of practical significance. Through air photo-interpretation, careful measurement of level and field observation, the geomorphological history of the basin can often be interpreted and the distribution of the separate alluvial deposits defined. Any necessary further subdivision on the basis of texture is often relatively simple and one is assured that each subdivision will possess the assembly of characteristics associated with the parent deposit and its subsequent history. In other words, each major subdivision is likely to deserve recognition as a separate soil series.

An understanding of the causes of soil change also provides guidance in the selection of sites for soil observations, sampling for analysis, and for field tests. Equally reliable data can be obtained from a smaller number of sites and the area to which each set of data is applicable can be assessed with greater confidence than is possible without this understanding.

These considerations emphasize the importance of establishing a preliminary working legend as early as possible in the course of the survey. Such a legend is essentially taxonomic in nature, since it must be based on genetic conclusions drawn from the observed characteristics of a few soils in relation to their environmental situation. Soil series previously recognized in the area, if any, are identified and further soil series are defined as the work proceeds.

Since many irrigation schemes are on recent alluvial land with deposition layers of varying texture, and without diagnostic horizons on which to base the usual soil series, special classification legends must be devised to indicate the textural variations (as well as other differences such as salinity, organic matter content, etc.). It has been found useful, during field work, to designate 50 cm layers according to their dominant texture (e.g. "A" mainly coarse, "B" mainly medium, "C" mainly fine textures), giving a legend of for example ACB (coarse over fine over medium soil). There are 27 possible combinations but as soon as sufficient data accumulates to determine the main kinds of textural profile which are present, the soils can be grouped into a few extensively occurring kinds (e.g. light over heavy, Lh; heavy over medium Hm; etc.). The same process can be continued to characterize the deep subsoils.

No existing system of high level taxonomic soil classification can yet be recommended as a framework for distinguishing soils in high intensity surveys. Therefore, soil units must be recognized and grouped into series in accordance with a genetic interpretation of the distribution of characteristics which they display in the field and in accordance with practical considerations of intensive mapping. This does not preclude recognition, where possible, of the general requirements of higher level soil classification in a selected taxonomic system in defining soil series. If these requirements can be recognized the report on the soil survey can indicate how the established series may be grouped at successively higher levels of generalization. Still wider potential application of the findings of the soil survey and of the development project as a whole can be achieved by preparing a correlation table showing the classification of the soils in various internationally recognized systems of soil classification, including the legend of the FAO/Unesco Soil Map of the World (1974). The value of this procedure to the survey itself lies in the assistance it provides in identifying areas of comparable soils elsewhere which may serve as a source of interpretative information.

Soil correlation, aided by taxonomic classification, is also important within the survey area, for the recognition of similarities in the nature of soils may be almost as important in planning development as the recognition of differences.

6.5.2 The Definition of Soil Mapping Units

It would be misleading to suggest that the recognition of soil series was more than an early step in the identification of the kind of soil mapping unit required in high and very high intensity soil surveys for irrigation development. In many irrigation projects, genetic considerations justify the recognition of only a very few soil series, which must be subdivided to reflect further soil and environmental factors of practical significance in irrigated agriculture.

The first step in developing a soil classification is to resolve the foreseeable interpretative objectives of the soil survey in terms of the nature, and the level of expression, of the soil characteristics which need to be distinguished. A purely theoretical list of required diagnostic criteria can be prepared before the survey begins. For example, Chapters 2 and 3 of this publication provide guidance on the soil and environmental criteria which need to be considered in relation to irrigated agriculture. Other diagnostic criteria relevant to rainfed agriculture, or to specialized crops or management practices may also need to be considered and the list enlarged accordingly. The resulting list then needs to be reviewed in the light of field experience to decide to what extent and in what way it is practical to apply these diagnostic criteria to actual soils conditions in the survey area.

The main characteristics of soil series, 1/ such as the nature and depth of soil horizons, is governed by their genesis. The soil surveyor has some latitude, however, in defining the exact limits between series. In deciding these limits, he should give consideration to criteria which will have the greatest practical interpretative significance.

Once a series has been defined, it will be apparent which of the important diagnostic criteria will remain unmapped within the series. These can form the subject of separate phases. 1/ Factors relating to the soil surface such as slope, microtopography, surface stoniness and rockiness, erosion and flooding hazard can be shown as phases wherever their expression will be significant in interpretation. Depending on the degree of variation permitted in the internal characteristics of the series, additional phases (or variants) 1/ may be needed to indicate significan differences in effective soil depth, texture, infiltration rate and/or permeability (based on actual measurements), or the presence of impermeable layers at depth.

If parts of the soil continuum are so varied that it is not possible to separate areas having important interpretative differences, these areas can be mapped as soil complexes. 1/ Every effort should be made to establish the proportions of the different kinds of soil in these complexes by systematic sampling, since this may determine whether or not they can be used for a particular purpose.

A basic soil map is intended to present factual information of lasting value. As far as possible, therefore, the soil units should be defined in terms of factual data relating to the more stable characteristics of the soils and their environment.

1/ For definitions of the units 'soil series', 'soil phase', 'soil variant' and 'soil complex' the reader is referred to the US Soil Survey Manual, Agricultural Handbook No. 18, Soil Conservation Service, USDA 1951.

Soil salinity presents a special mapping problem. Soils subject to salinity can be shown as a separate phase, but data on the level of salinity in different areas at the time of survey which are subject to short term variation, are better shown on a separate map.

6.5.3 The Soil Mapping Legend

The aim of a map legend is to make the map self-explanatory. A supporting text will be necessary to describe in detail the full range of characteristics of each kind of unit shown on the map and it is reasonable to expect the user to read the text first. He will be greatly inconvenienced, however, if he has to make continual reference to the text in order to understand the maps. The map legend, by itself, should remind the reader of the most significant aspects of the classification portrayed. Thus, it is not sufficient in the mapping legend to identify the soil units merely in terms of symbols; or in terms of complex taxonomic names, meaningful only to soil specialists; or in terms of locally named kinds of soils, possibly meaningful only to the surveyor and his immediate colleagues. For each soil symbol on the map, the map legend should include a brief explanation of the most significant soil characteristics represented, in terms designed to be informative to the widest possible range of users. Space must be provided, if need be on the back of the map or on a separate sheet, on which an adequate map legend can be printed (FAO 1970).

A large number of soil units are to be anticipated on a basic soil map, for distinctions have to be drawn in recognition of as wide a range of interpretative purposes as possible. Some distinctions will be significant for one interpretative purpose, others for another purpose, and the units will be grouped accordingly on later interpretative maps. The range of criteria taken into account in recognizing and correlating these units will almost certainly be too large for the individual criteria to be validly indicated by separate symbols on the map. Instead a limited range of symbols can be used to indicate the *kinds* of soil which have been differentiated. The range of characteristics possessed by each kind of soil will then be described briefly in the mapping legend and more completely in the supporting text.

On basic soil maps relating to high and very high intensity surveys it is often convenient to use a two or three-part symbol to designate each mapping unit, e.g.

$$\mathrm{BAs}\ \frac{a}{3mf}$$

The first part of the symbol (BA) indicates, with bold characters, the major kind of soil represented by the unit. If soil series have been recognized and have been allocated local names, it is convenient to use a mnemonic code of letters for this part of the symbol. Alternative large Arabic numbers can be used.

The second part of the symbol (s) in the example, is only needed when soil variants have to be recognized. The defined nature of a soil variant (e.g. a shallow variant) may depend on the nature of the major kind of soil to which it is related. The variant is indicated, therefore, by one or two characters (usually lower case letters) which directly qualify the major kind of soil. The nature of each variant has to be defined separately in the mapping legend and the text.

The third part of the symbol ($\frac{a}{3mf}$) in the example distinguishes the phases of the major kinds of soil. Since phases will normally carry the same significance for all major kinds of soil they need only be defined once in the map legend and the text. If more than 3 or 4 phases (and/or variants) need to be indicated, space can be saved on the map representing phases in the form of a fraction:

soil phases (e.g. salinity, alkalinity, stoniness)

site phases (e.g. slope, microtopography, erosion, flooding hazard)

Provided duplication is avoided in the allocation of code characters to each level of each phase, a zero level of each phase can be recognized at which the particular phase concerned is not represented in the mapping symbol. This procedure allows a very considerable reduction in the complexity of the mapping symbols needed.

CHAPTER 7

SOIL SURVEY INTERPRETATION AND LAND CLASSIFICATION

7.1 GENERAL CONSIDERATIONS

The interpretation of soil data for evaluating land is divided into soil interpretation and land classification. This distinction may surprise those accustomed to regard these activities as synonymous but it is in keeping with the definitions of soil and land (1.2.2) and its importance has been stressed by Kellogg (1962).

The significance of the soils information provided by survey and analysis, may not be understood by the users of a report and must be explained if full benefit is to be derived from the work. Soil interpretation is an essential part of a survey report, whether or not any land evaluation and classification is attempted. It should form the explanatory part of descriptions of mapping units, in which the significance of the specific soil conditions for plant growth and irrigation and agricultural management is pointed out. It is commonly also useful to devote a separate chapter to it in order to avoid repetition and facilitate comparisons between the various conditions in the area. It may also form the first stage of land classification.

A land evaluation procedure that permits development of interpretations by stages is very desirable. Practical difficulties commonly interrupt data collection, and some data can only be acquired over several years, so interpretation may have to begin before all the desirable data is available. Many planning decisions do not require precise quantitative assessments; simple comparisons may suffice to identify the most promising use possibilities and the practices that must be associated with them.

Successive stages of interpretation should reflect increased precision in the basic data and in definitions of the kinds of use. Recognition of the aims and assumptions of each stage helps to make clear the degree of precision intended, which must be explained; it also facilitates efficient survey planning.

The four-stage sequence outlined in Table 22 is similar to that recommended in Iran (Mahler et al. 1970). Qualitative and quantitative economic classifications are distinguished. The latter is only possible when specific knowledge exists of the methods of irrigation, of the expected costs and returns and perhaps of the ways in which expenditure will be financed and repaid, so it is essentially a multi-disciplinary operation. The qualitative classification should be developed as far as possible to provide the reliable physical basis for early planning and for later quantitative economic evaluation.

Soil survey interpretation is concerned with the practical significance of precise differences in the soils wherever they occur in the survey area. Land classification refers to specific areas. Besides the soil other factors must be considered such as location, accessibility, vegetation, hydrology, micro-climate, man-made structures, etc. Soil interpretations are tools of the resource scientist, permitting scientific exchange of experience on the qualities and potential of a given soil, whereas land interpretations are tools of the resource user or planner whose interests are localized and concerned with the total influence of the environment on his development objectives (Smyth 1972).

Both soil interpretations and land classification have operational problems, concerned with the environmental criteria relevant to a particular interpretation and their collective influence, and problems of presentation concerned with developing a clear, concise and unambiguous explanation of the findings for the widest possible audience. There may be similarities in the solutions to these problems.

Table 22

FOUR STAGES IN EVALUATING THE IRRIGATION SUITABILITY OF LAND
(adapted from Mahler *et al*. 1970)

TYPE OF OPERATIONS	BACKGROUND AND CRITERIA	DIFFERENTIATING FACTORS	ASSUMPTIONS	RESULTS
1 SOIL SURVEY	Relationships between soil morphology, land forms environment and physical-chemical soil characteristics.	Inherent characteristics of soils and land forms.	Genetic relationships between soil surface features and soil profile features in the area.	Characterization and delineation of soil mapping units.
2 SOIL SURVEY INTERPRETATION	General experience on influences of soil characteristics on the technical and economic feasibility of irrigation farming.	Present limitations of the soil, relating to salinity, topography, erosion, drainage, etc.	-Standard conditions of irrigation farming. -Irrigation water is not limiting. -No land improvement works are made.	Characterization and delineation of interpretative soil classes and subclasses. General management requirements of the different kinds of soil.
3 QUALITATIVE LAND CLASSIFICATION	General, local (available) experience on influences of land characteristics on technical and economic feasibility of irrigation farming, (including feasibility of land improvement) under future project condition.	Land qualities and characteristics, correctible and uncorrectible limitations of the lands in relation to crop and management requirements under future conditions of the project.	General conditions of water supply and irrigation farming as foreseen by project plans. Required land improvement works are made.	For each land unit: -Type and degree of land improvement requirements. -Land and water use recommendations. -Assessment of land suitability for irrigation farming <u>after</u> improvement (classes and subclasses).
4 QUANTITATIVE LAND CLASSIFICATION	Experimental results. Cost-benefit studies. Profitability of irrigation farming under future project conditions.	Land improvement costs. Annual costs. Income potential.	Specific conditions of the future irrigation development in the area.	Assessment of initial capital investment requirements and income potential for each land unit. Interpretation or review of results of 3 or revised standards for making 3 again.

7.2 SOIL SURVEY INTERPRETATION

7.2.1 Aims and Requirements of Soil Interpretation

Kellogg (1961) has described soil survey interpretations as predictions of soil behaviour under stated conditions. When carried out to provide a foundation for land classification for irrigation the principle aims of soil survey interpretation are:

- to determine which forms of land use offer sufficient promise on the soils surveyed, under the general environmental conditions of the area, to be regarded as relevant alternatives of use for planning purposes;
- to recognize characteristics of the soils which will place limitations of varying degree on the development of these relevant alternatives of land use;
- to simplify the basic soil map by grouping soil units having characteristics and sets of limitations that are similar in nature;
- to identify the management practices and inputs that will be required on each grouping of soils to take advantage of the favourable characteristics and to alleviate the various sets of limitations in order to develop a given form of land use on a worthwhile, sustained basis;
- to make a first estimate of productivity and a rating of relative merit of the different soils for the various uses (soil suitability classification).

An intention to irrigate is often basic to the planning of development projects in which soil surveys are undertaken. In such instances, the need to investigate alternatives of use may be questioned. However, a sound study of the economic feasibility of irrigation should always take into consideration the relative merit of other, possibly less expensive, forms of agricultural development starting with consideration of the physical possibility of alternative uses. Of course, if climatic conditions are very unfavourable the possibilities of rainfed agriculture, forestry or animal husbandry, can be dismissed very quickly. Even so, alternative forms of irrigated agriculture may still require comparison. These alternative forms may represent, for example, different production aims or different methods of applying water. The point to be emphasized is that neither soil nor land has intrinsic capability or intrinsic limitations; they have advantages and limitations for certain specific uses. An expression of a soil characteristic which is a severe limitation for one use, may be insignificant in relation to another use and may even favour a third.

The specific nature of interpretations makes it essential to decide the immediate objectives of interpretation as early as possible in the basic survey. At the same time the soil characteristics that are especially relevant to these objectives and the levels of each characteristic that have practical interpretative significance need to be determined. Otherwise there can be no guarantee that all the changes in the soils that are of importance to interpretation will be reflected by boundaries on the soil map. This point has been discussed in the previous Chapter in relation to the definition of soil mapping units and does not detract from the desirability of establishing the legend of the basic soil map on sound genetic principles (see 6.5.2).

The four chief requirements of a good interpretation are objectivity, accuracy, consistency and practical usefulness (Mahler et al. 1970).

To be objective, an interpretation must be based on facts which can be directly observed or measured in the area under study. To avoid confusion between observed fact and inferred interpretation basic data on all aspects of land should be collected in an operation distinct from that of the land classification.

To be accurate, the interpretations require to be based on exact data, precise definitions and interpretative norms. In part this requirement relates to the required accuracy of the basic soil survey which must conform with acceptable standards of observation density in relation to mapping scale, of soil characterization and description, and of variation within the soil unit. Accurate interpretations cannot be derived from inaccurate soil maps. The requirement also relates to the need for a systematic approach to the weighing of qualities and limitations in assigning soil units to interpretative classes and subclasses, with locally developed standards for rating individual criteria and for overall classification.

Subjective errors need to be avoided to achieve consistency. Like soils should be similarly interpreted throughout the survey area. Although rules and standards may have been developed to encourage objectivity and accuracy, not all soils will neatly fit the pre-established norms and some subjective judgment must be exercised. To minimize inconsistency in such judgment the interpretation should be approached concurrently from three directions:

- by an overall judgment; the soil as a whole (i.e. as the sum of its characteristics in its general setting) being compared with the concepts of the interpretative classes and placed within the class that appears to fit it best;
- by analysing each separate limitation of the soil with respect to the use in question and rating these limitations in accordance with established norms; classification is then determined by a comparison of these ratings with established specifications of the interpretative classes;
- by correlation with similar soils in similar settings which have been classified previously or, preferably, have already demonstrated their response to the use in question.

Mathematical, or 'parametric' methods of assessment in which data on soil characteristics are manipulated mathematically to yield an index of soil productivity, provide another approach to the problem. These methods, which are becoming increasingly sophisticated, are discussed briefly in Section 7.5.

If, when compared, these separate approaches yield contradictory results the validity of the basic survey data should first be checked before reviewing the rating of limitations and the class specifications.

To ensure practical usefulness the main interpretative objectives should be identified in advance, in consultation with the potential users, and the presentation should be appropriate to the stage of project development Broad assessments should be provided quickly as a guide to the main alternatives for development. Once the direction of development is clarified, increasingly precise and specific interpretations should be made and, for the final decisions on implementation of irrigation development, should be meaningful in quantitative economic terms.

7.2.2 The Selection and Rating of Diagnostic Features

Standard criteria and specifications for interpretative classifications must be provided in order to establish credibility and permit checking of the evaluation. Characteristics which influence suitability have been discussed in Chapters 2, 3 and 4, and in Appendix A.1. Their relative importance and ratings are locally specific, and should be judged in relation to the following factors:

- the precise use for which the land is evaluated,
- the assumptions on which the interpretative classification is based,
- the environmental conditions, especially climatic,
- special features requiring emphasis (e.g. drainage problems, salinity, available water).

Considerations relating to alternative uses must take account of production aims and management practices required to achieve them on a sustained basis. For example, different criteria and ratings will be appropriate for rice and wheat production, gravity and sprinkler application, and rainless or monsoon climates.

The assumptions strongly influence the rating of diagnostic features particularly as they concern the level of management, including know-how and anticipated expenditure. For example, the significance of soil texture may depend on the power source available (hand tools, animal up to heavy tractors) or know-how for sprinkler equipment or the availability of fertilizers. Because the assumptions are so critical, they must be made clear to the reader. For the first broad assessment sweeping assumptions may be necessary, for example that the quality and quantity of water will not be a restriction; in later stages they will be fewer and more precisely expressed, for example the stated quality of the water will affect the rating of some diagnostic features.

Soil survey interpretation is an "iterative process", proceeding by successive approximations (FAO 1976). Thus the first selected most promising land uses may be limited by certain soil characteristics. A use may be rejected or the inputs and management requirements revised; in the latter case the diagnostic requirements may change in significance, and the interpreter must go back and reconsider his ratings in the light of the new requirements. When the uses have been decided the criteria can be finally determined, and at this stage the completed soil survey should be reviewed to confirm that all significant changes are reflected in the soil boundaries.

This iterative process need not be very time-consuming since a preliminary study will limit the alternatives, and different production aims may have essentially similar soil requirements. Even large changes in the significance of diagnostic features may not require extensive changes in soil boundaries, for they are determined by natural factors unrelated to survey objectives, and only when soil change is gradual does the surveyor have latitude to adjust his boundaries to the need of his interpretations.

Separate ratings of the relevant diagnostic features may be required for each alternative land use. Such ratings are normally expressed as the range of a particular characteristic in each interpretative class or as a set of critical values, assuming that all other aspects of the environment are optimum. The development of the specifications are complicated by three considerations:

- economic implications: the interpretative classes have economic significance and so, therefore, do the specifications which control classification;
- inter-dependence: the significance of one characteristic often depends on others which vary independently;
- cumulative effect of limitations.

To be meaningful comparisons of soil suitability must take account not only of physical but also of economic possibilities of using and improving the soil. This calls for some degree of economic judgment, and information, to ensure that suitability classes provide a sound basis for subsequent economic and quantitative land classification.

Because individual soil characteristics do not influence suitability independently (unless very extreme), they must be considered jointly. The concept of "qualities" proposed with respect to soil by Kellogg (1961) can help in untangling these complex relationships. This concept will be considered further in the discussion of land qualities (in section 7.3.2).

The cumulative effect of limitations creates a separate problem. A soil with several moderate limitations is less suitable than a soil with only one. Sometimes general rules can be developed for downgrading soils with two or more limitations of similar or different importance, but informed subjective judgment is unavoidable.

7.2.3 Soil Suitability

A soil suitability classification appraises the suitability of different kinds of soil for a particular use assuming that all other aspects of the environment are optimum. Such classifications, although they may overlook important peculiarities of individual land tracts, can indicate that certain areas are less well suited to particular uses, and so preliminary planning decisions to reduce the range of more complex land classification studies.

The problems of designing interpretative classifications are essentially the same whether they relate to soil or land. Decisions must be taken on the number and the nature of the interpretative groupings to be recognized and the meanings of these groupings must be defined. Maletic (1966) has quoted three traditional rules for the development of a satisfactory and logical classification:

- the main separations within the classification must be based upon a single principle;
- the classification should be exhaustive; it should have room to include everything to be classified;
- the subdivisions in the classification should be mutually exclusive neither gaps nor overlaps should exist between the discrete groupings.

In practice, it is often difficult to comply with the first of these rules. Unless this is achieved there can be no certainty that the second and third rules are obeyed. Compliance can be achieved if the suitability classification relates to only one form of land use throughout and if suitability is assessed consistently in terms of diminishing economic benefit. Since for different land uses the nature of benefits (e.g. crop yield) and of inputs (e.g. labour, power, fertilizers, irrigation water) can be very varied it is likely that their relationships can only be assessed in economic terms. At the soil survey interpretation stage, when a soil suitability classification is usually made, the assessments would be essentially qualitative. Nevertheless, even at this stage it is possible to make a consistent use of a theme of diminishing economic returns to provide a clearly understood, if not very precisely expressed, basis for class separation.

The following categories of interpretative grouping are very commonly recognized in soil (and land) suitability classification:

suitability <u>classes</u>: distinguishing the degree of suitability of the soils (or lands).

suitability <u>subclasses</u>: distinguishing the <u>nature</u> of the class-determining <u>limitations</u> in soils (or lands) belonging to the same class.

suitability (or management) <u>units</u>: grouping soils (or lands) within a single subclass that require the same management practices.

Some flexibility is desirable in choosing the number of interpretative classes and subclasses which will be distinguished. In each survey there is a minimum number needed and a maximum which can be recognized. Within this range, the advantage of conveying additional information needs to be weighed against the risk of confusing the reader.

The six-classes of irrigation suitability of the U.S. Bureau of Reclamation have proved convenient in a wide variety of environments and may be summarized as follows:

Class 1	Highly suitable
Class 2	Moderately suitable
Class 3	Marginally suitable
Class 4	Restricted suitability (suited only to special crops or in special circumstances)
Class 5	Unsuitable, pending further study
Class 6	Unsuitable.

Soil suitability subclasses are conventionally symbolized by lower case letters immediately following the class number (e.g. 2w might indicate a subclass of Class 2 soils which suffered from a limitation of excess wetness). From 4 to 12 or more such subclasses may be recognized.

Soil suitability units are normally recognized only in intensive soil survey studies, such as those associated with irrigation development. By grouping soils with like requirements, the management requirements of large numbers of separately mapped areas can now easily be explained. Arabic numbers are normally assigned to soil suitability units within each subclass so that they can be identified in text and map. For convenience, the units are usually numbered consecutively in relation to their mapped position, from left to right and from top to bottom of each map. In the classification symbol the unit number is placed last, immediately after the subclass letter (e.g. 2w14 would be the fourteenth unit recognized in class 2w).

7.3 QUALITATIVE LAND SUITABILITY CLASSIFICATION

7.3.1 **The Scope of Qualitative Land Suitability Classification**

Much work has been devoted in recent years to developing a system for classifying land for agricultural purposes. The principles which have emerged as widely acceptable are set out in various publications (FAO 1974, FAO 1975, FAO 1976, FAO 1978, Beek 1978) to which reference should be made for a fuller account. In essence the Framework for Land Evaluation (FAO 1976) recommends qualitative and quantitative classification of land (not just soil) for well defined land utilization types, under unimproved or improved conditions by suitability orders, classes, subclasses and units.

The term 'qualitative land suitability classification' is not intended to imply that no quantitative data on yields or inputs is used in the assessment: on the contrary, both the ratings for classification and the benefits from development should be expressed as quantitatively as possible. It does imply that the data were insufficient to define the distinctions between classes in precise numerical terms (usually economic values).

Such qualitative classification may be only a working tool of the interpreter not intended for publication. It can provide a first approximation of the land classification in which physico-biological characteristics are integrated and the general character and relative suitability of the mapped units are indicated. If sufficient economic and related information is available the interpreter can proceed immediately to produce a quantitative economic land suitability classification. Particularly in developing countries, lack of experience and economic data may delay complete economic evaluation. The qualitative interpretation of the physical features of the environment must then be used and this is a recognized stage in land evaluation. The Framework for Land Evaluation provides for either parallel physical and economic studies or a two-stage approach with physical studies followed by quantitative economic evaluation.

It must be emphasized that evaluation must be for a specified land use type. On a worldwide or regional scale "irrigated agriculture" may suffice, but for most purposes it is necessary to specify the form of irrigation, the crops to be grown and the level of management envisaged.

7.3.2 Procedures for Integrating Physical Environmental Factors

The process of qualitative land evaluation comprises three steps: determination and description of the physical conditions of the land surveyed, determination of the requirements of the specific land utilization type for which the evaluation is being made, and matching of the requirements (crop or other) to the physical conditions. Each of these steps is a complex activity.

Procedures for description of the physical environment are described elsewhere in this bulletin. It should be noted however that the features to be described and the ratings for suitability need to be selected for their relevance to the defined use. A systematic approach is essential because of the wide range of characteristics which may be relevant and the need not to omit any.

The requirements of the land use type for which the evaluation is being made should be set down. Even if the data is inadequate this procedure will draw attention to gaps in knowledge which need to be filled, and will permit estimation of the reliability of the evaluation.

Matching comprises more than mere comparison of the physical requirements of crops with the land conditions to give a prediction of performance. It involves an iterative process of mutual adaptation of the definitions of the land use types and the land conditions as they become better known. It also permits systematic specification of the management and improvements needed for each land use type on each mapping unit, and hence of the required inputs.

The land characteristics which are measured and described for each mapping unit can be rated for suitability for the land use type. However the problem arises of the cumulative effect of limitations and of interactions between characteristics. One way to deal with this problem is through the concept of "land qualities" A land quality is a complex attribute of land which has a distinctive influence on the suitability of land for a specified use. At the highest level of generalization an example of a comprehensive land quality would be "gross productivity". This is the product of less complex land qualities such as "moisture availability" and "nutrient availability". The land qualities can be analysed in terms of land characteristics; for example, moisture availability can be analysed in terms of rainfall distribution, potential evapotranspiration, soil depth and water holding capacity.

A set of land qualities covering the requirements of the land use type determine the suitability of the land. As the qualities exert their influence in a manner distinct from each other they can be rated independently, and there is little or no overlap in their influence on land suitability.

Although the use of land qualities to cover all significant aspects of the environment is recommended, some difficulties are encountered. The major problem is the lack of knowledge of crop (or land use type) requirements and of how differences in certain qualities affect crops yield or cost of operation of an irrigation system. Although knowledge is lacking for statements of general applicability, it may be available for specific local conditions and should then be used. There may also be difficulty in combining land characteristics to form land qualities, since at present no generally applicable conversion tables have been set up. However the procedures for rating land qualities are being actively developed, and are discussed in several publications (Beek 1978, FAO 1978).

7.4 QUANTITATIVE ECONOMIC LAND EVALUATION

Quantitative land suitability evaluation in the Framework for Land Evaluation (FAO 1976) is the name given to evaluation in which the distinctions between classes are defined in common numerical terms which permit objective comparison between classes relating to different kinds of land use. Usually this means in economic terms, though other possibilities exist (for example "employment provided per hectare"). Qualitative land evaluation, although using as much quantitative date as is available, does not separate land classes by ratings expressed in monetary or other numerical terms and therefore it is usually difficult to compare the benefit from different land uses.

Quantitative classifications require detailed information on recurrent and non-recurrent investments and costs. They can only be done on a limited acreage, after intensive large scale mapping, and they are only valuable for a limited period.

Their preparation is a task for a multidisciplinary team, including agricultural economists, hydrologists and irrigation specialists. These experts do not have to be present throughout the survey work but must be able to take part in the iterative process of matching the requirements (including economic requirements) to the selected land qualities to determine the suitability for a land use type of which the definition is constantly reviewed.

It is necessary to distinguish between the procedures and ratings appropriate to economic land evaluation and the final cost-benefit analysis for feasibility studies and the definitive project formulation.

It is common to find that variations in economic factors have a much greater effect on suitability than variations in physical conditions. Changes in market prices, can easily make profitable a land use for which land was previously considered unuitable (or the reverse). Different assumptions about discount rates or amortization periods can also produce much greater variations in profitability than those caused by differing physical conditions. Of course, if a tract of land cannot produce a certain crop or support a certain use because of physical conditions, these have overriding importance. But commonly the boundary between suitable and non-suitable land is variable depending on economic considerations.

The system developed by the U.S. Bureau of Reclamation (1953) has been widely used and has proved effective in a wide variety of environments, and is frequently specified for feasibility studies by investment agencies. It is a quantitative classification, the economic rating being an expression of the relative repayment capacity. This criterion proved unsuitable in some regions, where government organizations did not require farm repayment of initial investments, and in some cases "net farm income" was used instead. Other minor adaptations have been made to take account of local circumstances.

The principles of the USBR system are outlined in Appendix A.1 and examples of its use in various environmental and economic conditions within and outside the USA are given in Appendix A.2. Further amendments are being made to the system by the USBR.

Quantitative or economic land classification, and to a lesser extent qualitative land evaluation, is now so complex and well documented a subject that it cannot be fully dealt with within the confines of this publication.

7.5 TRENDS IN LAND EVALUATION

Increased recognition of the importance of wise use of land arising out of concern for the human environment has drawn greatly increased attention to the methodology of land evaluation in recent years. Problems of land evaluation, not confined to irrigation development but relating to all rural land use purposes, were discussed at an international consultation convened by FAO at the Agricultural University, Wageningen, Netherlands in 1972 (Brinkman and Smyth, editors, 1973). At this meeting there was agreement on the need for increased precision in identifying the objectives of interpretation and for clear recognition of the possibilities of change in land, for better or for worse. An economic rather than a physical basis for comparing land suitability was seen to be necessary, on the grounds that land can be made suitable if the cost is justified. Basic to discussion at the meeting was the concept that land evaluation is meaningful only in relation to a clearly defined use and that the definition of the use must embrace both the objectives and the means by which these objectives will be achieved. When each use is precisely defined the possibilities of use alternatives on each land area have to be recognized. In fact, most of the features recognized at Wageningen as desirable in a land evaluation system are already embodied in the system of land classification of the U.S. Bureau of Reclamation, provided that the principles of that system are applied to alternatives of use (including, but not exclusively, different methods of irrigation).

A particular problem in evaluating land suitability is to obtain a satisfactory assessment of likely production following a change in land use or in management methods. In various countries parametric methods of solving this problem are being studied. Parametric methods entail (1) assigning numerical valuations to separate soil and land characteristics according to their relative significance (2) combining these numerical valuations according to a mathematical law designed to take account of their relationships and interactions to produce an index of performance which is (3) used to rank soils in order of (agricultural) value (Riquier 1972).

From the first application of the parametric method, probably that of Fackler (1928) in Bavaria which involved the simple addition of a few factors only, a variety of mathematical approaches have been tested. Particularly well known is the Index for rating agricultural soils developed by Storie (1937, revised 1944, 1948, 1955). The Storie Index is derived by the multiplication of a few selected factors, one being a rating based on the general character of the soil profile. Multiplicative methods have the advantage that they recognize the law of the minimum, yield being limited by the most unfavourable factor. This is especially significant when one factor, if unfavourably expressed, completely inhibits production (e.g. effective soil depth). Riquier, Bramao and Cornet (1970) proposed a multiplication method, based on seven physical and chemical characteristics of the soil, which includes provision for assessing the influence of soil improvements that modify or eliminate soil limitations. Other methods involving multiplication, or addition combined with subtraction, have been tested in the USSR (Blagovidov 1960; Taychinov 1971), Bulgaria (Poushkarov Institute 1970), Romania (Toaci 1964 and 1970), Trinidad and Tobago (Searl 1968), Canada (Millette and Searle 1969), France (Durand 1965 and Duclos 1971), and Iran (Sys and Verheye 1972). This last method developed by

Belgian soil scientists, is concerned specifically with soils of arid and semi-arid zones and aims to produce two indices: a capability index for irrigation and a land productivity index for a number of crops. No correlation is established, however, between capacity for irrigation and productivity. Some of the other methods include provision for calculating an enhanced index if the limitation of moisture shortage is removed but as yet, no method attempts to assess the full complexity of change associated with the introduction of irrigation ('the prediction principle' of the U.S. Bureau of Reclamation Land Classification).

The analytical capacity of electronic computers appears to offer a means for more thorough study of the complex interrelationships of factors and, subsequently, for employing much more complex mathematical models to estimate productivity. In a reference to this topic in a statement on land classification survey trends in the U.S. Bureau of Reclamation, Maletic (1967) has written:

"In the performance of land classification work, an important trend is toward more widespread application of computer technology. At present, work by Dutt (1964) has shown that the quality of water percolating through a soil profile can be adequately predicted through application of a computational programme that involves an integrated expression of the physical laws governing cation exchange, solution of soluble salts, and the dissolution and solution of gypsum. The prospect is good that such a programme could introduce the laws governing the solution and precipitation of calcium carbonate in the soil system. Working with Dr. Dutt, the Bureau of Reclamation has under development computer programmes aimed at predicting the future equilibrium exchangeable sodium and soluble salt levels of the soil with a given water quality. As the fundamental processes occuring in the soil are better defined and expressed in quantitative terms, it may be possible to develop computer programmes which would simulate irrigated conditions and provide a measurement of the chemical changes that will occur in the soil as a result of irrigation. Research in this direction will provide new and powerful tools for the selection of irrigated lands.

Production functions will also play a more important role in the performance of land classification work. Research by Heady and Dillon (1961) and associates has amply demonstrated that production functions provide highly useful and practical means for quantitatively assessing the expected productivity of land. Cooperative research now underway betwen Iowa State University and the Bureau of Reclamation is aimed at establishing production functions which can be used as a basis for classifying land. Use of such a technique would help considerably by providing a quantitative measure of effects of relevant soil characteristics on crop production."

CHAPTER 8

FINAL SELECTION, CLASSIFICATION, AND GROUPING OF LANDS FOR IRRIGATION DEVELOPMENT

8.1 INTRODUCTION

Irrigable land is defined by the **U.S. Bureau of Reclamation** (USBR 1953) as arable land under a specific plan for which a water supply is or can be made available and which is provided with, or planned to be provided with, irrigation, drainage, flood protection, and other facilities as necessary for sustained irrigation. It is developed within the arable area by consideration of any limitations imposed by the water supply, the costs of facilities and service to specific tracts, and the lands required for additional nonproductive rights-of-way and other purposes.

The area selected is generally limited by the available water supply, the availability of suitable land, or by costs of service. Therefore it is generally necessary to classify an area somewhat larger than the anticipated irrigable acreage so that there will be an opportunity to delete areas of marginal suitability. Although the soil scientist should be aware of the problems of determining irrigability, the major considerations during the irrigation suitability survey should be based on arability rather than irrigability.

8.2 DETERMINATION OF IRRIGABLE LAND

A final determination of the irrigable lands cannot be made until farm unit boundaries have been established and the location of all public roads, laterals, and turnouts has been determined. However, a close approximation of the irrigable area adequate for planning purposes can be made by trial and error ("paper layouts").

8.2.1 Deletions Involved in Determining Irrigable Land

After the irrigation suitability survey is complete, the arable area is reviewed to determine how much of it can be included in the irrigable area. For this the engineers must have topographic maps to make layout studies, from which they can delete from the arable area the rights of way for canals and laterals, the "high" land above the canals, and areas isolated by topography from the water source.

8.2.2 Plan Formulation

In nearly all irrigability studies alternative plans of development are usually formulated by the layout engineer with assistance from other members of the planning team, with the objective of obtaining the maximum amount of benefits at the minimum cost.

Plan formulation is the process of selecting the optimal land areas for development within the arable area. In some instances the lands will all lie below a short canal system and the irrigable area will be the maximum area of arable land that can be serviced. In other instances water supply may be insufficient to service all of the arable lands, or some lands may require such long canal systems, unusually expensive drainage systems, or pumping plants to lift water above the canal elevation that they are not worthwhile increments to leave in the irrigable area. In such situations each separable increment of land will need to be independently evaluated with respect to incremental costs and benefits. This procedure should develop the irrigable area which maximizes net benefits. The policy for determining the feasibility of incremental units may vary between projects and countries. The national or regional goal may be to increase the volume of agricultural production, to provide rural and urban job opportunities, to intensify and expand the economic base, to prevent agricultural decline, or to strengthen the rural level of living. In each case different criteria need to be developed to guide plan formulation.

If the responsibility for land development lies with the land owner, and it is determined that the project responsibility ends with delivery of water to the high point on the farm, it may be necessary for the soil scientist in cooperation with other members of the plan formulation team to assess the irrigability within each farm unit. Criteria similar to that used in determining project irrigability can be used. In this instance, the incremental costs for servicing isolated or high areas on each farm should be added to other land development costs as a means of determining whether such lands are indeed arable when all development costs are considered. Thus a high area on a farm unit may fit into a normal Class 3 category assuming usual costs for water delivery, but could be Class 6 (nonarable) if it requires a long and expensive elevated ditch. This would be due to the combination of field development costs plus on-farm water delivery costs. The assessment of the latter costs is usually not possible until the exact location and elevation of the project water service are known for each farm.

Any annual costs above those normally associated with arable land, such as pumping to a higher elevation, should be estimated when determining the irrigable acreage. The separable high area mentioned in the previous paragraph conceivably could be served by either a long elevated ditch or a pump. Comparison of alternative annual costs should be made and the least costly method accepted in determining the proper land class. Whenever the sum of the incremental costs plus the usual land development costs exceed the permissible costs, or the annual costs are so high that the lands could no longer pay the estimated charges, the lands should be excluded from the irrigable area.

8.3 LIMITING FACTORS AND CONSIDERATIONS FOR GROUPING LANDS

Suitability for irrigation, as measured by land class, should be an important consideration in irrigability studies. Where the water supply is insufficient to irrigate all of the arable lands, it is advantageous to eliminate from the project irrigable area those lands with high percentages of Class 3 rather than those with Classes 1 and 2, and also isolated tracts of arable land.

If widely diverse textural groups occur within a project, such as a small loamy sand area within a large fine textured area, or a small clay area within a generally sandy area, consideration should be given to deletion of the unusual soil from the irrigable area if it can be accomplished in an economic manner. The reason is because of the vastly different water requirements, management practices, and crop adaptability. Small areas of unusual soils will generally not respond as well as large areas because the important crops, marketing, and cultural practices will necessarily be geared to the predominant soil properties.

Where a highly mechanized sprinkler irrigation system would be used for a large area, it may not be practical to avoid irrigating small non-productive areas intermingled with better quality land. In such instances, the land class of the fields involved should be reduced to reflect the influence of inclusions with low production capacity. Thus, an area composed of 85 % Class 1 land with a relative productive capacity of 100 intermingled with 15 % land having a relative productive capacity of only 20 might be best mapped as Class 2 land having an average productivity of 88.

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THE US BUREAU OF RECLAMATION LAND CLASSIFICATION SYSTEM

A.1.1 Principles of the System

The irrigation suitability classification developed by the US Bureau of Reclamation (USBR) is an economic system for selecting and categorizing the quality of lands considered for irrigation development. Within it the lands are delineated into classes which reflect the capacity of the land to support adequately a farm family and pay water charges.

Certain general principles have been developed for selecting lands for irrigation. The Reclamation Manual (USBR 1951), Maletic (1962), and Maletic and Hutchings (1967) have identified them as the principles of prediction, of economic correlation, of arability-irrigability analysis, and of permanent-changeable factors.

Prediction Principle: The principle states that "the classes in the system must express the soil-water-crop interactions expected to prevail under the new moisture regime with irrigation." Such changes as rise of water table, changes in salinity or sodic conditions, modification of the surface by land forming, and changes brought about by soil amendments are examples of the type of possible changes that need to be evaluated in the prognosis.

Principle of Economic Correlation: The principle states that "in a particular project setting the physical factors of soil, topography, and drainage are functionally related to an economic value." This value is defined as payment capacity or the residual available to defray the cost of water after all other costs have been met by the farm operator (USBR 1951). Payment capacity varies considerably according to climate, cropping pattern, marketing opportunities, size of enterprise, and with it the economic value assigned to a specific land class determining parameter, such as the maximum allowable land development cost. Therefore low quality land may be included in a project where economic conditions are very favourable, while better quality land may be excluded in a less favourable area.

Principle of Permanent and Changeable Factors: This principle states that "the changes in land arising from irrigation development impose a need to identify characteristics that will remain without major change and those which will be significantly altered." The usual permanent factors include soil texture, depth of soil to gravel, cobble, or bedrock, depth to lime zone, claypans, hardpans, slopes and general macrorelief. Changeable factors include such items as salinity levels, exchangeable sodium percentage levels, pH, microrelief, fertility, water table levels, flood hazard, brush and tree cover, and stone cover.

The land classification survey is directed toward appraising the need for making physical changes, estimating the costs and appraising the degree of change that is economically justified. Factors normally considered permanent may be changeable under the projected conditions for a project. For example, an infertile sand overlying loam could be buried by finer material, as is sometimes done in Iraq, or mixing the sand with finer material at depth by deep ploughing as is done in some areas of the United States. The maximum cost which sould be expended for such work is a function of the economic conditions associated with the projected development.

Arability-Irrigability Principle: This principle states that "in the irrigation suitability study the first process is to identify land areas of sufficient productivity to warrant consideration and then as a later step identify the lands to be specifically included in the plan of development." The lands delineated as suitable for irrigation are termed the "arable lands." The lands selected for inclusion in the plan development are termed the "irrigable lands." Typical adjustments made in arriving at the irrigable acreage include elimination of such separable increments as lands located above water surface delivery elevations; isolated segments, odd-shaped tracts, and areas that cannot be efficiently fitted into a farm unit.

A.1.2 Terminology used in the USBR System

Precise meaning is attached to the use of the following terms within the USBR System:

Arable land: land which, in adequate sized units and if properly provided with the essential improvements of levelling, drainage, irrigation facilities, and the like, would have a productive capacity, under sustained irrigation, sufficient to: meet all production expenses, including irrigation operation and maintenance costs and provide a reasonable return on the farm investment; to repay a reasonable amount of the cost of project facilities; and to provide a satisfactory level of living for the farm family.

Irrigable land: arable land under a specific plan for which a water supply is or can be made available and which is provided with or planned to be provided with irrigation, drainage, flood protection, and other facilities as necessary for sustained irrigation.

Productive land: the maximum acreage of irrigable land subject to cropping; a measure which provides a basis for the determination of water requirements, canal capacities, and payment capacities. For conditions in Western U.S. the productive acreage is usually from about 3 to 6 % less than the irrigable acreage because of such nonproductive land uses as farm roads, farm laterals and drains, irrigation structures, fences, buildings, and feed lots.

Full irrigation service land: irrigable land which will receive its full water supply from one source.

Supplemental irrigation service land: irrigable land now receiving, or to receive, an additional or reregulated supply of irrigation water through new facilities.

Gross classification area: all lands mapped and classified in a given survey.

Land class is a category of land having either similar or quite contrasting physical characteristics yet has similar economic characteristics which affect the suitability of land for irrigation. It is an expression of a relative level of payment, capacity (or net farm income in several studies undertaken outside the United States).

Land subclass: a category within the land class identifying a deficiency or deficiencies.

Informative appraisal: an evaluation of selected physical factors designed to provide additional information for the planning, development, and operation of irrigation projects. These would include not only present land use, productivity, and land development levels, farm water requirement, and land drainability factors, but specific soil topographic and drainage deficiencies.

A.1.3 Economic Considerations: Use of Farm Budgets

Quantitative economic significance is given to the land classes and subclasses of the USBR System through farm budget studies which are made by agricultural economists. Farm budget studies are made for typical sized farms representative of each of the major land classes and subclasses by establishing appropriate cropping patterns, crop yields, average investment requirements, labour inputs, and projected crop or livestock sales. The farm budget is summarized by subtracting all of the farm expenses from the farm receipts to obtain an estimated net income. In U.S. studies net income is converted to a payment capacity per acre by subtracting a suitable family living allowance from the net income, and dividing the remainder by the number of irrigable acres on the farm.

Based on the farm budget studies and a knowledge of the estimated annual Operation, Maintenance and Replacement (OM&R) charges for water to the farm, an estimate can be made of the maximum amount of money that should be spent in developing land for irrigation. The current interest rate is used in this calculation. An example will illustrate the technique:

> Assume that farm budget studies show a payment capacity of $20 per acre for the best Class 1 land in the project area. Further assume that the annual OM&R charges are estimated to be $7.50 per acre. The latter charge is used as the minimal payment capacity for any land to be included in the irrigation projects. In this example there is a $12.50 difference per acre in payment capacity between the best land and the minimal quality of land which should be included in the project. This annual difference in payment capacity provides the basis for developing land classification specifications. The difference can be equated into either an equivalent investment component or into a reduction of productivity. At 6 % interest the $12.50 difference in payment capacity would be equal to the annual interest on approximately $208. Thus, if the productivity of rough terrain once graded would equal that of the Class 1 land, up to $208 per acre could be expended for land development work before the land would no longer be regarded as economically suited for irrigation development. A class 3t designation would be assigned to such land to reflect the investment requirement. Under these conditions of payment capacity poorer quality soils, if associated with lower land development requirements, could be included in the arable category as long as the resulting payment capacity equalled or exceeded $7.50 per acre.

Since land classes are an expression of payment capacity, their significance in precise monetary terms varies from project to project depending upon the local agricultural economic conditions. The land classes are usually specified in such a way that each arable class has an equal range of payment capacity within a given project area. In the example just cited, the payment capacity of the best land was $20.00 per acre and the poorest land to be included in the project would have a payment capacity of $7.50. Thus, the theoretical payment capacity range for each land class would be:

Class 1: $20.00–$15.84 Class 2: $15.83–$11.67 Class 3: $11.66–$7.50

These values can be used to compute the allowable development costs or range of productivity levels for each land class. Values of productivity levels or development costs associated with each land class are expressed in physical terms, however, in the land classification specifications.

It is more difficult to develop reliable farm budgets in countries where there is little previous experience of irrigation farming and where farm book-keeping is unknown. However, in such areas, an economic farm survey of existing crops, yields and cultural practices, supplemented with data from agricultural experiment stations and demonstration plots and from marketing studies, can usually yield points of reference from which acceptable estimates of economic productivity on land of different classes and subclasses can be made. Tables 23 A and B, derived from a study in the Lower Mekong Basin in Thailand (USBR 1970), illustrate the kind of estimates which can be made. Both tables relate to the production of paddy rice on land rated as Class 2Rs (see section A.1.5). Table A is an estimated projection of present conditions without improvements foreseen in a project; Table B makes allowance for such improvements.

Table 23A

COST AND RETURNS TO PADDY RICE PER HECTARE

Future Without Project Condition

(Class 2Rs land)	
Item	Amount ($)
Receipts (1.875 M tons at $85.00)	159.37
Expenses:	
Annual land clearing and dike repair	2.44
Seed (31.2 kg at $0.047)	1.47
Ploughing, 1st	7.29
Ploughing, 2nd	6.68
Harrowing (2x at $2.13)	4.26
Transplanting:	
Seedling bed preparation ($18.25 + 10 ha)	1.82
Pulling, bundling, and carrying ($19.12 + 10 ha)	1.91
Planting	8.20
Weeding (1x)	1.21
Harvesting:	
Cutting ($3.89/M ton)	7.29
Bundling ($0.29/M ton)	0.54
Carrying and stacking ($0.49/M ton)	0.92
Threshing, winnowing, and storing straw ($2.04/M ton)	3.83
Hauling and handling ($1.21/M ton)	2.27
Miscellaneous expense (labour, tools, etc.)	2.51
Land tax ($1.20/ha)	1.20
Land investment ($186/ha at 0.08)	14.88
Total expenses	68.72
Return to enterprise (receipts minus expenses)	90.65
Adjustment for operator's labour 1/	18.21
Net income	108.86

1/ Computed from Farm Labour Utilization Studies.

Table 23B

COST AND RETURNS TO PADDY RICE PER HECTARE
Future with Irrigation Project Condition

(Class 2Rs land)		
Item	Amount ($)	
	Wet season (2.81 M tons/ha)	Dry season (2.81 M tons/ha)
Receipts (2.81 M tons at $85.00)	238.85	238.85
Expenses:		
Annual field clearing and maintenance of water distribution system (15.56 days at $0.234/2 seasons)	1.82	1.82
Seed (31.2 kg at $0.047)	1.47	1.47
Ploughing, 1st	7.29	7.29
Ploughing, 2nd	6.68	6.68
Harrowing (3x at $2.13)	6.39	6.39
Transplanting:		
Seedling bed preparation ($18.25 + 10 ha)	1.82	1.82
Pulling, bundling, and carrying ($19.12 + ha)	1.91	1.91
Planting	8.19	8.19
Weeding (3x)	3.63	3.63
Fertilizer:		
Materials (16-16-8 ($0.106/kg) 312.50 kg)	33.12	33.12
Application (hand) (2x)	0.61	0.61
Pest control:		
Materials - BHC (25 kg/time at $0.36 kg)	(1x) 9.00	(2x) 18.00
-Sevin 85 (1.5 kg/ha at $3.11)	(3x) 14.00	(4x) 18.66
Application (hand)	0.76	1.52
Irrigation (labour)	(3x) 0.90	(10x) 3.00
Harvesting:		
Cutting ($3.89/M ton)	10.93	10.93
Bundling ($0.29/M ton)	0.81	0.81
Carrying and stacking ($0.49/M ton)	18.85 1.38	18.85 1.38
Treshing and winnowing ($2.04/M ton)	5.73	5.73
Hauling and Handling ($1.21/M ton)	3.40	3.40
Miscellaneous:		
Labour (preparing threshing ground, loading, etc.) (5%)	5.99	6.82
Materials (baskets, small tools, etc.)	0.86	0.86
Interest on credit for operating 1/	1.12	1.40
Land tax ($1.20 ha/2 seasons)	0.60	0.60
Land investment ($186/ha at 0.08/2 seasons)	7.44	7.44
Total expenses	135.85	153.48
Return to enterprise	103.00	85.37
Adjustment for operator's labour 2/	13.25	13.25
Net Income	116.25	98.62

1/ Assumes that the farmer purchases fertilizer and insecticides on credit.
2/ Computed from Farm Labour Utilization Studies.

4 Preparation of Land Classification Specifications

Various examples of land class specifications prepared by the USBR are given in Appendix A.2.

Land class specifications aim to express the anticipated influence of various mappable physical factors on the projected productivity level, cost of production and cost of land development. Parameters established within land classes for the pertinent soil, topographic, or drainage factors should each represent approximately the same range of influence in evaluating irrigation suitability. Thus the range of slope or amount of levelling selected for Class 1 land should represent about the same influence on suitability for irrigation as the range of soil depth or farm drainage requirement permitted in this class.

Correlation of the study area with nearby irrigated farms is usually an excellent means of relating various physical parameters to measure production levels if soil and other environmental conditions are similar. It is also important to compare the general levels of management in the two areas, in particular inputs of water and fertilizers. Inputs and management levels for the economics of the study should reflect average conditions.

If the research necessary to establish precise land classification specifications cannot be completed in the time available for land evaluation it becomes necessary to use considered judgement (it may not, in fact, be possible to prepare a quantitative evaluation). Under such conditions the soil scientist should make a special point of consultation with team members and other agricultural specialists in the project area.

Having once established the relative yield levels, development of specifications can proceed. Farm budgets are used for evaluating the relative impact of each selected parameter on net income and as a basis for calculating the maximum permissible development cost for each of the arable land classes, as described in the previous section.

Farm budgets are usually first developed for the best soil, topographic, and drainage conditions on the proposed project area. The yield level assumed for this condition will be the maximum for the area and will represent the 100 % productivity level. Costs used for land development on the best quality land will include a nominal amount for ditches, diversion structures, farm drains, and smoothing; these costs will be budgeted for all land classes. All other development cost estimates should reflect costs <u>above</u> the amount needed for the best quality land. As discussed in the previous section the lower limit of arability must also be established. This will vary among projects because OM&R charges may vary because of differences in the length of the project distribution and drainage system, lifts required, power rates, total seasonal water demands, and many other reasons.

Lower quality soil and rougher topography can be profitably used in areas having low cost water or where high value crops can be grown. On the other hand if water is expensive and the growing season short, the requirements for soil and topography are more severe. Thus, a preliminary estimate of water costs is essential to establish a lower cut-off point for arability in monetary terms before going on to establish the lowest acceptable productivity level for the least productive soil. The lower limit of arability in one project may be only 50 % of the productivity required in another project due to lower water costs. There should be corresponding differences in the physical specifications of Class 3 lands in the two projects.

Correlation area data often fail to encompass the entire range of existing deficiencies and judgement is then needed in establishing parameters. The lower limit of Class 3 shown in the General Gravity Specifications (Appendix A.2) is based on an average productivity level of about 70 % of that on the best Class 1 land. Lacking more precise information the reader could use the soil parameters in these specifications as a guide.

Topographic specifications, particularly those involving permissible land development costs, can be firmly based on farm budget appraisals. This is because allowable development costs are a direct function of the anticipated income potential. Necessary costs for preparing lands for irrigation have a direct bearing on their suitability for irrigation. Since money spent for land development could have been invested at the prevailing rate of interest, the income which could have been received from such an investment is effectively an annual cost against the land. Thus, if 5 % interest is the prevailing rate, every $100 invested in land development will reduce net income by $5 per year. A maximum permissible development cost can be projected, therefore, after the range of net income between the top of a Class 1 land and the bottom of a Class 3 land is known.

Land development costs are land class determining if they are to be the responsibility of the land owner. This may not be the case. Government, for example, may elect to include land development costs as project costs in which case the land class would be based only on the non-correctable soil, topographic, and drainage deficiencies. However, an estimate of development costs is still needed as a basis for calculation of total project costs. In most instances, an upper limit of land development costs should be established prior to the start of the classification so that lands with unusual high development costs can be segregated as nonarable.

Another manner in which correctable deficiencies can be handled is to reflect development cost in land values. This technique is particularly applicable when the deficiency is reflected in the selling price of the land for agricultural purposes. For example, in the forested areas of northwestern USA timbered areas may sell for less than cleared land. In such instances the difference between the two land values is not a land class determining cost. For example, if a cleared tract sells for $300 per acre and a timbered tract requiring $150 clearing cost sells for $200 per acre, only $50 per acre would be considered as a land class determining development cost associated with clearing timber.

A.1.5 Land Classes and Subclasses of the USBR System

a. Land Classes

In the USBR System land classes are based on the economics of production. Six land classes are normally recognized although the number of classes mapped in a particular investigation depends upon the diversity of the land conditions encountered and other requirements dictated by the objectives of the particular investigation. Four basic classes are used to identify the arable lands according to their suitability for irrigation agriculture, one provisional class, and one class to identify the nonarable lands (USBR 1951). Brief descriptions of the six classes follow:

Class 1 - Arable: Lands that are highly suitable for irrigation farming, being capable of producing sustained and relatively high yield of climatically adapted crops at reasonable cost. These lands potentially have a relatively high payment capacity.

Class 2 - Arable: Lands that have a moderate suitability for irrigation. These are usually either adaptable to a narrower range of crops, more expensive to develop for irrigation, or less productive than Class 1. Potentially these lands have intermediate payment capacity.

Class 3 - Arable: Lands that have a marginal suitability for irrigation. They are less suitable than Class 2 lands and usually have either a serious single deficiency or a combination of several moderate deficiencies in soil, topography, or drainage properties. Although greater risk may be involved in farming these lands than those of Class 1 and 2, under proper management they are expected to have adequate payment capacity.

Class 4 - Limited Arable or Special Use: Lands that are adaptable to only a very limited range of crops. For example, lands suited only to such single crops as rice, pasture, or fruit might respectively be shown as Class 4R, 4P, or 4F. Class 4 lands may have a range in payment capacity greater than that for the associated arable lands.

Class 5 - Non-arable: This land is temporarily considered as nonarable because of some specific deficiency such as excessive salinity, questionable drainage, flooding, or other deficiency which requires further studies to resolve. The deficiency or deficiencies are of such a nature and magnitude that special agronomic, economic, or engineering studies are required to resolve the costs or effect on the land. Class 5 designation is tentative and should be changed to either Class 6 or an arable classification during formulation of the recommended plan of development.

Class 6 - Non-arable: Land that is nonarable under the existing or projected economic conditions associated with the proposed project development. Generally, Class 6 comprises steep, rough, broken, rocky, or badly eroded lands, or lands with inadequate drainage, or other deficiencies. In some instances lands considered to be Class 6 in one area may be arable in another area because of difference in economic conditions.

In the basic system land suited only to crops having very special requirements, such as paddy rice, would usually be placed in Class 4. This is not very satisfactory in South East Asia, so the USBR (1967) has developed a modified system using two basic diversified crop classes and two basic wetland rice classes with one class to identify the nonarable lands, as follows:

Class 1 diversified crops - Arable

Class 2 diversified crops - Arable

Class 1R wetland rice - Arable

Class 2R wetland rice - Arable

Class 6 - Nonarable

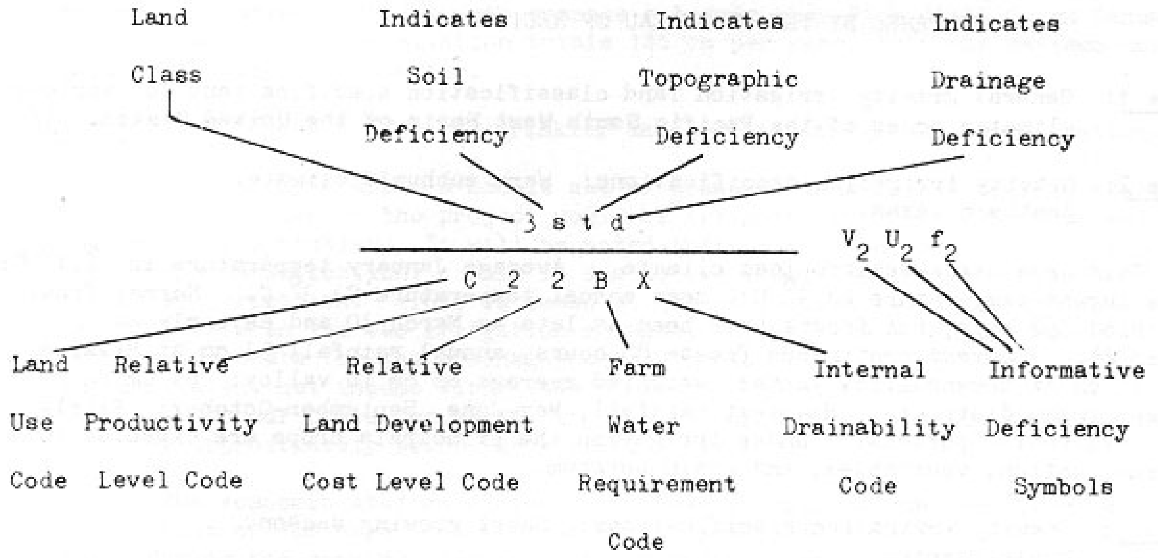
It will be noted that the relative merit of the arable classes in this classification is assessed in terms of net farm income rather than payment capacity.

b. Subclasses

The reasons for placing areas in a class lower than Class 1 are indicated by appending the letters 's', 't', and 'd', singly or in combination, to the class number to show whether the deficiency is in 'soils', 'topography' or 'farm drainage'. Thus, the basic subclasses of the land classes are s, t, d, st, sd, td and std. The interaction or accumulative effects of deficiencies may justify placing the land in a lower class (USBR 1951).

A.1.6 The USBR Mapping Symbol

Typically, the mapping symbol employed by the USBR takes the following form:



Apart from the class and subclass symbols, which form the numerator of the fraction and which have been described in the previous section, the following codes are used to form this symbol:

Land use codes, such as: C – irrigated cultivated, L – unirrigated cultivated, P – irrigated permanent grassland, W – wasteland and so on. Symbols may also be used to identify a specific crop.

Productivity and land development codes: productivity connotes the interaction of the economic factors of productive capacity and costs of production. It is defined as the capacity of land for producing a specified crop or sequence of crops under a given set of management practices. Land development costs are those borne by the farmer in preparation of the land for irrigation and specifically relating to the land which benefits. The two together determine the land class but additional information is provided by including each separately in the symbol. Each is rated 1, 2, 3, 4 or 6 depending on the class level to which it separately corresponds. Thus, in the example given, class 2 productivity and class 2 development cost (symbol 22 in the numerator) results in an overall land class 3.

Farm water requirement code: these appraisals take account of significant soil, topographic and drainage conditions, probable land use, method of irrigation and other factors which affect the type, frequency and depth of irrigation on a specific tract of land. They are rated in relation to average water requirements of the surrounding area: A – low, B – medium, and C – high.

Land drainability code: normally relates to conditions below a depth of 5 ft (150 cm): X – good drainability, Y – restricted drainability, and Z – poor or negligible drainability.

Additional informative symbols: these can be added to the main symbol as shown in the example to provide information on special conditions where the data is required for farm unit planning and land development. They might relate to soils, topography or drainage. They can be further qualified with subscript numerals to indicate a range in character e.g.: k_1, k_2, k_3 might indicate ranges of depth to gravel.

EXAMPLES OF LAND CLASSIFICATION SPECIFICATIONS

PREPARED BY THE US BUREAU OF RECLAMATION

Example 1: General gravity irrigation land classification specifications for various climatic zones of the Pacific South West Basin of the United States. 1/

Example 2: Gravity irrigation specifications: Warm subhumid climate. Southern Texas.

This area has a semitropical climate. Average January temperature is 16.1° C; average August temperature 28.9° C; mean annual temperature 23.3° C. Normal frost free period 362 days, but frosts have been as late as March 30 and as early as November 25. Longest continuous freeze 88 hours, annual rainfall 53 cm at Mission, Texas, 75 cm at Brownsville, Texas; weighted average 66 cm in valley; 61 cm in Mercedes, Texas district. Heaviest rainfall, May-June, September-October; fairly dry in intervening periods. Under irrigation the principals crops are expected to be citrus, cotton, vegetables, and grain sorghum.

Example 3: Gravity irrigation specifications: Short growing season. South Dakota.

This area of USA has a continental climate composed of hot summers, cold winters, and wide temperature fluctuations. Frost-free period in this area of South Dakota is 130 days; annual precipitation is about 48 cm (on Lake Plain), 75% during growing season, but distribution is erratic with dry periods. Peak rains are in June. Principal crops under irrigation are expected to be sugar beet, potato, corn, barley, alfalfa hay, and rotation pasture. About 8% of alfalfa is expected to be grown for seed production.

Example 4: Sprinkler irrigation specifications: Apple producing area. Washington State.

This area of the USA is well suited to the production of high quality apples. Average frost-free period is 200 days. Mean annual temperature is 10° C with extremes of 41° C to -25° C. Cold nights, warm days and ample sunshine produce crisp well coloured apples. Average precipitation 28 cm with only 7 cm during growing season. Apples are principal irrigated crop.

Example 5: Sprinkler irrigation specifications: General farming. Pacific Northwest of USA; Umatilla Basin, Oregon State.

Under irrigation the Umatilla basin is well suited to a wide variety of common crops. Precipitation is largely of cyclonic origin, incident to the eastward movement of low pressure areas over British Columbia. Average annual precipitation at Umatilla, Oregon, is about 19 cm, mostly occurring during the winter period. The average frost-free period is about 197 days. The extreme annual temperatures vary between 31° C and -30° C. Beans, corn, sugar beet, small grains, alfalfa, apples and peaches are the principal crops expected to be grown with irrigation development.

Example 6: Gravity irrigation specifications: Tropical soil area. Lower Mekong Basin, Thailand and Laos.

1/ Each example is illustrated by a Table in the following pages.

This area of Southeast Asia has a tropical climate with no frost. The winters are cool and dry, while the summers are hot and humid. In general there are three major types of weather phenomena which influence the climate; these are the monsoons, the inter-tropical front, and the cyclonic storm. The mean yearly temperature in the project area is 26.3° C and average extremes vary from 21.7° C in January to 29° C in April. Precipitation totals 146 cm per year, with the maximum during the period May through September.

Example 7: General combined sprinkler and gravity irrigation specifications.

This example shows a sample set of economic land classification specifications in which a portion of the project would be irrigated by gravity methods and the remainder by sprinkler. It will be noted that Class 1 has been omitted from the sprinkler classification. This is due to the lower net income anticipated with sprinkler irrigation. This is based on the assumption that although yields would be equal between the two irrigation methods, the additional annual operation and maintenance costs for the sprinkler method would reduce the best sprinkler land to and equivalent net income with Class 2 gravity lands. This analysis has recognized the lower labour costs for sprinkler, but the annual costs still exceeded the gravity lands by approximately $8.00 per acre ($20 per ha).

The economic studies incident to these specifications were based on a frost-free period of 160 days, and with an annual precipitation of about 56 cm, 75% of which falls during the growing season. The principal crops expected with irrigation are corn grain, corn silage, alfalfa hay, grain sorghum, sugar beet, and rotation pasture.

EXAMPLE 1: GENERAL LAND CLASSIFICATION SPECIFICATIONS FOR VARIOUS CLIMATIC SETTINGS

Arable Land Classes 1/

Land Characteristics 2/	Climate Zone A 3/				Climate Zone B			
	Class 1	Class 2	Class 3	Class 4 4/	Class 1	Class 2	Class 3	Class 4 4/
SOILS								
Texture (Surface 30 cm) 5/	LVFS–C	Peat&Muck LCS–C	MS–C	MS–C	LVFS–CL	Peat&Muck LS–C	MS–C	MS–C
Moisture Retention (AWHC–120 cm)	>12.5	11.25–15	6.25–11.25	6.25–11.25	>12.5	11.25–15	7.5–11.25	7.5–11.25
Effective Depth (cm)	> 100	75–100	50–75	25.5–50	> 100	75–100	50–75	25.5–50
Salinity (EC$_e$ x 10^{3}at equilibrium)	< 4	4.8	8–12	12–16	< 4	4–8	8–12	12–16
Surface sodic conditions (Slick spots) Percent of area affected (may be higher with favourable soil minerals)	no slick spots	0–25%	25–40%	40–50%	no slick spots	0–25%	25–40%	40–50%
Sodicity (exch.Na meq/100g soil with irrigation equilibrium)(May be higher with favourable soil minerals) 6/	< 2	2–3	2–3	3–4	< 2	2–3	2–3	3–4
Permeability of least permeable layer in soil(in place measurement)cm/hr	0.5–5	0.157–15.75	0.157–15.75	0.157–15.75	0.5–5	0.157–15.75	0.157–15.75	0.157–15.75
Permissible cobble %	10	10–25	25–50	same as Class 3	10	10–25	25–50	same as Class 3
" gravel %	15	15–50	50–70		15	15–50	50–70	
Rockiness (small outcrops)	none	0–2% of surface	2–10% of surface	10–20% of surface	none	0–2% of surface	2–10% of surface	10–20% of surface
Soil Erosion	For all classes: Severely eroded soils will be reduced one class. Eroded soils may be downgraded one class if circumstances justify, such as in combination with other deficiencies							
TOPOGRAPHY (or land development item)								
Stone for removal (m^3/ha)	< 20 7/	20–190	190–450	450–570	< 20	20–95	95–190	190–230
Slope (percent)	0.2 with g 0.32 0.5 with g 0.32	2–9 with g 0.32 5–15 with g 0.32	9.20 with g 0.32 15–25 with g 0.32	20–30 with g 0.32 25–40with g 0.32	0.2 with g 0.32 0.5 with g 0.32	2–5 with g 0.32 5–9 with g 0.32	5–15 with g 0.32 9–25 with g 0.32	15–20 with g 0.32 25–35 with g 0.32
Surface levelling 6/	Medium	Heavy	Very heavy	Very heavy	Medium	Heavy	Very heavy	Very heavy
Tree removal (amount of cover) 6/	Medium	Heavy	Very heavy	Very heavy	Medium	Heavy	Very heavy	Very heavy
IRRIGATION METHOD 6/	Lands not suited for gravity irrigation because land grading would permanently reduce the soil fertility below arable limits, or the cost would exceed arable limits, or the field pattern is too complex, may be considered for sprinkler irrigation, if they meet all other requirements for arable land.							
DRAINAGE								
Soil Wetness	For all climate areas: Class 1-Ground or perched water table below 125 cm on sandy soils or below 150 cm on loamy or finer soils during the growing season (with or without drainage). For Class 2, ground or perched water table between 75–125 cm on sandy soils or 100–150 cm on loams or finer during the growing season. For class 3, ground or perched water table between 30–75 cm during the growing season.							
Air Drainage 6/	Good air drainage	Good air drainage	Restricted air drainage	Good air drainage	Good air drainage	Good air drainage	Restricted air drainage	Good air drainage
Depth to Drainage Barrier cm 6/	150	120	90	60	200	150	120	90
Surface Drainage 6/	Minor problem	Restricted	Very restricted	Minor problem	Minor problem	Restricted	Very restricted	Minor problem

Arable Land Classes 1/ cont.

	Climate Zone C				Climate Zones D and E			
	Class 1	Class 2	Class 3	Class 4 4/	Class 1	Class 2	Class 3	Class 4 4/
SOILS								
Texture (Surface 30 cm) 5/	LVFS–CL	Peat&Muck LS–C	MS–C	MS–C	FSL–CL	LFS–C	Peat&Muck LS–C	LH–C
Moisture Retention (AWHC–120 cm)	>12.5	11.25–15	7.5–11.25	7.5–11.25	> 12.5	10–12.5	7.5–10	7.5–10
Effective Depth (cm)	>100	75–100	50–75	30–50	>100	75–100	50–75	30–50
Salinity ($EC_e \times 10^3$ at equilibrium)	< 4	4–8	8–12	12–15	< 4	4–8	8–12	12–16
Surface sodic conditions (Slick spots) Percent of area affected (may be higher with favourable soil minerals)	0–10%	10–25%	25–40%	40–50%	0–10%	10–25%	25–40%	40–50%
Sodicity (exch.Na meq/100g soil with irrigation equilibrium)(may be higher with favourable soil minerals) 6/	< 1	1–2	2–3	3–4	< 1	1–2	2–3	3–4
Permeability of least permeable layer in soil(in place measurement)cm/hr	0.5–5	0.157–15.75	0.157–15.75	0.157–15.75	0.5–5	0.157–15.75	0.157–15.75	0.157–15.75
Permissible cobble %	10	10–25	25–50	same as Class 3	10	10–25	25–50	same as Class 3
" gravel %	15	15–50	50–70		15	15–50	50–70	
Rockiness (small outcrops)	None	0–2% of surface	2–10% of surface	10–20% of surface	None	0–2% of surface covered	2–10% of surface	10–20% of surface
Soil Erosion	see previous page							
TOPOGRAPHY (or land development item)								
Stone for removal (m^3/ha)	<20	20–95	95–190	190–230	< 20	20–45	45–95	95–130
Slope (percent)	0–2 with g 7/ 0.32 0–5 with g 0.32	2–5 with g 0.32 5–9 with g 0.32	5–15 with g 0.32 9–25 with g 0.32	15–20 with g 0.32 25–35 with g 0.32	0–2	2–5	5–15	15–20
Surface levelling 6/	Light	Medium	Medium heavy	Medium heavy	Light	Medium	Medium heavy	Medium heavy
Tree removal (amount of cover) 6/	Light	Medium	Medium heavy	Medium heavy	Light	Medium	Medium heavy	Medium heavy
IRRIGATION METHOD 6/	see previous page							
DRAINAGE – Soil Wetness	see previous page							
Air Drainage 6/	Good air drainage	Good air drainage	Restricted air drainage	Restricted air drainage	Not applicable to this climate zone			
Depth to Drainage Barrier cm 6/	250	175	150	120	250	200	175	120
Surface Drainage 6/	No problem	Minor problem	Restricted	Restricted	No problem	Minor problem	Restricted	Restricted

1/ Class 6 lands are all other lands not meeting the criteria for arability in each climatic area.

2/ Each individual characteristic represents a minimum requirement and unless all other factors are near optimum, two or more interacting deficiencies may result in land being placed in a lower class.

3/ Climate Zone A has the longest growing season and most favourable climate for irrigated crop production.

4/ Consider class 4 as a special class, such as for pasture or fruit.

5/ All figures have been changed to metric and rounded.

6/ Added items.

7/ g is the soil erodibility factor.

EXAMPLE 2: BUREAU OF RECLAMATION - WARM SUB-HUMID CLIMATE [1]
Detailed Land Classification Specifications for Gravity Irrigation

Land characteristics	Class 1 - Arable	Class 2 - Arable	Class 3 - Arable
SOILS			
Texture	Sandy loam to friable clay loam	Loamy sand to clay	Loamy sand to clay
Depth to sand, gravel or cobble	90 cm + - good free working soil of fine sandy loam or finer; or 105 cm of sandy loam	60 cm + - fine sandy loam or finer; or 75-90 cm of sandy loam to loamy sand	45 cm + - fine sandy loam or finer; or 60-75 cm of coarser textured soil
Depth to bedrock	240 cm plus or 225 cm with minimum of 15 cm of gravel overlying material or sandy loam throughout	Same as Class 1	Same as Class 1
Alkalinity	Exchangeable sodium not to exceed 10%. May be slightly higher in subsoil under good internal drainage conditions	Exchangeable sodium not to exceed 15% in the surface 30 cm and not to exceed 20% in upper 15 cm	Exchangeable sodium not to exceed 15% in the surface 30 cm and not to exceed 20% in the upper 75 cm
Salinity	Conductivity of the saturation extract not to exceed 4 mmhos/cm at equilibrium conditions with irrigation	Conductivity of saturation extract not to exceed 4 mmhos/cm in surface 30 cm. May exceed 8 mmhos/cm below 75 cm, but no higher than 12 mmhos/cm, all values to be at equilibrium with irrigation	Conductivity of saturation extract not to exceed 4 mmhos/cm in surface 30 cm and not to exceed 12 mmhos/cm in the profile. These values to be at equilibrium with irrigation
TOPOGRAPHY			
Slope	0 - 2%	0 - 2%	0 - 2%
Length of irrigation run	150 m or more	90-150 m	30-90 m
Undulation	Grading not to exceed 1 500 m^3/ha or $ 300 per ha	Grading required between 1 500 and 4 000 m^3/ha or $ 750/ha	Grading required totalling between 4 000 and 7 000 m^3/ha or $ 1 300/ha
DRAINAGE			
Surface	Little or no surface drainage required	Shallow surface drains required not to exceed $ 450/ha. Combined development costs shall not exceed $ 750/ha	Shallow surface drains required, but not to exceed $ 1 000/ha. The combined development costs shall not exceed $ 1 300/ha
	No subsurface drainage required	Subsurface tile drains required, but not to exceed a cost of $ 450/ha or a total development cost of $ 750	Subsurface tile drains required but not to exceed cost of $ 1 000/ha or a total development cost of $ 1 300

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[1] Adapted from South Texas Area, Texas Basins Project.

EXAMPLE 3: BUREAU OF RECLAMATION - CARE UNIT - SOUTH DAKOTA - REGION 6 (Short Growing Season)
Detailed Land Classification Specifications Gravity Irrigation

Land characteristics	Class 1 - Arable	Class 2 - Arable	Class 3 - Arable
SOILS			
Texture (2 micron clay)	Sandy loam, loam, and silt loam	Loamy sand to clay loam, and silty clay loam inclusive. Clay loam and silty clay loam occuring as a single horizon below the surface associated with medium textures in other portions of profile.	Loamy sand to silty clay inclusive
Depth to incoherent sand	90 cm or more of free working soil of fine sandy loam to silt loam, or 105 cm of sandy loam	60 cm or more of free working soil of fine sandy loam through clay loam, or 75 cm of loamy sand	45 cm or more of free working soil of sandy loam through clay loam, or 60 cm of loamy sand
Hydraulic conductivity - **undisturbed**	For all classes. Not less than 0.5 cm/hr in 0-60 cm zone and not less than 0.15 cm/hr in the 60-120 cm zone. In a layered profile having varying rates, the minimum will be controlling. These values will be applied in the field by excluding from the arable area all soils with a solonetz horizon and all soils with "clay pan" in the upper 60 cm of soil which display all or most of the following characteristics: textural class silty clay or silty clay loam; apparent density greater than 1.4 as indicated by sheen appearance of cleavage surface, compaction or porosity; consistence hard when dry and sticky when wet; few or no visible pores. Questionable areas will be related to known soils on which field permeability (Winger tests) have been determined.		
Salinity	Salinity is not considered to be a deficiency in lands having suitable permeability and adequate drainage.		
Alkalinity	For all classes. Exchangeable sodium may not exceed native gypsum in excess of 10%. If less than 10% clay, exchangeable sodium may be in excess of gypsum by 20%. The distinguishing characteristics of this factor in laboratory analyses are: very slow disturbed permeability rate, usually low total salt with wide pH spread. In the field, this condition is recognized in association with the solodized horizon (clay pan) of most nonarable soil types.		
TOPOGRAPHY			
Slope	Less than 2% in general gradient	Less than 5% in general gradient	Less than 8% in general gradient
Irrigation pattern	120 m minimum run, 3 ha minimum size	90 cm minimum run, 2 ha minimum size	45 m minimum run, 1 ha minimum size

Example 3 cont.

Land characteristics	Class 1 - Arable	Class 2 - Arable	Class 3 - Arable
Surface levelling	0-400 m^3 excavation per ha. 0.0-7.2 cm average cut and fill	400-850 m^3 excavation per ha. 7.2-14.4 cm average cut and fill	850-1 400 m^3 excavation per ha. 14.7-25.5 cm average cut and fill
Cover (Tree, 15-40 cm diameter)	0-30 trees per ha	30-75 trees per ha	75-150 trees per ha
DRAINAGE			
Surface (Outlets)	0-400 m^3 excavation per ha	400-850 m^3 excavation per ha	850-1 400 m^3 excavation per ha
Internal	Project drainage is assumed for all arable lands. Presence of water table should be mentioned in profile notes, when encountered.		

Class 6 This includes all lands that do not meet minimum specifications for Class 3.

EXAMPLE 4: LAND CLASS SPECIFICATIONS FOR DETAILED LAND CLASSIFICATION FOR SPRINKLER IRRIGATION
Manson Unit, Chelan Division, Chief Joseph Dam Project, Washington

Land Class Requirements for Fruit (Apple) land

Land Characteristics	Class 1 F - Arable	Class 2F - Arable	Class 3F - Arable 1/	Class 6 - Nonarable 2/
SOIL				
Texture	Medium sandy loam to friable clay loam	Loamy sand to friable clay loam in upper 75 cm	Fine sand to friable clay in upper 75 cm	Sand to slowly permeable clay
Depth To open understrata	90 cm or deeper	60 cm or more of sandy loam or finer material. 75 cm or more of loamy sand	45 cm or more of sandy loam or finer material. 60 cm or more of loamy sand	45 cm of sandy loam or finer or < 60 cm of loamy sand
To tight or compact clayey zones	Below 1.50 m unless evident no internal drainage or aeration problems are present or likely to develop	Below 1 m unless evident no internal drainage or aeration problem are present or likely to develop	Below 45 cm unless no evidence of severe root restriction	Poorer than Class 3
Salinity and Alkalinity	Soil and topographic conditions such that any harmful salts present or removable through normal irrigation	Soil and topographic conditions such that any harmful salts present are removable through normal irrigation	Soil and topographic conditions such that any harmful salts present are removable through normal irrigation	Salinity and alkalinity problems are not correctable by normal irrigation
Arsenic Levels	Arsenic levels in the soil profile less than 50 ppm and no soil removal required	Arsenic in the 0-30 cm depth can be greater than 50 ppm if concentrations are less than 50 ppm below 30 cm depth. Removal and replacement of upper 30 cm of soil contemplated to rehabilitate orchard	Arsenic 50 ppm or more in and below 30 cm depth. Removal and replacement of all contaminated soil contemplated to rehabilitate orchard	Not a factor
TOPOGRAPHY				
Slope	Up to 25% for long slopes on the same plane. Less for complex or short slopes	Up to 30% for long uniform slopes on the same plane. Less for short slopes. Increased costs of cultural practices affected by slope not to exceed those of 1F lands by more than $ 35/ha	Up to 35% for nonuniform irregular slopes.	Slopes may be in excess of 35%

Example 4 cont.

Land Characteristics	Class 1F - Arable	Class 2F - Arable	Class 3F - Arable 1/	Class 6 - Nonarable 2/
Relief	Not a factor with sprinkler method of irrigation	Not a factor with sprinkler method of irrigation	Not a factor	
Size and Shape	60 m minimum width **2 ha minimum size**	30 m minimum width **1 ha minimum size**	Less than 30 m minimum width or less than 0.5 minimum size	
Cover:				
Stone	Up to 40 m^3 requiring removal or where not removed annual operating costs increased not **more than $15/ha**	Up to 95 m^3 requiring removal or where not removed annual operating costs increased not **more than $45/ha**	Up to 150 m^3 requiring removal or where annual operating costs increased not more than $ 75/ha	
Brush	Removal cost insignificant	Removal cost insignificant	Removal cost insignificant	Not a factor
DRAINAGE				
Water	Soil and topographic conditions such that no problem anticipated	Soil and topographic conditions such that good soil aeration can be maintained to at least 120 cm. Farm drainage outlet construction not to exceed 300 m shallow open or tile drains per ha of area served. May include land with a few slightly chlorotic trees in orchard	Soil and topographic conditions are such that good soil aeration can be maintained to at least 90 cm	Good soil aeration cannot be maintained to 90 cm depth
Air	Slope and position of land such that air drainage not impeded	Slope and position of land such that adequate air drainage seems probable	Slope and position such that some restriction of air drainage likely. Heating essential for frost protection and profitable production	Air drainage very poor

1/ Class 4H: Manson Irrigation District lands now in suburban use, which are in small holdings of less than 0.5 ha located within or near town or lake shore of the project.

2/ 6W: Lands presently irrigated with water provided by the Lake Chelan Reclamation District, but which do not meet the minimum specifications for the arable classes above.

6I: Indian allotment lands having a maximum annual water charge of $ 5/ha.

EXAMPLE 5: DETAILED LAND CLASSIFICATION SPECIFICATIONS - SPRINKLER IRRIGATION
Umatilla Basin, Oregon

Land Characteristics	Class 4S(1) Arable	Class 4S(2) Arable	Class 4S(3) Arable
SOIL			
Texture	Fine sandy loam to friable clay loam	LPS, and medium sandy loam to permeable clay loam	Loamy sand to permeable clay
Depth to:			
Gravel, sand and/or cobbles; permeable ash layer; permeable cemented soil hard pan or caliche	90 cm of good free working soil	60 cm of good free working soil, sandy loam or heavier. 90 cm of loamy sand	45 cm of good free working soil, sandy loam or heavier. 60 cm of loamy sand
Semi impervious materials including cemented hardpan, caliche or caliche capping over hardpan or ash layer	150 cm of good free working soil	120 cm of good free working soil	90 cm of good free working soil
Basalt occuring in extensive flat terrain	Greater than 240 cm	Greater than 240 cm	Greater than 240 cm
Alkalinity of soil paste	No evidence of black alkali, pH 8.6 or less. May be slightly higher where soils are calcareous, salts low and drainage conditions are very favourable	pH 9.0 or less, may be moderately higher where soils are calcareous, salts low, and drainage conditions are favourable	pH 9.2 or less, may be higher where soils are calcareous, total salts low and drainage conditions favourable
Salinity	Leaching costs within class 1 development cost limits and equilibrium salinity conditions < 4 millimhos/cm	Leaching costs not more than maximum development costs for class 2 lands and equilibrium salinity conditions 8 millimhos/cm	Leaching costs not more than maximum development costs for class 3 lands and equilibrium salinity conditions 12 millimhos/cm
Available water holding capacity (readily **available**	3.75 cm in upper 30 cm, 15 cm in upper 120 cm	3 cm in upper 30 cm, 11.25 cm in upper 120 cm	2 cm in upper 30 cm, 7.5 cm in upper 120 cm
TOPOGRAPHY			
Slope	Moderate rolling slopes up to 6% in general gradient	Moderately rolling slopes up to 12% in general gradient	Moderately rolling slopes up to 20% in general gradient

Example 5 cont.

Land Characteristics	Class 4S(1) Arable	Class 4S(2) Arable	Class 4S(3) Arable
Surface (Irregularity u, or complexity g)	Not more effective in reducing net farm income than a 6% slope	Not more effective in reducing farm income than a 12% slope	Not more effective in reducing net farm income more than a 20% slope
Size and shape	Not less than 5 ha with shape suitable for economical sprinkler irrigation	Not less than 3 ha with shape suitable for sprinkler irrigation at moderate cost	Not less than 2 ha with shape suitable for sprinkler irrigation at reasonable cost
Cover			
Cobble	Not more than 19 m^3/ha	Not more than 57 m^3/ha	Not more than 95 m^3/ha
DRAINAGE			
Soils and topography	Soil and topographic condition such that no specific farm drainage requirement is anticipated	Soil and topographic condition such that up to 115 m of shallow drains per ha will be required	Soil and topographic conditions such that up to 210 m of shallow drains per ha will be required
Land position	Land use and productivity not modified by seasonal high water table	Seasonal high water table sufficient to reduce productivity or land use in amounts comparable to shallow 4S(2)s lands	Seasonal high water table sufficient to reduce productivity to pasture production and other limited use, but not sufficient to reduce yields below those anticipated for shallow 4S(3)s lands

NONARABLE LAND Lands which do not meet the requirements of higher land classes and small areas of arable land within larger bodies of nonarable land. These are designated as class 6. Also includes rights-or-way and other lands in nonfarming use.

Minimum permissible development costs for levelling, grading, smoothing, leaching, farm drainage, clearing, etc. where no change in class required \$ 35.00, where developed lands will be of class 2 quality or better \$ 105.00, where developed lands will be of class 1 quality \$ 175.00. Symbolization example: $\frac{\mathrm{3st}}{\mathrm{L31cx}}\ \mathrm{g}^{2}$

EXAMPLE 6: USBR LAND CLASSIFICATION SPECIFICATIONS
RECONNAISSANCE GRADE LAND CLASSIFICATION
PHASE II INVESTIGATION PA MONG PROJECT, LAOS AND THAILAND
April 1970

	For diversified crop production		For wetland rice production	
Land characteristics	Class 1 - Arable	Class 2 - Arable	Class 1R Arable	Class 2R Arable
Soils				
Texture				
Surface, 0.30 cm	Fine sandy loam to clay loam	Loamy fine sand to permeable clay	Fine sandy loam to clay	Loamy sand to clay
Subsurface	Sandy loam to permeable clay	Loamy fine sand to permeable clay	Loamy sand to clay	Sand to clay
Depth (after land development)				
To clean sand or gravel	$>$ 90 cm	$>$ 60 cm	$>$ 60 cm	$>$ 30 cm
To pisolites in permeable matrix	$>$ 90 cm	$>$ 60 cm	$>$ 60 cm	$>$ 30 cm
To permeable **armour**	$>$ 150 cm	$>$ 90 cm	$>$ 60 cm	$>$ 45 cm
To relatively impermeable zone (water)	$>$ 210 cm	$>$ 210 cm	$>$ 210 cm	$>$ 210 cm
Available water capacity	15 cm or more in 120 cm depth with 2.5 cm in 0.30 cm	8 cm or more in 120 cm depth with 2.5 cm in 30 cm	not applicable	not applicable
Reaction				
pH in 0.01 M $CaCl_2$	$>5.0<7.7$	$>4.0<8.0$		
pH in H_2O (1:1)	$>5.5<8.2$	$>4.5<8.5$		
pH in (anaerobic)			>5.5	>5.0 may be less provided alumin**ium** active iron are satisfactory
Acidity 1/				
Neutral salt exchange acidity	None	May be moderate		
Buffered salt exchange acidity	May be moderate	May be moderate		
Anion exchange Acidity	May be moderate	May be moderate		
Inorganic (acid sulphate soil)	None	None	None	None

1/ Appraisal is dependent on change characteristics and ion populations as related to cropping pattern.

Example 6 cont.

Land characteristics	Class 1 - Arable	Class 2 - Arable	Class 1R Arable	Class 2R Arable
Sodium (at equilibrium 2/) Exchangeable sodium percentage	< 20	< 20		
Sodium-adsorption-ratio (soil solution)			< 20	< 20
Cation-exchange capacity (at soil pH) of surface soil, 0-30 cm	>10 meq/100 g	>5 meq/100 g	>10 meq/100 g	>3 meq/100 g
Base status				
Calcium		>2.0 meq/100 g		
Magnesium		>1.0 meq/100 g		
Potassium		>0.4 meq/100 g		
Sodium		>0.2 meq/100 g		
Reduction products				
Active iron				
Soil solution (after prolonged flooding)			< 200 ppm	< 500 ppm
Salinity (at equilibrium under irrigation). Electrical conductivity				
Saturation extract	<4.0 mmhos/cm	<10.0 mmhos/cm		
Soil solution			<4.0 mmhos/cm	<8.0 mmhos/cm
Topography				
Slope	< 2% >0.25%	<5% >0.25%	<2%	<5%
Drainage				
Flooding	None	None		
Internal 3/	Good	Good	Very slow	Slow

CLASS 5s - UNRESOLVED POTENTIAL, DIVERSIFIED CROPLAND

Includes lands having unresolved potential for irrigation development involving only diversified cropping. These lands meet all the requirements of arability for diversified cropland Class 2 except for effective soil cation exchange capacity and have soil textures of fine sandy loam or finer.

CLASS 5 - TENTATIVELY NONARABLE

Includes lands which will require additional economic and engineering studies to determine their irrigability. This designation (5) is particularly suited to areas above proposed canal lines pending to determination of feasibility of service. Also applies to suspected high or isolated lands within the known service area and lands subject to seasonal inundations requiring project flood protection works.

CLASS 6 - NONARABLE

Includes lands which do not meet the minimum requirements for the other land classes, and are not suitable for irrigation. They include lands with soils that are very shallow over armour, sandstone, or other formation impervious to root or water; lands with salt affected soils that are reclaimable with difficulty because of texture, position, substratum condition, etc; lands with extremely coarse textured surface soils, soils having low available water capacity rough rocky and severely channel-dissected lands; high areas such as hillocks and river levees; overflow and runoff channels; permanent waste and swamp areas; lands having excessively steep or complex topography; and all other obviously nonarable areas.

2/ Appraisal for diversified crop production is dependent on type of clay and cropping pattern.

3/ In arability studies drain spacing and economic correlation will determine whether the land should be utilized for diversified crop or wetland rice production.

EXAMPLE 7: SAMPLE LAND CLASSIFICATION STANDARDS: GRAVITY AND SPRINKLER IRRIGATION

		Class 1 - Arable		Class 2 - Arable		Class 3 - Arable	
		Gravity	Sprinkler	Gravity	Sprinkler	Gravity	Sprinkler
SOILS	S						
Texture		Sandy loam through clay loam except as noted below		Loamy sand through permeable clay	Loamy sand through clay loam	Loamy sand through permeable clay	Fine sand through permeable clay
Coarse	v	Sand permitted below 90 cm		Loamy coarse sand or sand permitted below 60 cm	Same as gravity	Loamy coarse sand or sand permitted below 32.5 cm	Loamy coarse sand or coarse sand permitted below 30 cm
Fine	h	No clay, silty clay, or sandy clay in upper 30 cm		Permeable clay permitted below 30 cm	Same as gravity	Entire profile may be permeable clay if drainage adequate	Same as gravity
Available water-holding capacity	q	15 cm or more in the upper 120 cm		Greater than 11 cm in the upper 120 cm	Same as gravity	Greater than 7.5 cm in the upper 120 cm	Same as gravity
Depth over incoherent clean gravel sand	k	90 cm of sandy loam or heavier, may be 75 cm if gravel contains some fines, must meet minimum water-holding requirements for class		At least 60 cm of sandy loam or heavier, 75 cm of loamy fine sand, must meet minimum water-holding requirements for class	Same as gravity	A minimum of 45 cm of sandy loam or heavier or 60 cm of loamy sand, must meet minimum water-holding requirements for class	No minimum but must meet minimum water-holding requirements for Class 3
Exchangeable sodium	a	Exchangeable sodium will not be a problem in the presence of adequate drainage. Less than 2 meq/100 g of soil or less than 15 ESP at equilibrium		Permeability may be somewhat impaired but sodium will not be a major problem in the presence of adequate drainage	Same as gravity	Permeability may be impaired by exchangeable sodium but under equilibrium there will not be more than 3 meq/100 g or more than 20 ESP for heavier soils. There must be at least 0.3 cm/hr of permeability in top 60 cm	Same as gravity

Example 7 cont.

		Class 1 - Arable		Class 2 - Arable		Class 3 - Arable	
		Gravity	Sprinkler 1/	Gravity	Sprinkler	Gravity	Sprinkler
Salinity	a	Salt content can be maintained at a level not to exceed 4 mmhos/cm at equilibrium		Salt content can be maintained at a level not to exceed 6 mmhos/cm at equilibrium	Same as gravity	Salt content can be maintained at a level not to exceed 8 mmhos/cm at equilibrium	Same as gravity
TOPOGRAPHY	T						
Gradient	g	0-2% in general gradient		2-3.5% in general gradient	General gradient not to exceed 5% but may include small escarpaments or other topographic features which exceed this slope limitation when land use considerations would dictate their inclusion	3.5-5% in general gradient	Same as Class 2 sprinkler but may include slopes up to 8%
Irrigation pattern	j	Minimum of 5 ha in size and runs of 150 m or or longer		Minimum of 3 ha in size and runs of 120 m or longer	At least 16 ha in rectangular fields 180 m or more in width. Adjacent lands suitable for gravity irrigation may be included in the 16 ha	Minimum of 2 ha in size and run of 90 m or longer	Same as Class 2 sprinkler
Levelling requirement	u	0-755 m^3 of excavation per ha when soil permits		755-1 510 m^3 of excavation allowed there where soil permits	May spend up to $12/ha to make land tillable and suitable for movement of sprinkler system 2/	1 510-2 360 m^3 of excavation allowed where soils permit	May spend up to $40/ha to make land tillable and suitable for movement of sprinkler system 2/

1/ Because of high annual costs there is no sprinkler Class 1.

2/ Cost does not include sprinkler equipment. Cost of sprinkler equipment would vary between $ 30 and $ 60 per ha depending on the system selected.

Example 7 cont.

	Class 1 - Arable		Class 2 - Arable		Class 3 - Arable	
	Gravity	Sprinkler	Gravity	Sprinkler	Gravity	Sprinkler
Cover c Stone and cobble r	Up to $35/ha for clearing, allowing $4 per 60 cm tree and $3/m³ of stone removal		Up to $65/ha for clearing	Maximum of $12/ha	Up to $100/ha for clearing	Maximum of $40/ha
Total permissible development cost	$0-$35/ha which would include cost of grading, farm laterals, drains, structures, clearing, and soil amendments		$35-$65/ha	Up to $12/ha 2/	$65-100/ha	Up to $40/ha 2/
DRAINAGE D						
Surface (on farm) o	Allow $35/ha for surface outlet excavation		Allow up to $65/ha for surface outlet excavation	Allow up to $12/ha for surface outlet excavation	Allow up to $100/ha for surface outlet excavation	Allow up to $40/ha for surface outlet excavation
Subsurface	Surface outlets for each farm and all deep drainage will be provided as a project expense. The final determination of drainability will be made by the Drainage Branch. Lands otherwise arable but considered nondrainable will be designated by a $\frac{00}{Z}$ in front of the regular land classification symbol.					
Class 6 - Nonarable. Lands which do not meet the minimum requirements for arable land.						

2/ See note on previous page.

FIELD TESTS ON SOIL MOISTURE RELATIONSHIPS

IN-PLACE PERMEABILITY TESTS USED FOR SUBSURFACE DRAINAGE INVESTIGATIONS 1/

B.1.1 Auger-hole Tests for Permeability

Introduction

The auger-hole permeability test measures the average horizontal permeability of the soil profile from the static water table to the bottom of the hole when an impermeable layer is at the bottom of the hole, or to a few inches below the bottom of the hole when an impermeable layer is at some distance below the bottom of the hole.

A number of workers have described the auger-hole test: Maasland and Haskew (1957) discussed in great detail the analytical details; Van Bears (1958) and the U.S. Bureau of Reclamation (1976).

Equipment

Equipment requirements are somewhat flexible, but the following items have been used successfully:

4 inch diameter auger with three 5 foot handle extensions
Recorder board, recording tape, and float apparatus
Tripod
Measuring rod or tape
Hole scratcher
Bailer or pump
Stopwatch
Inside calipers
Computation sheets and clip board
Burlap
Perforated casing or wire-wound screen when and as required
Mirror or strong flashlight
Windshield.

A 4 inch diameter auger is preferred. It can be either the Dutch type, Orchard type, or Durango type 2/. The Orchard or Durango type is generally best for use in lighter textured (sandy) materials, and the Dutch type in heavier, stickier soils. Samples from the Durango-type auger are less disturbed than those from the other two types and can be more easily examined for soil structure.

The recorder board, recording tape, and float apparatus are preferred instead of an electric sounder or other measuring equipment. The float and recorder board is preferred because it is inexpensive and easy to construct, is simple to operate, and provides a permanent record. The board commonly used is 2 inches thick by 4 inches wide by 10 inches long. A notch $2\frac{1}{2}$ inches long and wide enough to hold the roller is drilled 1 inch from one end and $\frac{1}{2}$ inch from a side. A nylon roller, taken from a regular chair caster is installed in the notch and fastened in place.

1/ By R.J. Winger, Jr., Division of Drainage and Groundwater Engineering, US Bureau of Reclamation.

2/ See Section 6.4.6 iii.

Note: Measurements given in text are left as in the original, they have not been changed to metric.

A pointer is fastened directly over the roller to act as a reference point during the test. A 2 inch diameter recess is drilled near the roller to hold the stopwatch and is located so that the recorder can see the stopwatch and mark on the recording tape without taking his eyes from the stopwatch. A threaded metal plate is attached to the under side of the board on the opposite end from the roller and stopwatch. The threads should be the same as used on any planetable tripod.

The float should be less than 3 inches in diameter and weighted at the bottom so it will drop fast. It should also be sufficiently buoyant so there will be no lag in the pointer as the water table rises in the hole. The float should have sloping shoulders so it will be less likely to catch on pebbles or roots on the sides of the open hole or on the joints and performations when casing is used. The counterweight used to keep the float string tight should be only slightly lighter than the float. The recorder tapes are 5 foot tracing cloth strips cut 1/4 inch wide. Paper staples are fastened at both ends so the strip can be connected to the float and counterweight.

A rigidly constructed tripod can be used. Planetable tripods furnish a rigid support and a fast method of setting up and levelling the measuring board.

A 15 foot measuring rod graduated in tenths of a foot can be made, or a tape with a weight on the bottom can be used. Or, to minimize equipment, the three 5 foot extensions for the auger can be marked and used as a measuring rod.

A hole scratcher can be made in a number of ways. The easiest method is to use a 3½ inch diameter by 3 inch long wooden cylinder with small nails protruding from 1/8 to 1/4 inch. The heads of the nails after they have been driven into the cylinder are cut off so there will be sharp edges to break up the seal around the periphery of hole caused by the auger. A ½ inch coupling is placed in the center of the cylinder so the scratcher can use the same extension pipe as the auger.

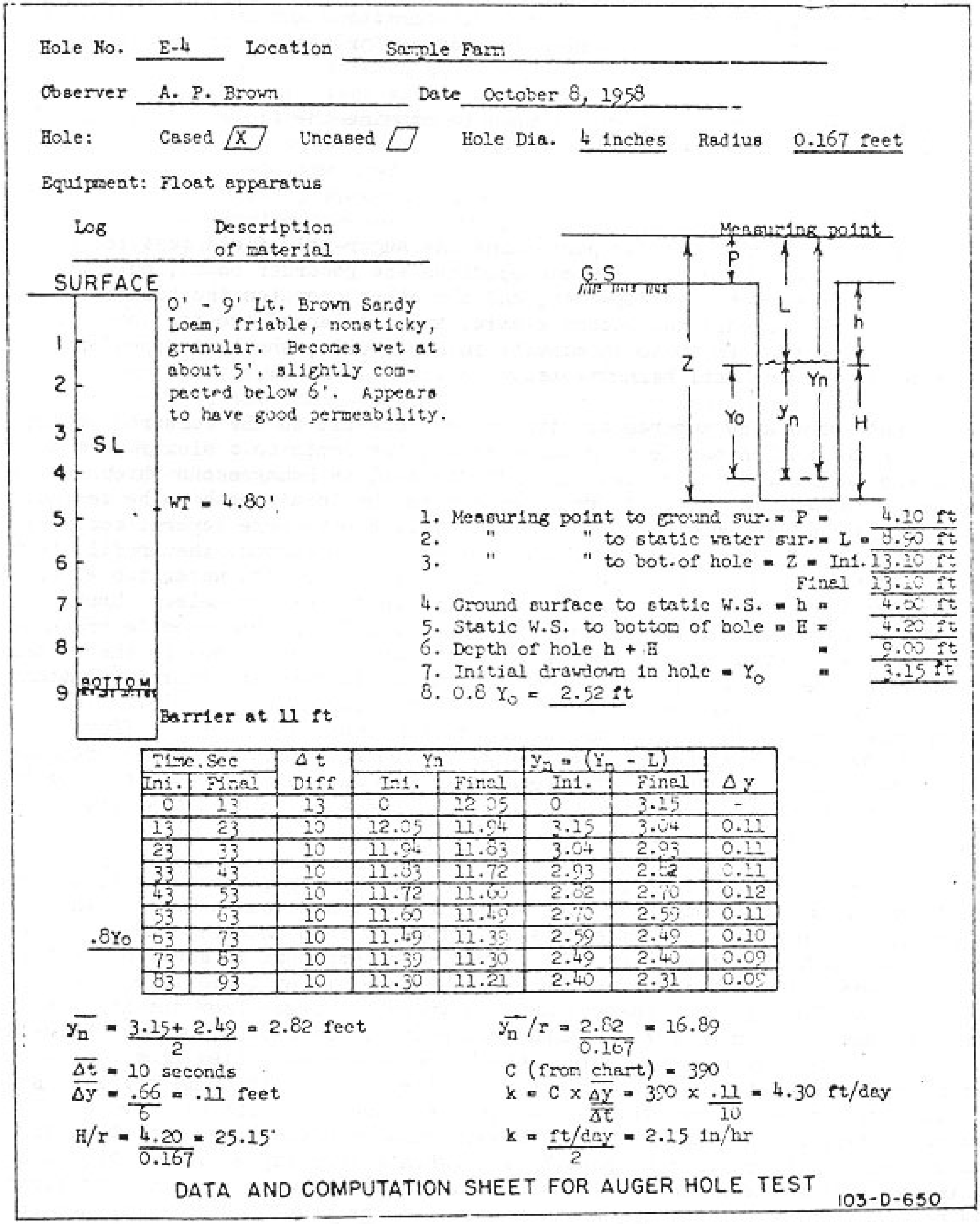
A bailer can be made from a 3 foot length of 3½ inch downspout, with a rubber or metal foot valve at one end and a handle at the other end. Bailers longer than 3 feet will be difficult to get in and out if the hole is not straight. The hole in the foot valve should be large to allow water to enter as rapidly as possible. The bailer should be weighted at the bottom so it will drop fast when more than one bail is required to empty the hole. A light weight pump capable of pumping about 20 gallons per minute can be used in place of the bailer.

Any standard second and minute stopwatch is satisfactory when the float apparatus is used. All readings should be made from a single reference time which is the beginning of bailing, and all time during a test should be accounted for.

An ordinary pair of inside calipers can be used to determine the diameter of the hole. To prevent the points of the legs from gouging the walls of the auger hole, small flat plates are welded to the legs. A rod screwed into the top of the calipers is used to determine the hole diameter at depth. The average hole diameter is used in the calculations. The diameter cannot be checked below the water table with ordinary inside calipers because the water surface reflects the light and prevents a visual determination of the contact of the calipers with the sides of the hole. For this reason, the average hole diameter is determined by the average of measurements made about 1 foot below the ground surface and just above the water table.

Computation sheets should be made up, using the example shown in Figure 4.

The burlap is used to prevent muck from entering at the bottom of the hole. A piece about 2 feet square is required for each hole.



Hole No. E-4 Location Sample Farm

Observer A. P. Brown Date October 8, 1958

Hole: Cased ☒ Uncased ☐ Hole Dia. 4 inches Radius 0.167 feet

Equipment: Float apparatus

Log	Description of material
SL	0' - 9' Lt. Brown Sandy Loam, friable, nonsticky, granular. Becomes wet at about 5'. slightly compacted below 6'. Appears to have good permeability.

WT = 4.80'

Barrier at 11 ft

1. Measuring point to ground sur. = P = 4.10 ft
2. " " to static water sur. = L = 8.90 ft
3. " " to bot. of hole = Z = Ini. 13.10 ft
Final 13.10 ft
4. Ground surface to static W.S. = h = 4.50 ft
5. Static W.S. to bottom of hole = H = 4.20 ft
6. Depth of hole h + H = 9.00 ft
7. Initial drawdown in hole = Y_o = 3.15 ft
8. 0.8 Y_o = 2.52 ft

	Time, Sec		Δ t	Yn		$y_n = (Y_n - L)$		
	Ini.	Final	Diff	Ini.	Final	Ini.	Final	Δ y
	0	13	13	0	12.05	0	3.15	-
	13	23	10	12.05	11.94	3.15	3.04	0.11
	23	33	10	11.94	11.83	3.04	2.93	0.11
	33	43	10	11.83	11.72	2.93	2.82	0.11
	43	53	10	11.72	11.60	2.82	2.70	0.12
	53	63	10	11.60	11.49	2.70	2.59	0.11
.8Yo	63	73	10	11.49	11.39	2.59	2.49	0.10
	73	83	10	11.39	11.30	2.49	2.40	0.09
	83	93	10	11.30	11.21	2.40	2.31	0.09

$\overline{y_n} = \frac{3.15 + 2.49}{2} = 2.82$ feet

$\overline{\Delta t} = 10$ seconds

$\overline{\Delta y} = \frac{.66}{6} = .11$ feet

$H/r = \frac{4.20}{0.167} = 25.15$

$\overline{y_n}/r = \frac{2.82}{0.167} = 16.89$

C (from chart) = 390

$k = C \times \frac{\Delta y}{\Delta t} = 390 \times \frac{.11}{10} = 4.30$ ft/day

$k = \frac{\text{ft/day}}{2} = 2.15$ in/hr

DATA AND COMPUTATION SHEET FOR AUGER HOLE TEST

103-D-650

Figure 4: Data and computation sheet for auger hole test

Perforated casing or wire-wound well screen is necessary in unstable soils. It should have the same or slightly larger outside diameter as the auger hole, so as it is pushed into the ground there is a definite contact between the casing and the periphery of the hole. Commercial well screen with at least 10% perforated area is the most desirable; however, if this is not available, a thin-walled downspout casing with 4-5% performations should be satisfactory. Abouth sixty 1/8- by 1 inch hacksaw perforations per foot will give 4-5% perforations and have negligible effect on limiting the amount of water entering the casing for most agricultural soils tested.

A mirror or strong flashlight is used to examine the sides of the auger hole and facilitate measurements with the calipers.

Procedures

The most efficient team for performing the auger-hole field test for permeability consists of two men. One man operates the recorder board, puts the float in the hole, and operates the stopwatch, and the other operates the bailer. After the water level in the hole has become static, an experienced two-man team can perform the entire test in 10 to 15 minutes in most soils, the time depending upon the permeability of the soil being tested.

The hole should be augered as straight as possible to the required depth, which in turn depends on the depth to water table, the depth to a slowly permeable zone, and the soil strata to be tested. If the soil is homogeneous throughout the profile to be tested, the hole can be excavated to the total depth to be tested. When the soil is heterogeneous, it is usually desirable to make several tests at varying depths. If the material is highly permeable throughout the profile to be tested, it is best to stop the hole about 2 or 3 feet below the water table, so that one bailing will draw the water down to about the bottom of the hole. Upon completion of the augering, the sides of the hole should be scratched to break up any sealing effect caused by the auger. The burlap is then forced to the bottom of the hole and tamped lightly to prevent any materials from entering the bottom. The water table is then allowed to reach its static level in the hole. To eliminate possible sealing caused by the auger and to develop the best flow characteristics, the hole should be pumped or bailed one or two times before starting the test. Careful measurements are made of the depth to the static water table from the ground surface, the total depth of hole, and the distance from the static water table to the bottom of the hole.

To begin the test, the tripod with the recorder board, recording tapes, and float apparatus is placed near the hole so the float can be centered over the hole and moved freely into it. The float is then lowered into the hole and, when it becomes steady at the static water table level, the zero mark is made on the tape and the counterweight positioned so the full change of water table level can be recorded. The float is then removed and the water is bailed from the hole as quickly as possible to minimize the amount of water which returns before the readings are started. For best results most of the water should be bailed from the hole so the test can be completed before the water level rises to half of its original height, or 0.5 H. One or two passes with the bailer are usually sufficient for most agricultural soils. As the last bail is withdrawn from the hole, the float is placed in the hole as quickly as possible. (When a very rapid rise of the water level in the hole is experienced, it is sometimes advantageous to leave the float in the hole and below the bailer during the bailing process. This minimizes the amount of water returning into the hole before the first reading can be made). The stopwatch is started at the moment of withdrawing the first bailer and should be run continuously until the test has been completed.

When using the recorder board and float mechanism, it is most convenient to use equal time intervals, starting from the initial tick mark. As the intervals come up on the stopwatch, the operator marks the tape with a small tick mark opposite the pointer. Measurements are continued until the recovery of water in the hole equals about 0.2 of the depth initially bailed out; or, stated another way, until a reading on the measuring tape of 0.8 Y_o has been reached, Y_o being the distance the water in the hole was lowered by bailing. Upon completion of the test, the final time is recorded at the last tick mark on the recorder tape. Any irregularities in the record can be quickly observed on the recorder tape, and if readings are highly irregular, the test should be rerun after a static water table has been reestablished. Only the period covering the equally spaced tick marks is used in the computations. There will be usually one irregular spacing at the beginning while the float is settling down. As the water rises and the hole fills, the marks will no longer be equally spaced, but will become closer with each reading. The beginning of the shorter spacings usually compares fairly well with the 0.8 to 0.75 Y_o calculation.

Calculations

Upon completion of the auger-hole field test for permeability, the time intervals and the corresponding distances between tick marks on the recorder tape are transferred to the computation sheet. Sample computations are shown in Figure 4. Care should be taken in selecting consistent consecutive time intervals and water table rises to be used in determining $\overline{y_n}$, $\overline{\Delta y}$, and $\overline{\Delta t}$ ($\overline{y_n}$ is the average distance from static water table to the water surface in the hole during the test period; $\overline{\Delta y}$ is the average incremental rise during incremental time intervals; and $\overline{\Delta t}$ is the average incremental time interval between ticks, usually a constant when the float apparatus is used).

The C values 1/ determined from the charts of Figures 5 and 6 are for conditions where the barrier is considered to be at infinity and at zero distance, respectively, below the bottom of the hole. The way Maasland and Haskew (1957) plotted C against the dimensionless parameter $\overline{y_n}/r$ makes the determination of C easy for a wide range of values of H/r and $\overline{y_n}/r$. For the usual case where there is no barrier above the bottom of the hole, Figure 5 should be used. The permeability can be determined by multiplying the C factor by $\overline{\Delta y}/\overline{\Delta t}$. The permeability will be in feet per day, and by dividing by 2 the permeability in inches per hour can be obtained.

Limitations of the Auger-hole Test

While the auger-hole test furnishes reliable permeability data for most conditions, the results are entirely unreliable under artesian conditions; that is, when the hole penetrates a permeable zone under pressure underlying an impermeable zone. Another condition which usually makes the test difficult to perform and gives unreliable data as well, is when there are small sand lenses between less permeable layers. These and sand lenses drain quickly and do not always indicate the permeability of the soil that should be used for drain spacing computations. Another condition where the test cannot be used is when the water table is at or

---

1/ Editorial note:
The C value is a co-efficient used in the calculation of permeability, thus:

$$\text{permeability} = k = C \text{ multiplied by } \overline{\Delta y}/\overline{\Delta t}$$

Figures 5 and 6 show variation in the value of C for different values of H/r and $\overline{y_n}/r$ where 'H' is the depth to the bottom of the hole from the static water surface and 'r' is the radius of the auger hole.

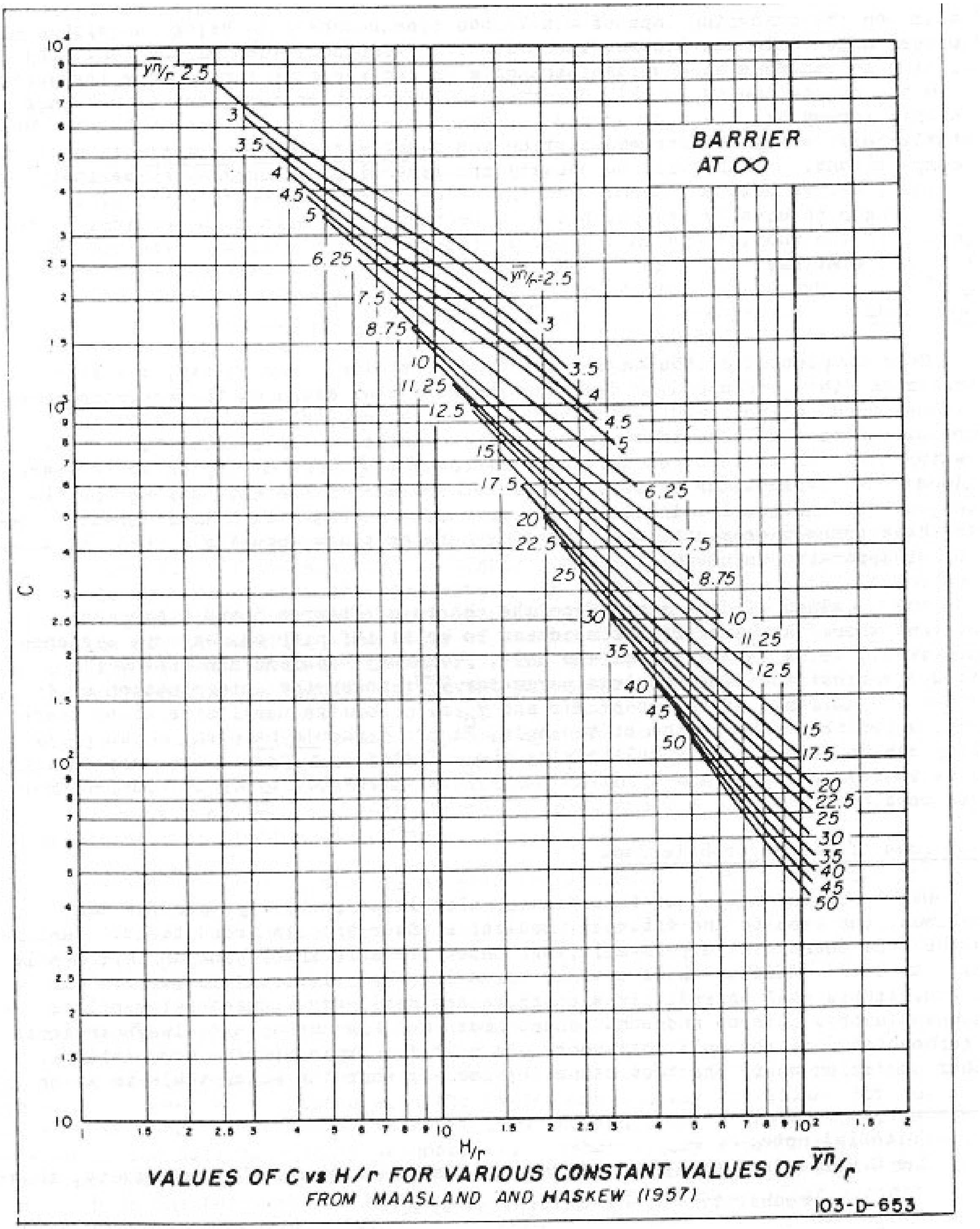
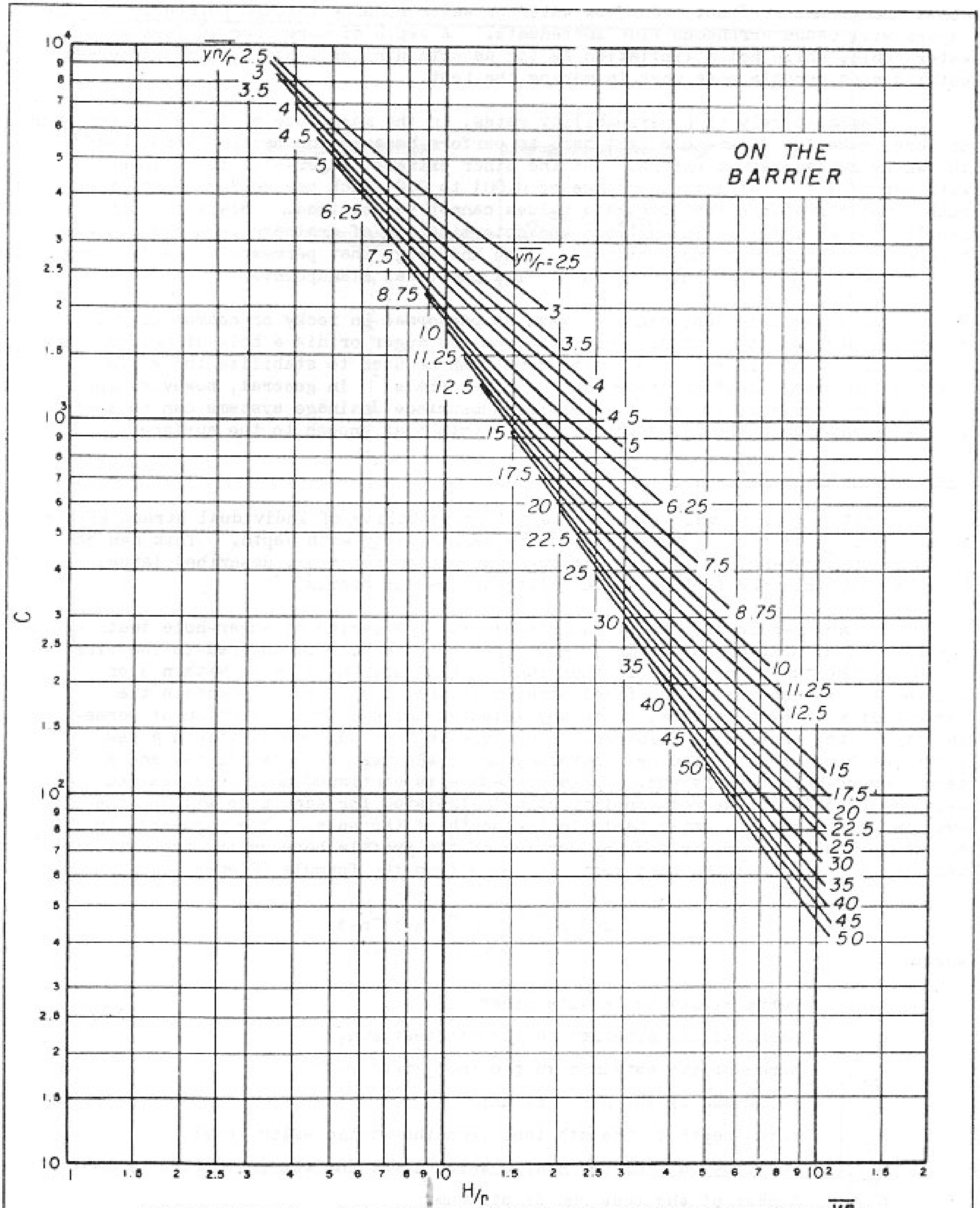


Figure 5: Graph of the coefficient C used in calculating permeability from auger hole tests (with barrier at infinity)



VALUES OF C vs H/r FOR VARIOUS CONSTANT VALUES OF $\overline{yn}/r$

FROM MAASLAND AND HASKEW (1957)

103-D-652

Figure 6: Graph of the co-efficient C used in calculating permeability from auger hole tests (where hole reaches barrier)

above the ground surface. Surface water or water running through permeable surface layers will cause erroneous rise increments. A depth of more than 20 feet to water table, while not a limitation as far as obtaining reliable data is concerned, entails considerable more work in making the test.

Comparatively high permeability rates, in the magnitude of 10 inches per hour or more, make the auger-hole test hard to perform because the bailer cannot remove the water as fast as it enters. At the other extreme, auger-hole tests in soils with permeability rates in the range of 0.001 to 0.01 inch per hour usually give such erratic readings that accurate values cannot be obtained. However, such results can be valuable in analysis and determination of drainage requirements even though exact values are not obtained. The knowledge that permeabilities are very high or very low can be quite useful from a practical standpoint.

The auger-hole test cannot always be performed in rocky or coarse gravel material, because it is usually not practical to auger or dig a hole of uniform size through these materials. Casing can sometimes be used to stabilize the walls of the hole in case a test is needed in these materials. In general, however, most agricultural soils being investigated for subsurface drainage systems can be tested by the auger-hole method if a water table exists near enough to the surface.

Step Tests in Layered Soils

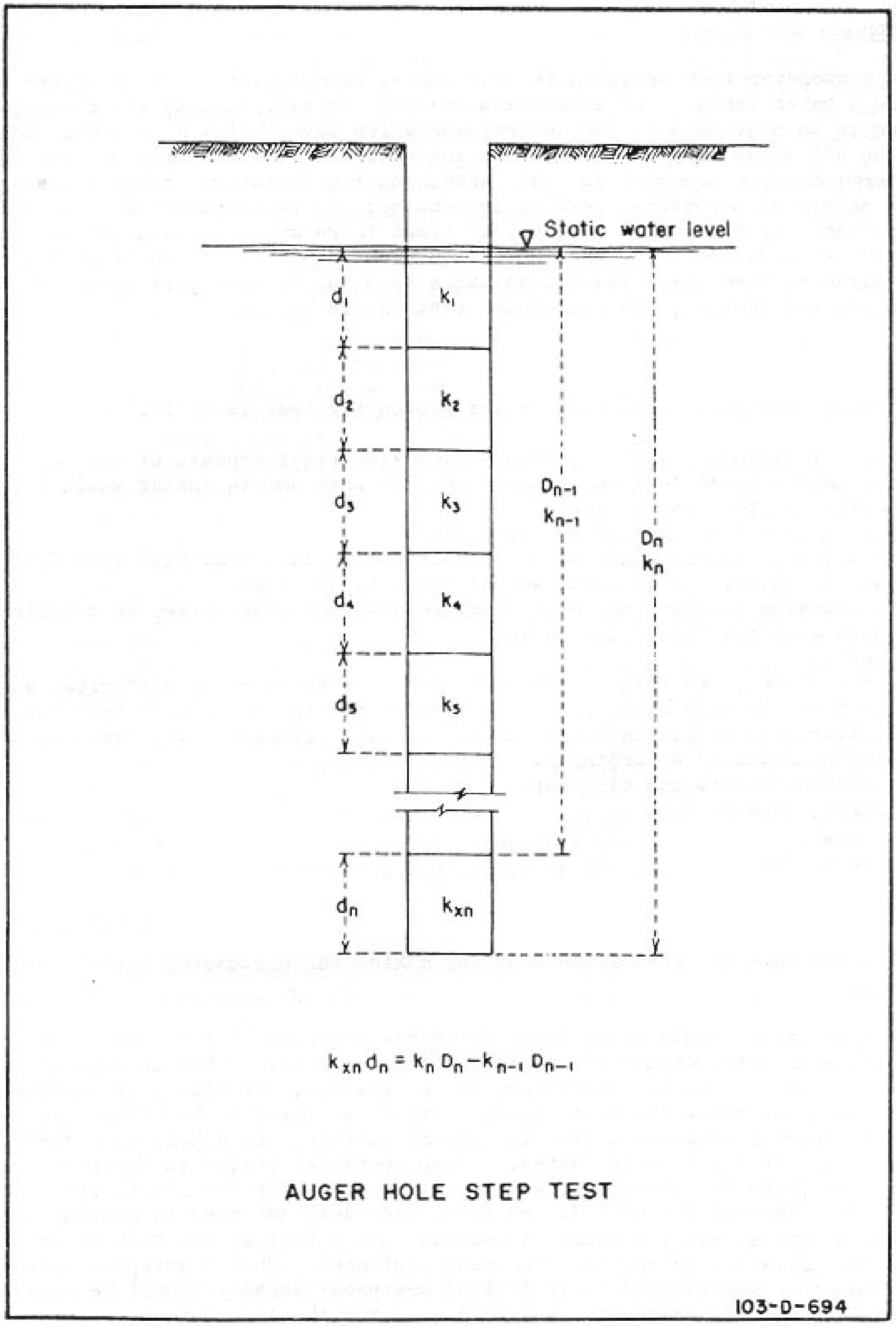
Sometimes it is valuable to know the permeability of individual strata within a soil profile or to know the variation in permeability with depth. This can be found by an auger-hole step test although the piezometer test, described later, may be more adaptable for testing permeability at greater depths.

The auger-hole step test consists simply of a series of auger-hole tests at the same hole location but at different depths. The hole is augered to the first depth and the auger-hole test is then run. This depth will be to within 3 or 4 inches of the bottom of the first stratum if the objective is to obtain the permeability of each stratum, or to any selected depth if the variation of permeability in the profile is required. The hole is then augered to within a few inches of the bottom of the next stratum, or to the next selected depth, and a second auger-hole test is run. This procedure is continued until the desired depth is reached. The permeability value calculated for each step will be the average value from the water table to the depth of the hole. The permeability for the individual stratum, or for the portion of the profile between the depth of one test and the depth of the next test, is found from the formula (Figure 7):

$$k_{xn} \, d_n = k_n \, D_n - k_{n-1} \, D_{n-1}$$

where:

k_{xn} = permeability to be determined,
k_n = permeability obtained in the nth test run,
k_{n-1} = permeability obtained in the (n-1) test run,
d_n = thickness of the nth stratum,
D_n = total depth of the nth test from the static water level,
D_{n-1} = total depth from the static water level for the (n-1) test, and
n = number of the test run or stratum.



$$k_{xn} d_n = k_n D_n - k_{n-1} D_{n-1}$$

Figure 7: Derivation of formula for calculations in auger-hole step test

B.1.2 Piezometer Test for Permeability

Introduction

The piezometer test measures the horizontal permeability of thin layers in soils below a water table. In subsurface drainage investigations, its primary application is to provide data for determining which layer below a proposed drain depth is the effective barrier layer. An indication of the location of this layer can be determined from permeability data obtained from disturbed (remolded) samples taken at a change of structure, texture or density; or from observation of dense shale, sandstone, or bedrock. However, at times there may be some doubt as to which layer should be considered the barrier. When permeability tests on disturbed samples are not available, when they give inconclusive results, or when more reliable determinations are desired, the piezometer test should be used.

Equipment

Suggested equipment required for the piezometer test is as follows:

Casing of minimum 1 inch ID, thin-walled electrical conduit of suitable length for depths to 10 feet and black iron pipe with smooth inside walls for depths greater than 10 feet
Screw auger which fits inside the casing
Pipe-driving hammer, consisting of a piece of 2 inch iron pipe that fits over the casing, with a 10 pound weight fixed to the pipe
Hand-operated pitcher pump with flexible hose and foot valve, or a bailer which will fit inside the casing
Stopwatch
Recorder board, recording tapes, and float apparatus or an electrical sounder. The float is made similar to the one used for the auger hole test but of smaller size to fit into the smaller diameter casing. The counterweight must be adjusted accordingly.
Computation sheets and clipboard
Measuring tape or rod
Windshield
Casing puller

Procedures

A two-man team has been found best for making the piezometer field test for permeability.

The test layer should be at least 12 inches thick so that a 4 inch length of uncased hole, or cavity, can be placed in the middle of it. This is especially important if there is a marked difference in the texture, structure, or density of the layers above and below the test layer. After the layer to be tested has been selected, the topsoil is removed from the ground surface, and a hole is augered to within 2 feet of the layer to be tested. Some operators prefer to auger 6 to 12 inches, then drive the casing, repeating this process for the entire length of the hole. This is a slower method, and experience does not seem to warrent its use. Other operators jet the casing to within 2 to 3 feet of the test layer and then auger and drive the casing the remaining distance. This requires additional equipment, and in a waterlogged field jetting equipment usually cannot be moved in. The augering and driving procedure is always used for the last 2 feet to insure a good seal and also to minimize soil disturbance. The casing is stopped at the depth selected for the top of the 4 inch long cavity, and the cavity is augered below the casing.

The size and shape of the cavity are important in the test, so care should be taken to make it the predetermined length and diameter. If the soil in the test layer is unstable and the cavity will not remain open during the test, screens should be made that can be pushed down inside the casing. For a 1 inch IC casing and a 4 inch cavity, the screen should be 5 inches long and 15 /16 inch OD, with a rigid point welded on the bottom. A pole about 3/4 inch in diameter can be used to push the screen to the bottom of the cavity. If a small bent nail or hook is placed on the opposite end of the pole, the screen can sometimes be reclaimed at the end of the test by hooking the nail into the screen and pulling it up into the casing. The cavity is cleaned by pumping or bailing water and sediment out of the hole until the discharge is clear.

After the static water table has been established, the recorder board and float apparatus are set up, and the float dropped down the casing. When the float comes to rest, the pointer is set at zero on the recorder sheet. The float is then removed from the hole, and the water pumped or bailed out. A small foot valve for attachment to the end of the suction line on the pitcher pump can be made similar to larger commercial types, or a bailer similar to that used in the auger-hole test can be made from small conduit. On stopping pumping or bailing, the float is immediately dropped down the casing, and when it starts to rise, a tick mark is made on the recorder tape and at the same time the stopwatch is started. In using the recorder board and float, it is easier to select a convenient time interval between observations and corresponding tick marks on the recorder sheet. When an electrical sounder is used, it is more convenient to select an increment of equal water level rise which will give a convenient, though variable, time interval. It is not essential to remove all of the water from the piezometer because measurements can be obtained and used anywhere between the static water table level and the initial bailed-out level, but use of three or four readings during the first half of the rise will give more consistent results.

When the piezometer test is used to determine the barrier layer, tests must be made in two or more layers. This can be done by first making the test in the top layer and then augering and driving the same casing progressively to the next layers to be tested. The barrier layer is not necessarily the layer with the lowest permeability, but rather the layer that has a marked decrease in permeability as compared with the weighted permeability of the more permeable layers above it.

Calculations

After completion of the piezometer test, the permeability is calculated from the equation developed by Kirkham (1945), which is as follows:

$$k = \frac{(D/2)^2 \log_e (Y_1/Y_2) \times 3,600}{A\ (t_2 - t_1)}$$

where:

k = permeability (inches per hour),

Y_1 = distance from static water level to level at time t_1 (inches),

Y_2 = distance from static water level to level at time t_2 (inches),

D = diameter of casing (inches),

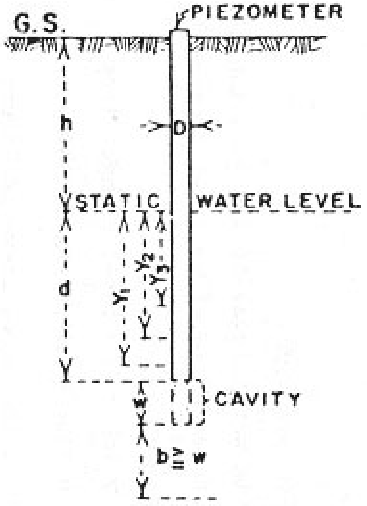
$t_2 - t_1$ = time (seconds) in which water level changes from Y_1 to Y_2, and

A = a constant for a given flow geometry (inches).

The factor A may be taken from the curve shown in Figure 8. The curve is valid when d and s are both large compared to w (d = distance from the static water level to bottom of piezometer; s = distance below bottom of cavity to top of the

Location: Hole C-2--Sample Farm

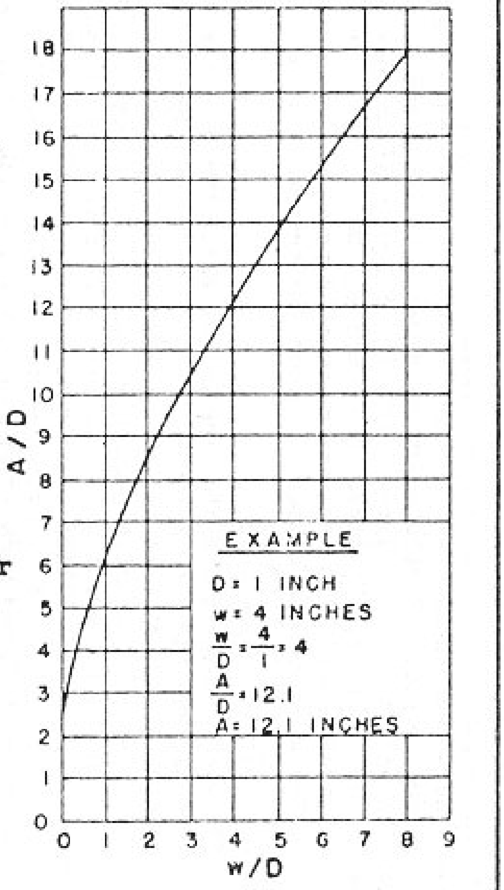
Observer: A. P. Brown **Date:** October 9, 1958



h = 86.40 Ground surface to static water level (inches)
D = 1.0 Inside diameter piezometer and cavity (inches)
d = 93.60 Static water level to bottom of piezometer (inches)
w = 4.0 Length of cavity (inches)
A = 12.1 Constant for a given flow geometry taken from curve (inches)
k = Permeability (inches per hour)
b = Depth to texture change
Y_1, Y_2, Y_3 = Distance from static water level to water level at times t_1, t_2, t_3 (inches)
(t_2-t_1) = Time for water level to change from Y_1 to Y_2 (seconds)

$$k = \frac{3{,}600\,\pi\,(D/2)^2 \log_e (Y_1/Y_2)}{A\,(t_2-t_1)} \text{ in. per hr}$$

Time (sec)		Y (inches)		A	t_2-t_1	Y_1/Y_2	$\log_e$ Y_1/Y_2	3,600 π x $(D/2)^2$	k
Ini	Final	Ini	Final						
0	30	86.00	77.90	12.1	30	1.104	0.099	2827.44	0.77
30	60	77.90	70.25	12.1	30	1.109	0.104	2827.44	0.81
60	90	70.25	63.00	12.1	30	1.115	0.107	2827.44	0.85
90	120	63.00	57.27	12.1	30	1.100	0.095	2827.44	0.74
120	150	57.27	51.64	12.1	30	1.109	0.104	2827.44	0.81
						Average for 5 readings = 0.80			



A as a function of D and w.
REDRAWN FROM LUTHIN & KIRKHAM (1949)

DATA AND COMPUTATION SHEET FOR PIEZOMETER TEST

103-D-600

Figure 8: Data and computation sheet for piezometer test

next zone; and w = length of cavity). According to Luthin and Kirkham (1949), when s = 0 and d is much greater than w, the curve will give an A factor for w = 4 and D = 1 which will be approximately 25% too large.

In addition to the curve, a sample calculation sheet is shown on Figure 8.

Limitations of the Piezometer Test

One of the principal limitations in the use of the piezometer test for permeability is that it cannot be used in gravel or coarse sand material due to installation and sealing difficulties. Even when the hole can be augered in these materials, rocks on the sides of the hole might dent or rip the casing. Also, when the casing bottoms in coarse gravel, it is impossible to obtain a satisfactory seal.

Twenty feet is about the practical limit in depth, both for installation and water removal. Duplicate tests in soils of very low permeability, in the range of 0.001 to 0.01 inch per hour, are always in a low range, but they can vary as much as 100%. This much variation is of little consequence in this range. Test layers less than about 10 to 12 inches thick, between more permeable materials, will not give reliable results, probably because of the influence of the more permeable materials. The size of the casing is a matter of preference, as long as it is 1 inch or more in diameter. Pipe diameters of 4 inches or more are difficult to install at depths over 10 feet.

B.1.3 Shallow Well Pump-in Test for Permeability

Introduction

The shallow well pump-in test for permeability is also called the well permeameter test, and it is used when the water table is below the zone to be tested. Essentially, this test consists of measuring the volume of water flowing laterally from a well in which a constant head of water is maintained. The lateral permeability determined by this test is a composite rate for the full depth of the hole being tested, but reflects, primarily, the permeability of the more permeable layers.

Equipment

Equipment required for the shallow well pump-in test is as follows:

3 and 4 inch soil augers
Side scratcher, consisting of a 3½ inch diameter by 3 inch long cylinder with small nails protruding about 1/8 inch. A ½ inch coupling is placed in the center of the cylinder so the scratcher can use the same pipe as the auger
Casing, perforated
Burlap to be placed in the bottom of the hole to keep the hole clean when perforated casing is used
Water supply tank truck of at least 350 gallon capacity with gasoline-powered water pump
25 feet of 1 inch garden hose for rapid filling of head tank from supply tank
Head tank, 50 gallon minimum, carefully calibrated in cubic feet with zero marking at the top. This tank should have fittings so that two tanks can be connected when required.
Wooden platform to keep head tank off the ground to prevent rusting
A 1 inch diameter pipe 4 feet long, to be driven into the ground to keep tank in position when nearly empty
Large graduate for final filling of tanks
Carburetor which must fit inside the casing
Rod threaded to fit threads on top of the carburetor, used to regulate depth the carburetor is lowered into the hole

Sufficient 3/8 to ½ inch ID flexible rubber tubing or 3/8 inch pipe to connect tank to carburetor
Flexiglass cover, 12 by 12 inches by ¼ inch, with hole in center for carburetor rod and two other holes, one for rubber tubing and one for measuring water level and temperature of water in the hole
Steel fence posts with post driver; four required per site (needed only when site must be fenced)
Wire for fencing site - approximately 85 feet
Thermometer which can be lowered into hole, Centigrade preferred
Watch
10 foot steel tape
Clipboard and computation sheet
16 inch tiling spade

The carburetor used in the shallow well pump-in-test can be constructed out of different material and can be made in different shapes. The only requirements are that it must fit inside a 4 inch hole, have the required capacity, and control the water level within 0.05 foot plus or minus. Minimum material to construct a carburetor that has proven satisfactory consists of the following:

15 inches of 3/4 x 1/8 inch metal strap
One John Deere carburetor float, needle valve, and needle valve seat
Two 3/4 x 1/4 inch bushings
One 3/4 inch coupling

Procedure

A two-man team can efficiently install the equipment and conduct the shallow well pump-in test for permeability. The hole for the test should be hand augered, first with a 3 inch auger and then reamed out with a 4 inch auger. A complete log, including texture, structure, mottling, colour, density, and compaction, should be obtained for use as a guide in interpreting results. Upon completion of the hole to the desired depth, it should be carefully scratched to break up any slight compaction caused by the auger and to remove any loose material that might be on the sides. This scratcher moved up and down in the hole will break any hard seal on the periphery which the brush could not break. In unstable soils, a thin-walled casing should be installed, with perforations extending from the bottom up to the predetermined controlled water level. For a 4 inch casing, 60 uniformly spaced perforations per foot, 1/8 inch wide by 1 inch long, have proved satisfactory. These many perforations will somewhat weaken the thin-walled casing, so a commercial well screen is preferred if available. If the tests are being conducted in silts or fine sands, better permeabilities have been obtained by augering the hole about 1 inch larger than the casing and packing the outside of the casing with coarse washed sand. This apparently keeps the silt in place and from flowing against the casing.

The carburetor float apparatus should be installed and approximately positioned. The carburetor is then connected with tubing and pipe to the calibrated supply tank, which is on an anchored platform beside the hole. The 3/8 or 1/2 inch tubing will allow sufficient water to flow into the carburetor when testing moderately permeable soils. The hole should then be filled with water to approximately the bottom of the carburetor. The valve on the supply tank is opened and the height of the carburetor is carefully adjusted so that the water level will be held at the desired depth. The use of the plexiglass cover to keep material out of the hole and to hold the carburetor float adjusting rod facilitates observation of the carburetor during the test. The time and the reading on the tank gage are recorded when everything is operating satisfactorily. The tank should be checked and refilled when necessary. A record is kept of the time, tank gage readings, and volume of water added, each time the site is visited. Reading times are determined by material being tested and might vary from 15 minutes to 2 or 3 hours. Stevens or similar automatic recorders to keep a complete record of water movement into the hole are desirable, but are not a necessity. When water temperature fluctuations exceed 2°C, viscosity corrections should be applied. Figure 9 shows the equipment for this test.

If the test water contains suspended material, it should be run through a filter tank between the supply tnak and the carburetor. Polyurethane foam appears to work very well as a filter material.

By using the nomograph shown in Figure 10 for estimating the minimum and maximum volume of water to be discharged during a pump-in permeability test, a fairly reliable estimate can be made on how much water should be discharged into the hole before the readings become unreliable. To use the nomograph, the specific yield must be estimated from the texture and structure of the soil. Then knowing h/r and h, the minimum and maximum amounts of water to meet the conditions set up in the mathematical model can be determined. As soon as the minimum amount has been discharged into the soil, the permeability should be computed after each reading. When a relatively constant permeability value, with viscosity corrections, has been reached and the total quantity discharged into the soil is about the same as the computed value, the test can be terminated. If a relatively constant permeability value has not been reached by the time the computed maximum amount has been discharged into the soil, the test should be continued a few hours longer with readings made every hour. All soils do not meet the mathematical assumptions, and it is not always easy to select the correct specific yield from the texture and structure. However, the maximum amount to be discharged into the hole as computed from the nomograph is a good indicator, and when about 1½ times this amount has been used without reaching a relatively constant permeability, any permeability selected can be classed as doubtful.

Computations

A sample computation sheet for the shallow well pump-in test is shown in Figure 11. Figures 12 and 13 show nomographs used in the computations.

Limitations of the Shallow Well Pump-in Test

One of the principal limitations of this test for permeability is that about a day and considerable equipment are required to conduct it. Also, a relatively large amount of water is required, especially if the material has a permeability over 2 to 3 inches per hour. In test zones high in sodium, the water used should contain 1.500 to 2.000 ppm of salts, preferably calcium. Another limitation is that the hole cannot be augered to accurate dimensions in rocky material or coarse gravels. Also, according to comparison of electric analog test results and comparisons with values from the auger-hole test, the h/r ratio must be equal to or greater than 10.

B.1.4 Ring-Permeameter Test

Introduction

In most drainage studies, the lateral permeability of the soil is required for drain spacing determinations. Usually it is assumed that the vertical permeability is sufficient to permit deep percolation from irrigation and rainfall to reach the saturated zone in which it moves horizontally. Sometimes, however, there are slowly permeably layers that interfere with percolation and cause perched water tables. Thus, a means of determining the vertical permeability of such a suspected tight layer is sometimes desirable.

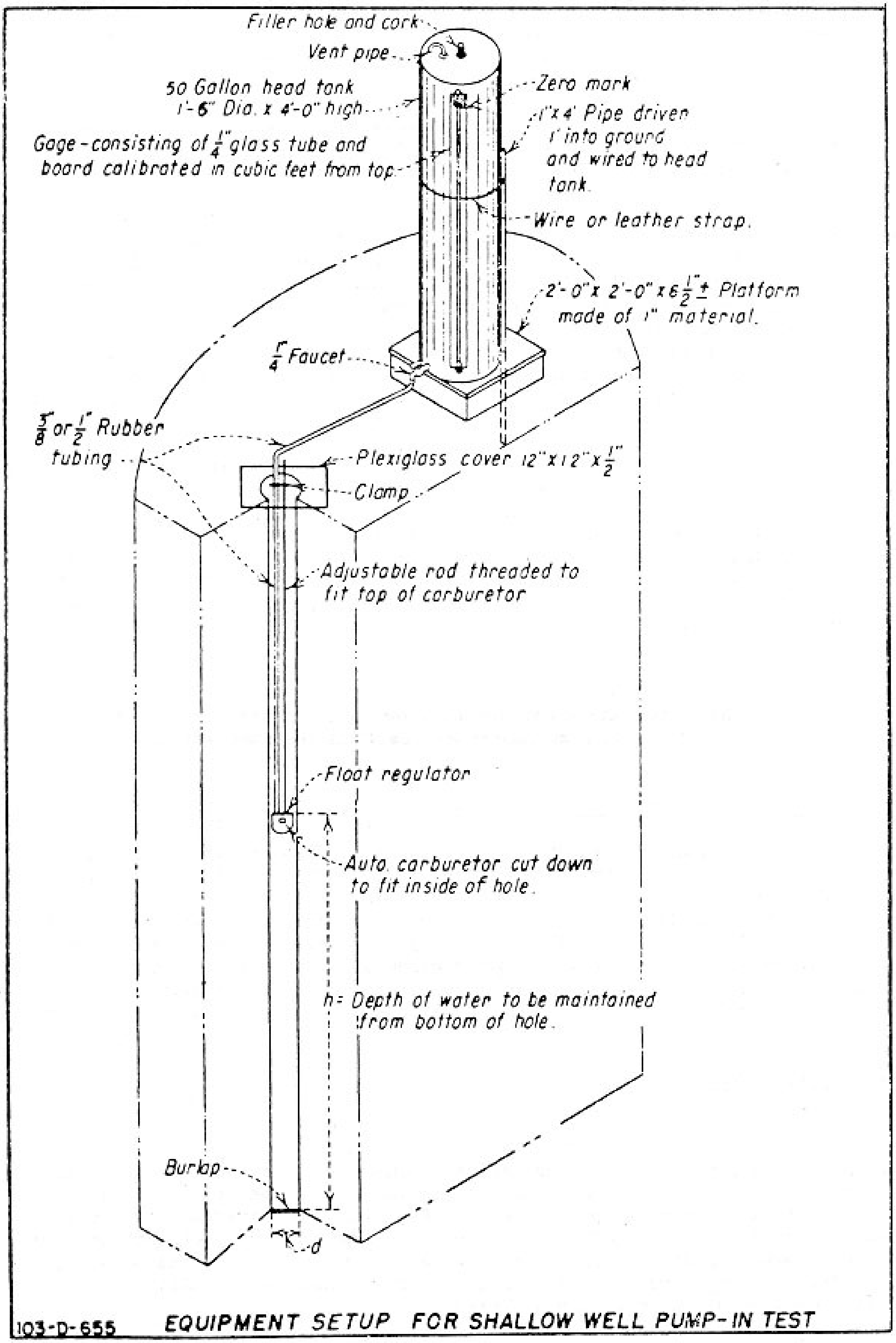
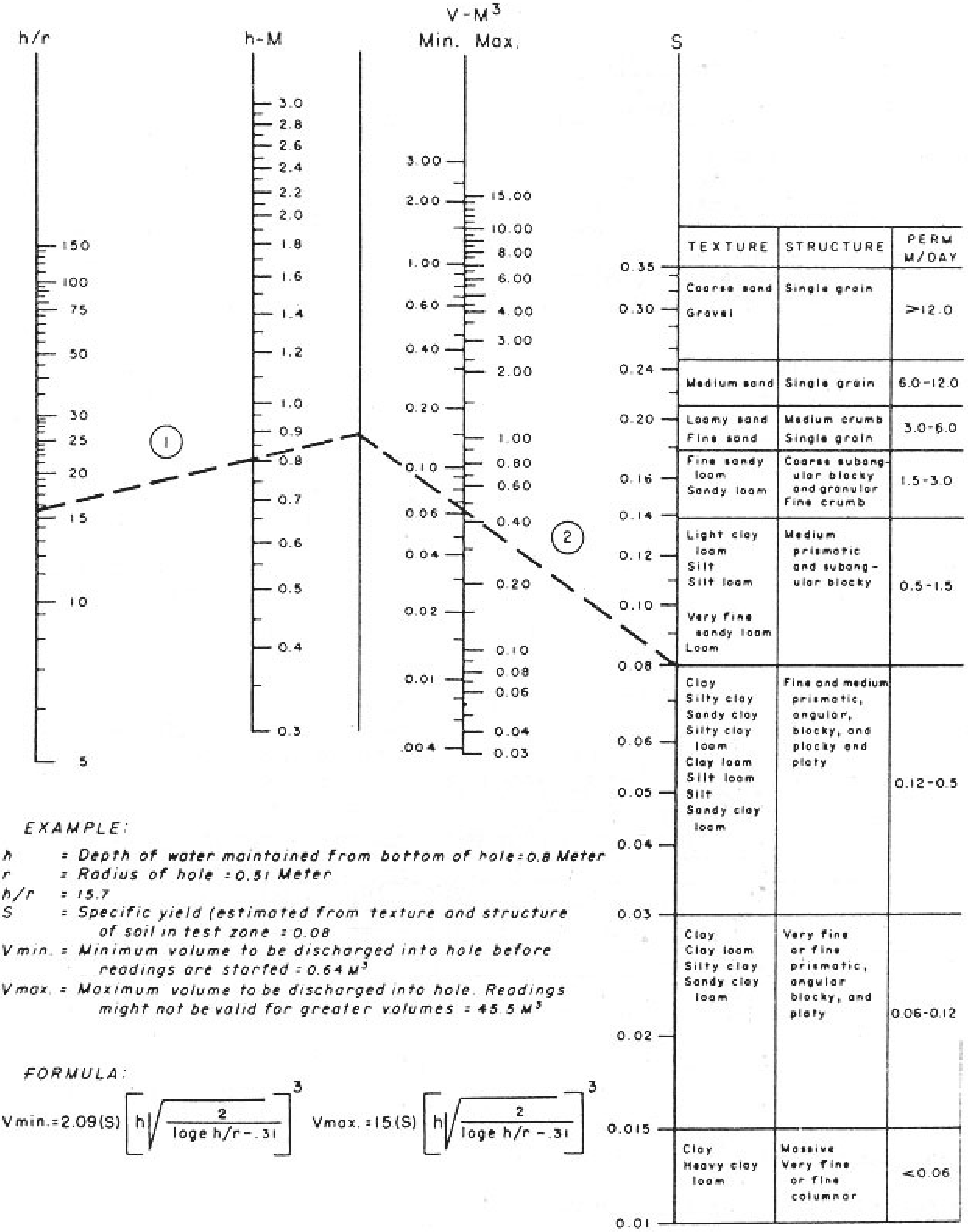


Figure 9: Equipment set-up for shallow well pump-in test



TEXTURE	STRUCTURE	PERM M/DAY
Coarse sand Gravel	Single grain	>12.0
Medium sand	Single grain	6.0-12.0
Loamy sand Fine sand	Medium crumb Single grain	3.0-6.0
Fine sandy loam Sandy loam	Coarse subangular blocky and granular Fine crumb	1.5-3.0
Light clay loam Silt Silt loam Very fine sandy loam Loam	Medium prismatic and subangular blocky	0.5-1.5
Clay Silty clay Sandy clay Silty clay loam Clay loam Silt loam Silt Sandy clay loam	Fine and medium prismatic, angular, blocky, and plocky and platy	0.12-0.5
Clay Clay loam Silty clay Sandy clay loam	Very fine or fine prismatic, angular blocky, and platy	0.06-0.12
Clay Heavy clay loam	Massive Very fine or fine columnar	<0.06

EXAMPLE:

h = Depth of water maintained from bottom of hole = 0.8 Meter
r = Radius of hole = 0.51 Meter
h/r = 15.7
S = Specific yield (estimated from texture and structure of soil in test zone = 0.08
V min. = Minimum volume to be discharged into hole before readings are started = 0.64 M^3
V max. = Maximum volume to be discharged into hole. Readings might not be valid for greater volumes = 45.5 M^3

FORMULA:

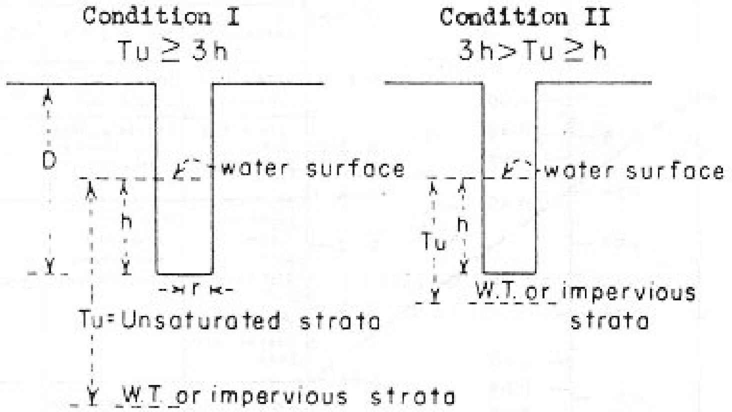
$$V\text{min.} = 2.09(S)\left[h\sqrt{\frac{2}{\log_e h/r - .31}}\right]^3 \qquad V\text{max.} = 15(S)\left[h\sqrt{\frac{2}{\log_e h/r - .31}}\right]^3$$

Figure 10: Nomograph for estimating the minimum and maximum volume of water to be discharged during a pump-in permeability test (for measurements)

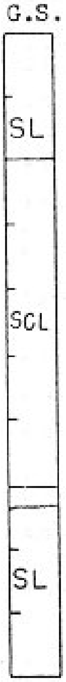
Location: Hole C-3--Sample Farm

Observer: A. P. Brown Date: October 8, 1958

D = 6.0 total depth of hole (feet)
r = 0.167 radius of hole (feet)
W.T. or impervious strata = 7.0 depth below ground surface (feet)
Tu = 4.5 depth of W.T. or impervious strata from surface of water maintained (feet)
h = 3.5 depth of water maintained from bottom of hole (feet)



Log of hole



0' - 2' Lt. Br. Sandy Loam, friable, nonsticky.

2' - 7' Lt. Grayish Brown Sandy Cla Loam, friable, slight stickiness, damp at about 7'. Fair permeability. Slight compaction at 6' to 7'.

W.T. 7.2'
7' - 10' Lt. Brown Sandy Loam, friable, good permeability, nonsticky.

Initial		Final		Time, min	Tank reading, cu ft		Q, cubic ft/min	Temp of water, °C	Viscosity of water, Centipoise	Adj Q,/1 cubic ft/min	Perm, in/hr
Date	Time	Date	Time		Initial	Final					
10- 8-58	0800	10- 8	1100	180	0	6.12	0.034				
10- 8-58	1100	10- 8	1400	180	0	5.97	0.033				
10- 8-58	1400	10- 8	1800	240	0	6.00	0.025	Note: Connected two barrels			
10- 8-58	1800	10- 9	0530	690	0	12.41	0.018		for greater capacity		
10- 9-58	0530	10- 9	1130	360	0	6.82	0.019	16	1.1111	0.019	0.90
10- 9-58	1130	10- 9	1800	390	0	7.65	0.020	19	1.0299	0.019	0.90
10- 9-58	1800	10-10	0530	690	0	12.10	0.018	13	1.2028	0.020	0.95
10-10-58	0530	10-10	1130	360	0	6.63	0.018	15	1.1404	0.019	0.90

Remarks: No trouble with apparatus, assumed test satisfactory and results reliable.

Calculation: $\frac{h}{r} = \frac{3.5}{0.167} = 20.96$ $\frac{h}{Tu} = \frac{3.5}{4.5} = 0.78$
Q (average after stabilization) = 0.019 cubic foot per minute
3h (or 3 x 3.5) > Tu (4.5) > h (3.5), so use Condition II

From Nomograph: k = 0.90 inch per hour

/1 See Figure 15 for adjustment procedure.

DATA AND COMPUTATION SHEET FOR SHALLOW WELL PUMP-IN PERMEABILITY TEST

103-D-647

Figure 11: Data and computation sheet for shallow well pump-in permeability test

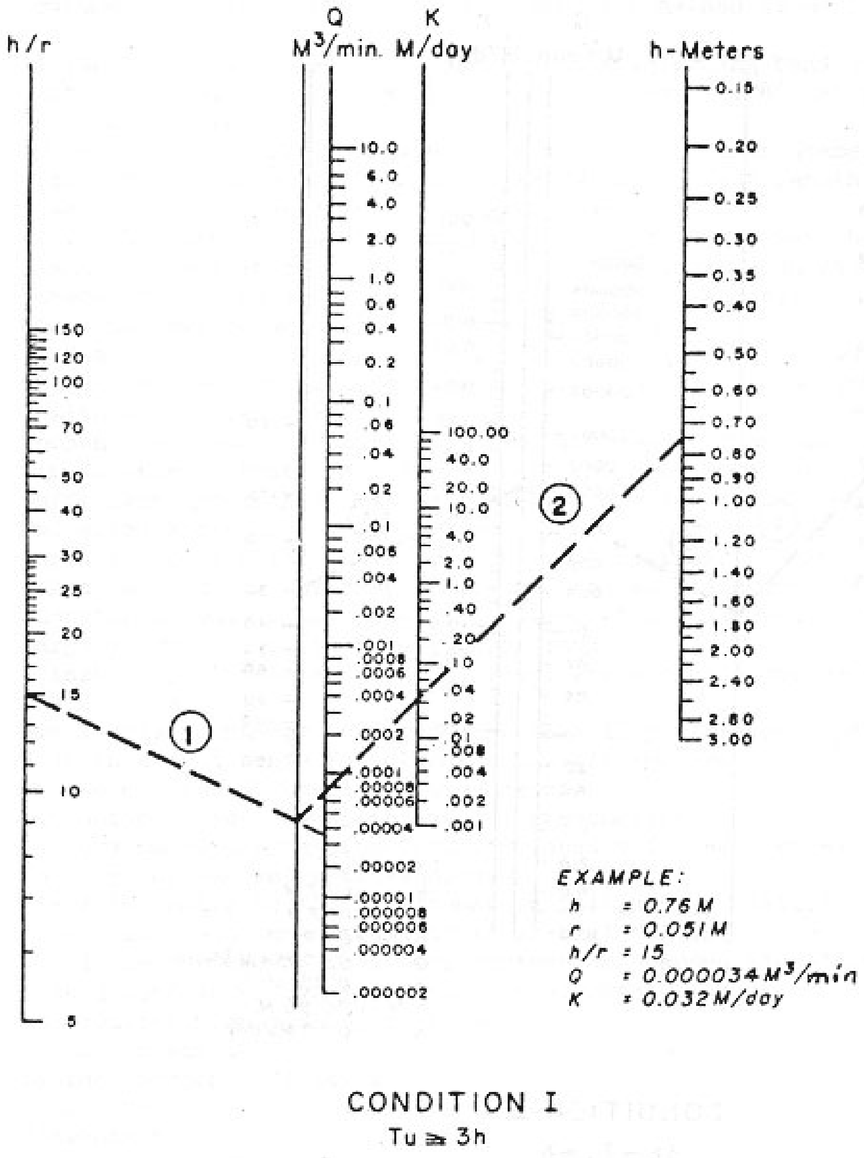
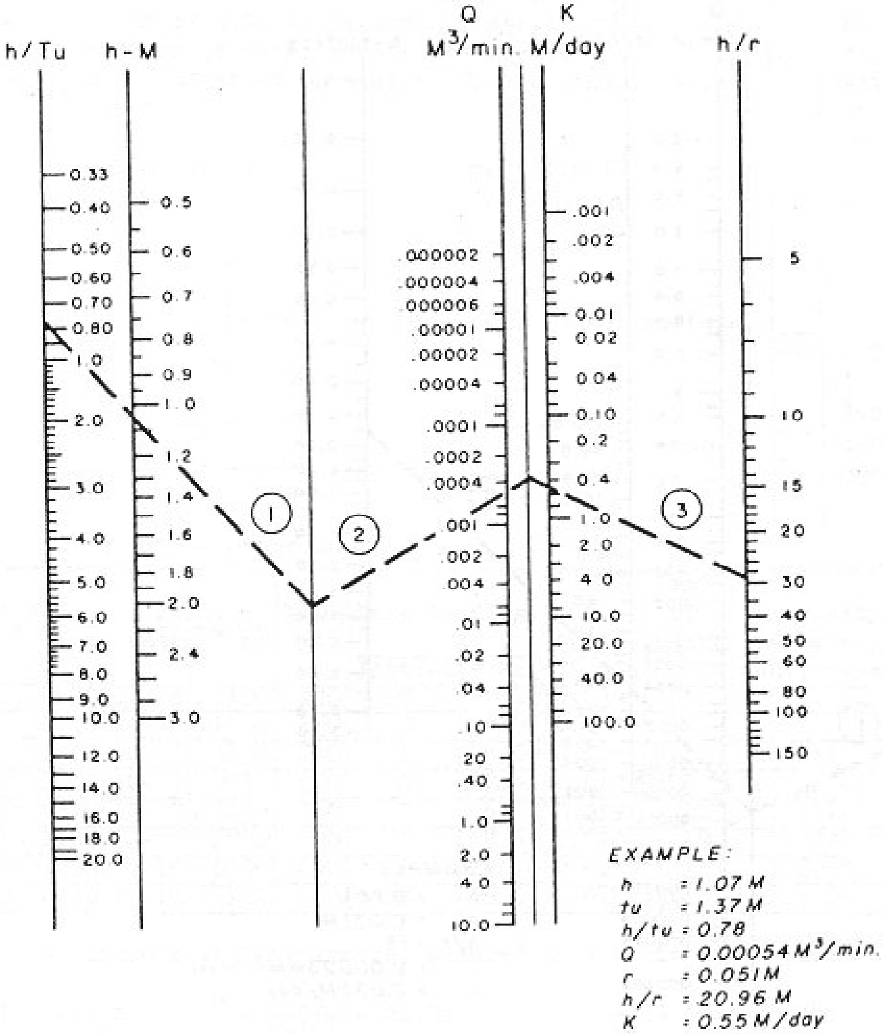


Figure 12: Nomograph for determining permeability from shallow well pump-in data: Condition I, with depth to unsaturated strate (Tu) equal or more than three times the depth of the hole below the water surface (h), i.e. Tu >3h



CONDITION II

$3h \geq Tu \geq h$

Figure 13: Nomograph for determining permeability from shallow well pump-in data: Condition II, with depth to unsaturated strate (Tu) equal or greater than depth of hole below water surface (h), but less than three times this depth, i.e. $3h \geq Tu \geq h$

The ring-permeameter test is a somewhat specialized method of obtaining vertical permeability of a critical zone in place. The test is based, generally, on Darcy's law for movement of liquids through saturated material. The test is slow, but the results are uniformly dependable and can be obtained at reasonable cost. Tensiometers and piezometers are used to confirm attainment of saturated conditions, absence of a perched water table, and fulfillment of the requirements of Darcy's law.

Equipment

Equipment required for the ring-permeameter method is as follows:

14 gage steel welded-seam cylinder with reinforcing band on top and sharpened bottom edge (with seam ground down flush), 18 inches ID by 20 inches high
20 inch diameter field driving disc with 17-3/4 inch diameter center ring to fit inside the 18 inch cylinder, with a 2 foot length of 1 inch pipe welded in the center for a hammer guide
50 to 75 pound driving hammer (heavy steel cylinder with hole in the center and pipe welded to center which fits over the 1 inch pipe on driving disc)
Water-supply tank truck of at least 350 gallon capacity
Gasoline-powered water pump to fill tank truck
25 feet of 3/4 inch garden hose, used to fill tank from water truck
50 gallon head tank with manometer carefully calibrated in cubic inches with zero marking at top
Wooden platform to support head tank to keep it from rusting
1 inch pipe, 4 feet long, driven into the ground to keep the tank upright
Sufficient 3/8 inch ID rubber tubing to connect tank to carburetor
Two carburetors
Threaded bolts which fasten to the steel cylinder and support the adjustable rod which holds the carburetors at the desired elevation
Adjustable rods to hold the carburetors at the desired elevation
Large graduate for final filling of tanks
½ inch ID piezometers 18 inches long, rigid copper tubing (two needed for each site)
Small driving hammer to fit over ½ inch ID piezometer pipe
7/16 inch wood auger for cleaning out piezometers
Fine sand to fill cavity in piezometers
Bentonite to seal tensiometers and piezometers
Mercury manometer tensiometers (two needed for each site)
Mercury for manometer tensiometers
Distilled water to fill tensiometers initially; distilled water is desirable but unnecessary after initial filling
Small ear syringe to fill tensiometers and remove air after they are filled
1 inch wood auger for installing tensiometers
Thermometer, centigrade preferred
10 foot steel tape
24 inch carpenter's level
White chalk
Clawhammer
Wire-cutting pliers
Clipboard and reference sheets
16 inch tilling spade
Short-handled, square-tipped shovel to clean out hole
Bucket with rope for removing soil from hole
10 foot ladder
Washed sand of uniform size, passing No. 14 sieve and retained on No. 28 sieve

Cover for the 18 inch cylinder to reduce evaporation and keep out debris
Steel fence posts with post driver; four required per site (needed only when site must be fenced)
Wire for fencing site, approximately 85 feet

Procedure

A two-man team can efficiently install equipment and conduct the ring-permeameter test. One labourer to help dig the hole will speed up the installation. After the site has been selected and the zone of critical permeability determined, a 4 x 4 foot hole is excavated to within 3 inches of the zone to be tested. The last 3 inches are excavated when the equipment is ready to be installed, taking care not to walk in the 18 inch area to be tested. This area, which will be inside the 18 inch cylinder, is checked with a carpenter's level to assure that it is level before the cylinder is placed on it. The cylinder is marked with chalk 6 inches from the bottom edge and driven into the soil with the field driving disc and hammer until the chalk mark is at the soil surface. The cylinder should be kept level during driving and the blows should be as powerful and steady as practicable. After the cylinder has been driven to the desired depth, the soil immediately against its inside wall is tamped lightly to prevent channeling along the sides. About 1 inch of clean, uniform, permeable sand is spread over the area inside the cylinder to minimize puddling of the soil surface during the test. The outside periphery of the cylinder is also tamped to keep water from channelling down along the sides and causing erroneous readings in the tensiometers.

Next, the two 18 inch piezometers are marked 9 inches from the sharpened bottom and installed on opposite sides of the cylinder about 3 to 4 inches from it. They are installed by driving 2 or 3 inches with a driver and then augering out the core, continuing this process until the 9 inch mark is at ground level. Care should be taken that the piezometers do not turn or come up with the auger during installation. A 4 inch cavity is then augered below the piezometer and filled with clean, fine sand. As an additional means of preventing channelling along the sides, a 1 : 1 bentonite-soil mixture is tamped around the piezometer. The piezometer is then filled with water and checked to see that it is functioning properly. If the water falls in the piezometer, the installation is satisfactory, and a small can is placed over the piezometer to keep out dirt and water during the rest of the installation. If the water does not fall, the piezometer should be flushed with a pitcher or stirrup pump and reaugered if flushing does not clear it. The two calibrated and tested tensiometers are then installed on opposite sides of the cylinder and 3 to 4 inches from it on a line at right angles to that of the piezometers. The calibration and testing for these should be done in the laboratory, so that the tensiometers are ready to install when taken to the field. Instructions for calibrating and testing them can be obtained from the manufacturer of the tensiometers. During the testing, 100 on the scale is set at zero tension, so that pressures caused by rising water table can be observed. The holes for the tensiometers are excavated with a 1 inch soil auger to a depth of 9 inches. A small amount of dry soil is then dropped into the hole, followed by a small amount of water. The tensiometer is then placed in the hole, with the glass tubes facing away from the sun, and worked up and down in the mud to obtain a good contact between the porous cup, the mud, and the undisturbed soil. The annular space around the tensiometer is filled and tamped with dry soil to within about 1 inch of the soil surface. A 1 : 1 soil bentonite mixture is then added to prevent channelling. Extreme caution should always be exercised when using bentonite to assure that none of it drops into the piezometers or into the testing ring. Mercury is then placed in the tensiometer cup and the tubes filled with water. A small ear syringe is used to remove air from the tensiometer tube.

The carburetor float apparatus should be installed and adjusted to hold a constant 6 inch head in the cylinder. The carburetor is connected to the head tank with the rubber tubing. The tank should always be anchored and the gage should face away from the sun. The cylinder is then filled with water to the 6 inch mark, and the valve of the carburetor opened. The hole outside the cylinder should also be filled to a depth of 6 inches. When all adjustments have been made and the tensiometers are full, the time and water content of the tank are recorded. The hole outside the cylinder should be kept approximately full to the 6 inch depth during the entire test period. It is desirable, but not essential, to use an extra tank and carburetor for this purpose, but if this is not available the hole outside of the cylinder can be filled to a 6 inch depth each time the site is visited. Figure 14 shows the equipment for this test.

The head tank should be checked two or three times a day, depending upon the percolation and permeability rates, and filled as necessary. Each time the site is visited, a record should be made of the time, the volume of water in the tank, the gage readings of the tensiometers and piezometers, and the temperature and the permeability computed. When the tensiometer gages read approximately 100 (zero tension), no water shows in the piezometer, and water is moving through the 6 inch test layer at a constant rate, it can be assumed that the requirements of Darcy's law have been met. Tensiometers vary in different soils and it is not always possible to get the 100 reading. If they stabilize at readings between 100 and 105, they are probably indicating saturated conditions for that particular soil. Also, it is not necessary for both tensiometers to have the same reading as long as they both read in this range.

If the saturated front should reach a zone less permeable than the layer being tested before the requirements of Darcy's law are met, a mound of water will build up into the test zone. When this happens, the hydraulic gradient will be less than unity, and the base of the soil column being tested will be at greater than atmospheric pressure. This condition will be shown by both piezometers and tensiometers. At the time the piezometers show that a mound has reached the bottom of the cylinder, the test will no longer give a true permeability value. When this happens, the tests will either have to be stopped or the mound lowered below the bottom of the cylinder. When the material between the bottom of the cylinder and the less permeable zone has a fair rate of permeability, it is sometimes possible to lower the water table mound by augering a number of holes around the outside periphery of the cylinder approximately 10 inches from the sides. These holes, when filled with sand, will act as inverted drainage wells, and under most conditions will lower the mound. If the holes do not provide the necessary drainage, the testing equipment must be moved down to the less permeable zone and the test rerun.

At the close of the test, the soil is excavated from around the outside of the cylinder and cut for a short distance under the cylinder. A chain placed around the cylinder and pulled by a truck will usually break the soil across the bottom so it can be examined for root holes, cracks, and possible channelling.

Computations

Permeability computations for the ring-permeameter test are very simple. The formula used is a form of the Darcy flow equation:

$$k = \frac{VL}{tAH}$$

where:

k = permeability in inches per hour,

V = volume of water passed through the soil in cubic inches,

A = cross-sectional area of the test cylinder in square inches,

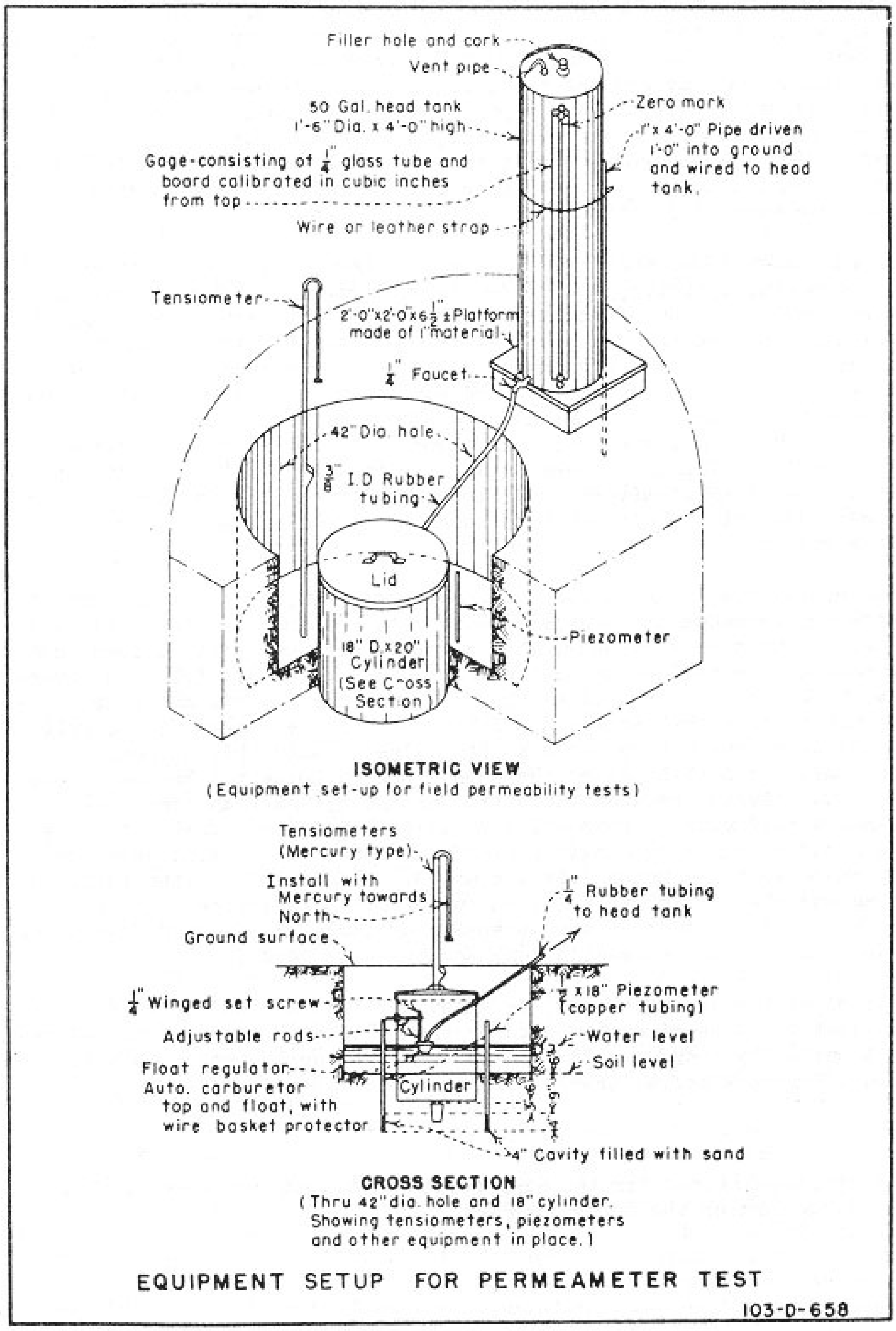


Figure 14: Equipment for ring-permeameter test

t = time in hours,

L = length of the soil column in inches, and

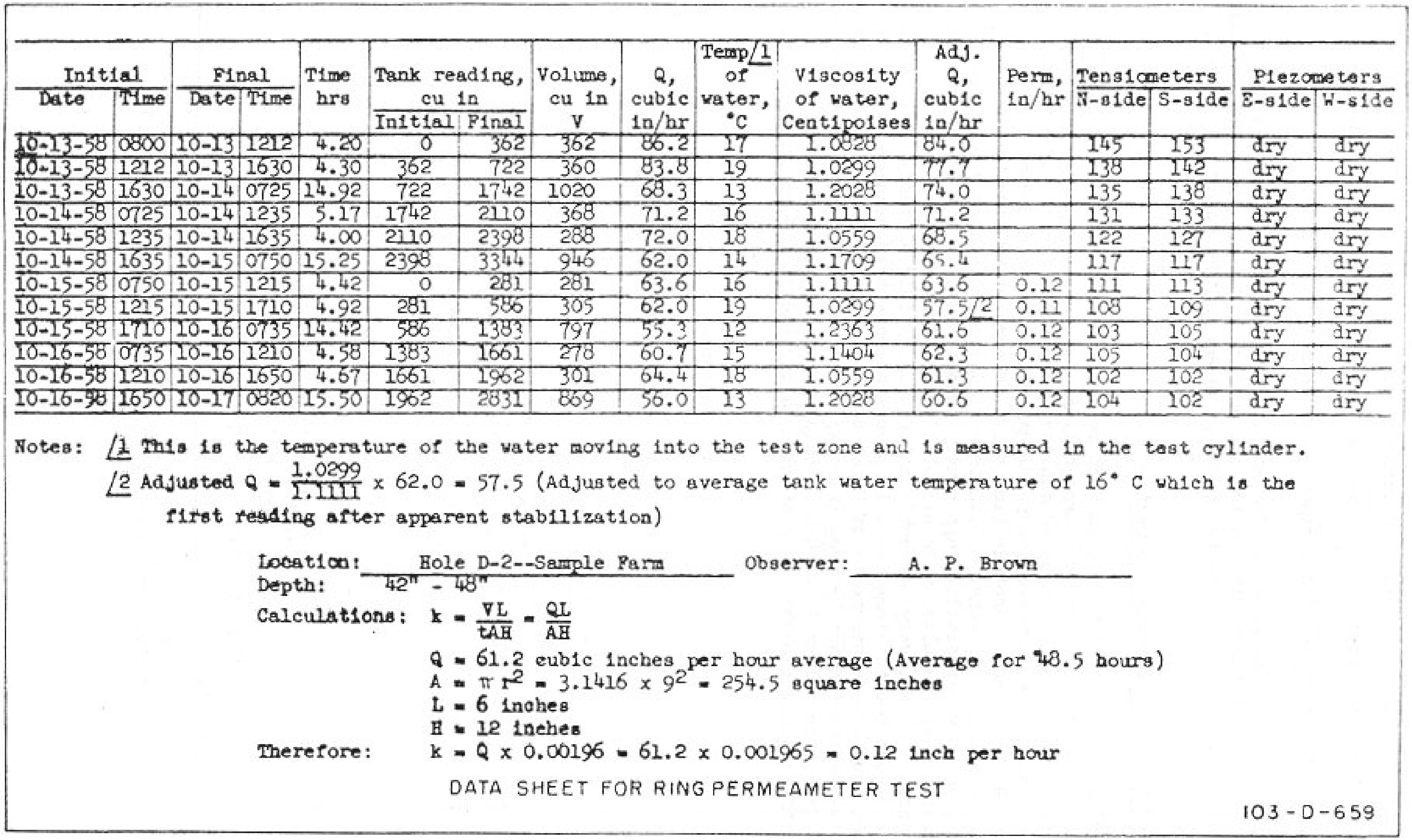
H = height of the water level above the base of the ring, in inches.

A sample data sheet and computations are shown in Figure 15.

When fluctuations in the water temperature exceed 2°C, viscosity corrections should be made. This usually results in more uniform permeability values, as can be illustrated by using the temperature readings shown in the sample data sheet, Figure 15.

Limitations of the Ring Permeameter Test

The principal limitation in this test is that the material directly below the test zone must have equal or greater permeability than the test zone. Also, it must extend to a sufficient depth below the test zone that a steady state flow is reached for at least three consecutive readings before any water mound builds up to the bottom of the cylinder. Another limitation is where there are progressively tighter soils below the test zone. With this condition, a steady state flow is never reached, and the permeability apparently becomes less as the test proceeds. Another condition which results in unreliable data is when the test zone is immediately above a thick, very permeable material. A fairly steady state flow can be obtained, but the tensiometers will never indicate zero tensions below the test zone, and thus the requirements of Darcy's law are not met. As in most in-place methods, the test cannot be used in rocky or coarse gravel materials because the cylinder cannot be driven into such materials, and even if the cylinder could be installed there would probably be channelling along the inside periphery of the ring.



Initial		Final		Time hrs	Tank reading, cu in		Volume, cu in V	Q, cubic in/hr	Temp/1 of water, °C	Viscosity of water, Centipoises	Adj. Q, cubic in/hr	Perm, in/hr	Tensiometers		Piezometers	
Date	Time	Date	Time		Initial	Final							N-side	S-side	E-side	W-side
10-13-58	0800	10-13	1212	4.20	0	362	362	86.2	17	1.0828	84.0		145	153	dry	dry
10-13-58	1212	10-13	1630	4.30	362	722	360	83.8	19	1.0299	77.7		138	142	dry	dry
10-13-58	1630	10-14	0725	14.92	722	1742	1020	68.3	13	1.2028	74.0		135	138	dry	dry
10-14-58	0725	10-14	1235	5.17	1742	2110	368	71.2	16	1.1111	71.2		131	133	dry	dry
10-14-58	1235	10-14	1635	4.00	2110	2398	288	72.0	18	1.0559	68.5		122	127	dry	dry
10-14-58	1635	10-15	0750	15.25	2398	3344	946	62.0	14	1.1709	65.4		117	117	dry	dry
10-15-58	0750	10-15	1215	4.42	0	281	281	63.6	16	1.1111	63.6	0.12	111	113	dry	dry
10-15-58	1215	10-15	1710	4.92	281	586	305	62.0	19	1.0299	57.5/2	0.11	108	109	dry	dry
10-15-58	1710	10-16	0735	14.42	586	1383	797	55.3	12	1.2363	61.6	0.12	103	105	dry	dry
10-16-58	0735	10-16	1210	4.58	1383	1661	278	60.7	15	1.1404	62.3	0.12	105	104	dry	dry
10-16-58	1210	10-16	1650	4.67	1661	1962	301	64.4	18	1.0559	61.3	0.12	102	102	dry	dry
10-16-58	1650	10-17	0820	15.50	1962	2831	869	56.0	13	1.2028	60.6	0.12	104	102	dry	dry

Notes: /1 This is the temperature of the water moving into the test zone and is measured in the test cylinder.

/2 Adjusted $Q = \frac{1.0299}{1.1111} \times 62.0 = 57.5$ (Adjusted to average tank water temperature of 16° C which is the first reading after apparent stabilization)

Location: Hole D-2--Sample Farm Observer: A. P. Brown

Depth: 42" - 48"

Calculations: $k = \frac{VL}{tAH} = \frac{QL}{AH}$

$Q = 61.2$ cubic inches per hour average (Average for 48.5 hours)

$A = \pi r^2 = 3.1416 \times 9^2 = 254.5$ square inches

$L = 6$ inches

$H = 12$ inches

Therefore: $k = Q \times 0.00196 = 61.2 \times 0.001965 = 0.12$ inch per hour

DATA SHEET FOR RING PERMEAMETER TEST

103-D-659

Figure 15: Data sheet for ring-permeameter test

APPENDIX B.2

INFILTRATION MEASUREMENT USING DOUBLE RING INFILTROMETER

Introduction

The infiltration capacity or rate at which water enters the soil under given conditions has been described in section 2.5.1. It refers to the vertical entry of water into the soil surface and should not be confused with hydraulic conductivity, or permeability, which is a measure of the ability of a soil to transmit water in all directions, horizontally as well as vertically (section 2.5.2). Two figures are of interest - the initial intake rate (say in the first hour) and the equilibrium or basic intake rate when the intake has become constant after several hours.

The rate of infiltration can be measured by observing the fall of water within two concentric cylinders driven into the soil surface. The use of a double ring, with measurement confined to the inner ring, minimizes error due to flow divergence in directions other than the vertical. If metal cylinders are not available the outer one can be substituted by an earth dike.

Water of the same quality as will be used for irrigation should preferably be used, or misleading results may ensue. Quirk (1957) has demonstrated substantial increases in infiltration rates by increasing the electrolyte concentration of the applied water.

The test should normally be run for six hours (and not less than four). The amount of water required depends on soil conditions. One 200 litre drum may suffice on impermeable clays whereas sandy soils may take four or five drums. The test does not work well on cracked clays as the water disappears too fast and the results are too variable to be reliable. The initial water content during soil survey operations is likely to be variable, but the test cannot be done on saturated soil. Evaporation rates are usually too low to be significant, but if the infiltration rate is very low and the weather is hot and dry it is necessary to correct for evaporation.

Three to five replicates should be run at each site. It is often convenient to make the tests close to a sampled profile pit so that complete data on the soil is obtained. The test can be made on bare or vegetated soil. The later may be more useful for irrigation uses, but the rate under a grass sward is usually substantially higher than on cultivated land. The vegetation must be clipped down so that it does not break the water surface and loose material which would float should be cleared off.

Equipment

Steel cylinders, 40 cm high. Seam is ground smooth on inside. One end should be bevelled from outside to inside. For ease of transport they should be of different diameters to fit inside one another: the inner ones about 28-33 cm and the outer ones 50-60 cm.

Driving plate made of 1.9 cm steel.

One hardwood 15x15 cm timber having 0.6 cm steel plate bolted to one side.

Means of storing and transporting water (water trailer or drums, bucket, hosepipe).

7 kg sledge hammer, or heavy weight with handle.

Hook gauge.

Burlap cloth.

Auger and shovel.

Scissors or shears for clipping vegetation.

1 000 ml graduated cylinder or triangular ruler.

Watch or stopwatch.

Forms for observations. Graph paper.

Procedure

The pairs of cylinders should be installed 3-10 m apart on sites representative of the soil to be tested. Drive cylinders into the soil to approximately 15 cm depth, by placing the driving plate over the cylinder with a heavy timber on top. Rotate the timber every few blows and check that penetration is uniform and vertical. Tap the soil firm next to the inside and outside of the cylinders. Place burlap cloth (or similar) over the soil to dissipate the force of the water and reduce turbidity. Get everything ready for all the replicates before starting the test.

Fill both cylinders to a depth of about 10 cm and record the time and the height of the water in the inner cylinder using a hook gauge (made from thick wire or welding rod with a sharpened point).

Do the same for the replicates. Repeat the measurement after 10, 20, 30, 45, 60, 90, 120 minutes and each hour for the remainder of the test (more often if the infiltration rate is rapid).

The infiltration can be measured either by measuring the distance of the water surface from the top of the cylinder before and after topping up (using a triangular ruler with the hook gauge) or by measuring (with a 1 000 ml measuring cylinder) the amount of water required for topping up to a fixed hook gauge (707 ml of water is equal to 1 cm depth in a 30 cm cylinder). The former is simpler when different diameter cylinders are used. The outer cylinder should be kept at approximately the same level as the inner one: it is important that it should never be filled higher than the inner cylinder or the measured water level may rise instead of fallig.

The recordings should be entered on a form and the average hourly rates calculated. The curves of infiltration vs time should be plotted on graph paper and the cumulative amount of water infiltrated also plotted as a check. (There is ample time to do this in the field between measurements and it should be done at once so that errors can be rectified). If one cylinder gives a widely different rate from the others (perhaps because of a hidden insect burrow) it should be rejected in making the averages.

After the test period the cylinders are removed and an excavation should be made through the centre of the 30 cm cylinder site in order to draw the outline of the wetted soil on graph paper. In some conditions an auger can be used to delineate the wetted area; in sandy or moist soil the wetting pattern may be too deep or indeterminate to outline.

From the graph the values of the maximum initial infiltration rate and the basic rate can be obtained. Measurements should be made at several sites on the same soil series to obtain a reliable average. The infiltration rates for various soils can then be compared, and the diagram of the wetting pattern is helpful in explaining differences between them (for example claypan soils may have a rapid initial intake which soon decreases to very slow, whereas loamy friable soils may have a lower initial intake rate but a higher final rate).