Over-pumping groundwater in northern Jordan, the case of Irbid governorate: a conceptual model to analyze the effects of urbanization and agricultural activities on the groundwater level and salinity

Taleb Odeh[1] Alsharifa Hind Mohammad[2] Hussam Hussein[3][4][*] Mamoon Ismail[5] Thair Almomani[6]

1   The Hashemite University - Prince Al Hassan Bin Talal Faculty of arid lands - Zarqa 13133 Jordan

2   The University of Jordan - Water, Energy and Environment center - Amman 11942 Jordan

3   International Agricultural Policy and Environmental Governance, University of Kassel, Steinstrasse 19, Witzenhausen, 37213, Germany

4   Water Security Research Centre, School of International Development, University of East Anglia (UEA), Norwich, NR4 7TJ, UK

5   Water Authority of Jordan - Groundwater Basins Protection Directorate – Amman 11183 Jordan

6   Ministry of Water and Irrigation of Jordan - Division of Water Strategies - P.O.Box   2412-11181 Amman Jordan

*   Correspondence: email: hh.hussam.hussein@gmail.com

Abstract： Irbid governorate has the highest population density in Jordan and most of its water demand is supplied by groundwater. Both natural population growth and waves of migrations increased the number of its inhabitants during the last forty years. The increased number of inhabitant resulted in extending the urban and agricultural areas. Also, the demand for domestic water uses increased as a result of the increased number of inhabitant, while the extended agricultural area meant increasing the water demand for irrigation. Due to the expansion of urban areas, water was required for the construction sector. Most of the water resources needed for these sectors came and comes from groundwater resources. Nowadays, the increased water demand is putting a strain on the groundwater resources, which are currently over-exploited beyond their safe-yield. As a result of the continuous pumping, the groundwater level is decreasing rapidly and the salinity increasing gradually. This paper presents a conceptual model we have produced to measure this process through an integrated approach of remote sensing and Geographic Information Systems (GIS).

Keywords: Conceptual modeling; groundwater resources; Jordan; water demands; remote sensing; GIS

Introduction

Literature on water resources in Jordan focused on hydrological approaches and engineering solutions to water scarcity, with regional attention to the Jordan Valley, and to the Amman governorate. Extensive literature has been published on issues related to the water crisis in Jordan, which makes it impossible to fairly review within a brief literature review. In particular, Jordan is said to be among the most water scarce countries in the world, facing serious problems related to water shortages, which negatively affect its entire development [1-5]. Recent research showed that the Jordanian government has been exploring several solutions to increase the water supply in the country, from building the Wahda Dam, the Disi Canal project recently completed, and supporting the construction of the Red Sea – Dead Sea Canal [6-8]. Literature on water resources and water policies in Jordan has investigated mainly the cases of Amman governorate- where most of the population resides – and of the agricultural activities in the Jordan Valley

[9-11]. Previous research has adopted geospatial techniques for improved water management in the country [12]; Withheritrrong et al., [13] analysed estimation of the effect of soil texture on nitrate-nitrogen content in groundwater using optical remote sensing – although not for the case of Jordan -; Dogrui et al. [14] analysed groundwater modeling in support of water resources management and planning under complex climate, regulatory, and economic stresses, although not specifically in the case of Jordan; and Mohammad et al. [15] recently investigated the impact of droughts in the Yarmouk Basin, in Jordan, by monitoring the droughts through meteorological and hydrological drought indices. Nevertheless, what emerges from the review of the relevant literature is that little research has been done on the impacts of the evolving human activities – specifically of agricultural and urban activities – on the groundwater resources in the governorate of Irbid. This paper aims to make a novel contribution by presenting a conceptual model to measuring the process of human urbanization and increased agricultural activities over time according to an integrated approach of remote sensing and Geographic Information Systems (GIS) applied to the Irbid Governorate.

78

Study area and background information

80 Jordan has an area of about 89.34 Km² that is divided into 12 governorates, and Irbid governorate
81 has an area of about 1.572 km² (Fig. 1). As a result of the tectonic events and geomorphological
82 processes, Irbid governorate has high relief topography [16] (Fig. 2). Because of the variations of
83 elevations, there are different rainfall patterns in the region, as showed in Figure 3, [17-18]. Irbid
84 governorate has the second biggest population in the country, after the capital city Amman,
85 however Irbid has the highest population density in Jordan [19].

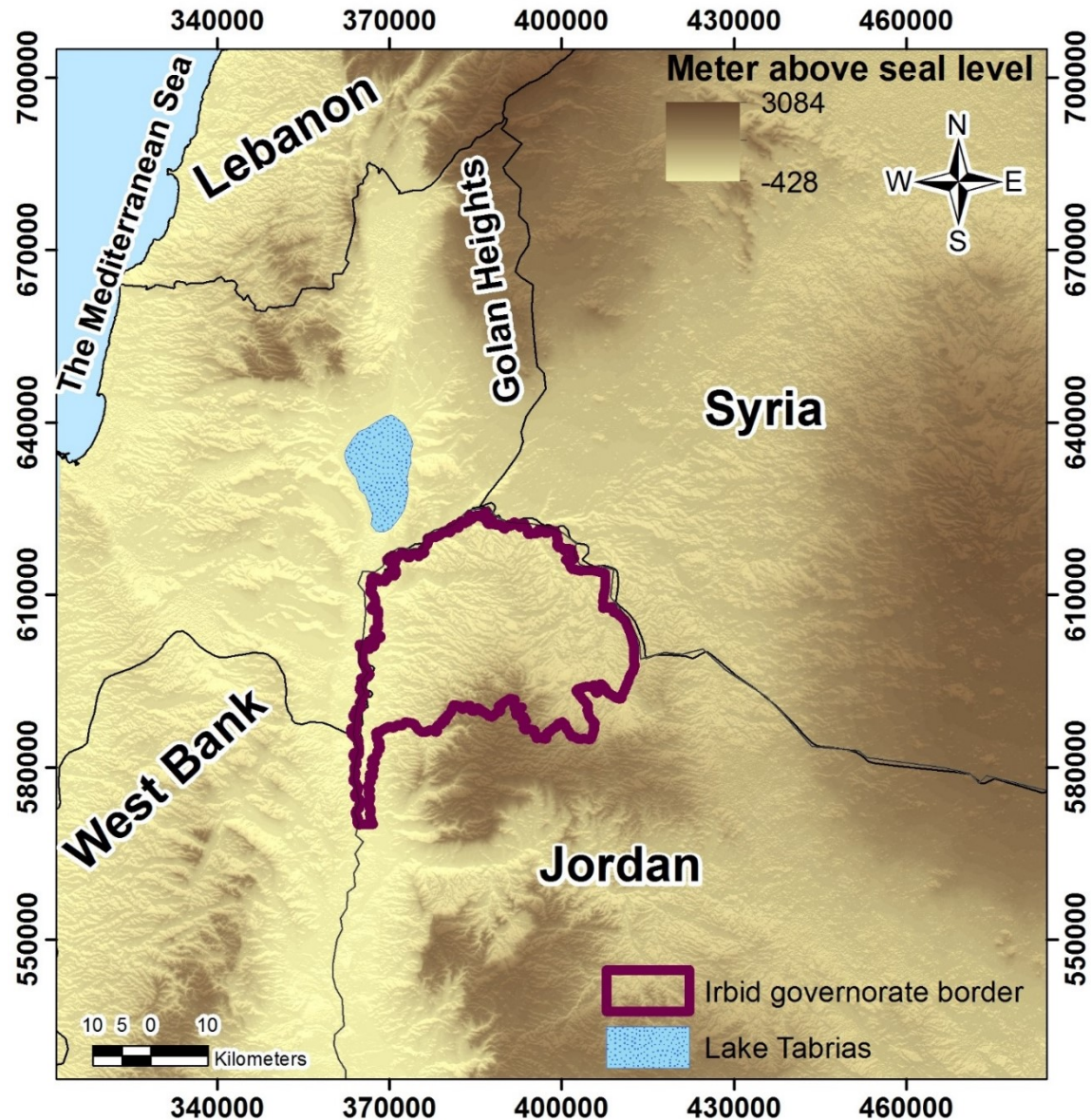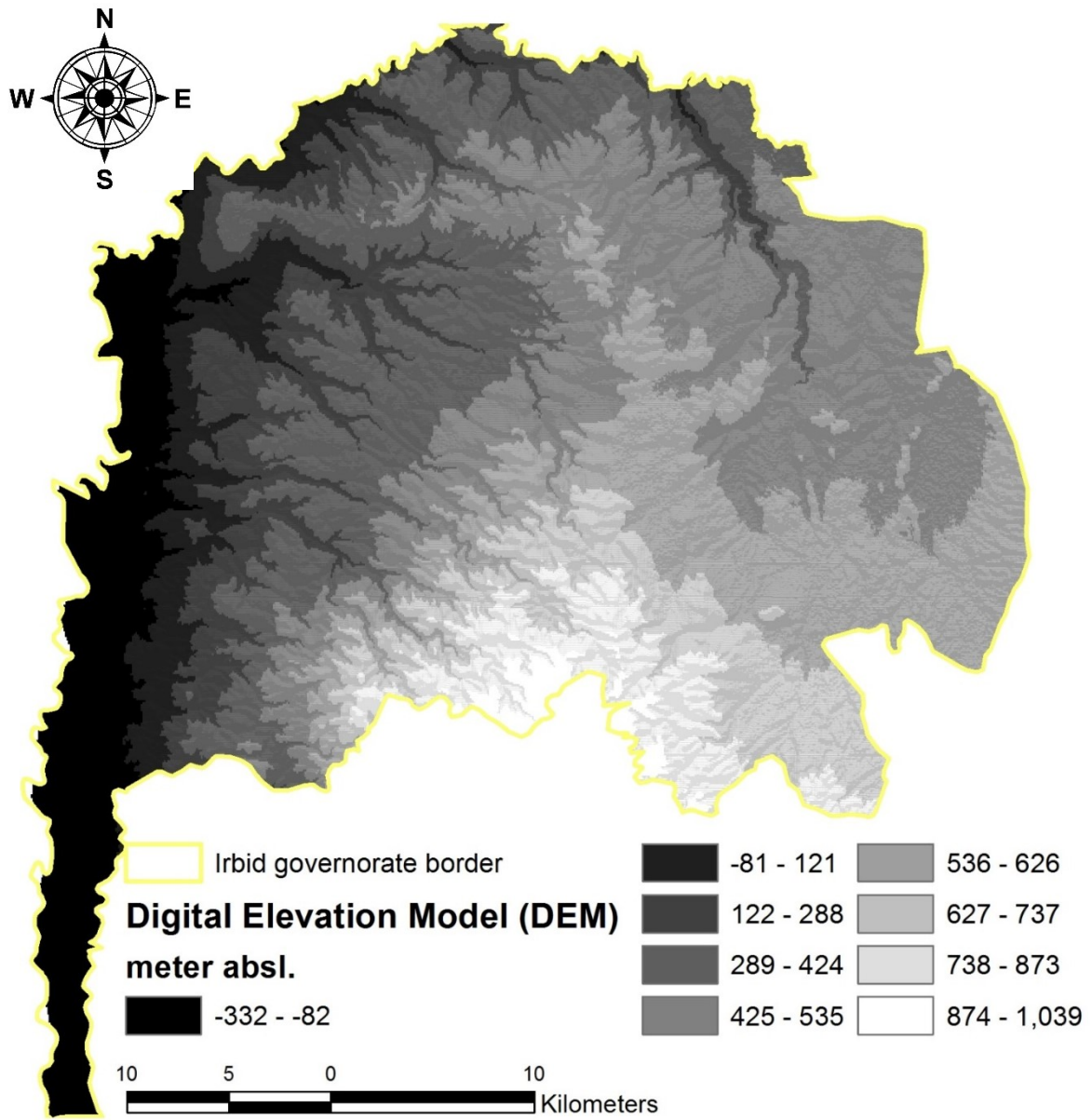**Fig.** 1: Study area location so called Irbid governorate. It has a border with Syria, west bank and Israel. It has the city of Irbid that has the second biggest population in Jordan after the capital Amman.
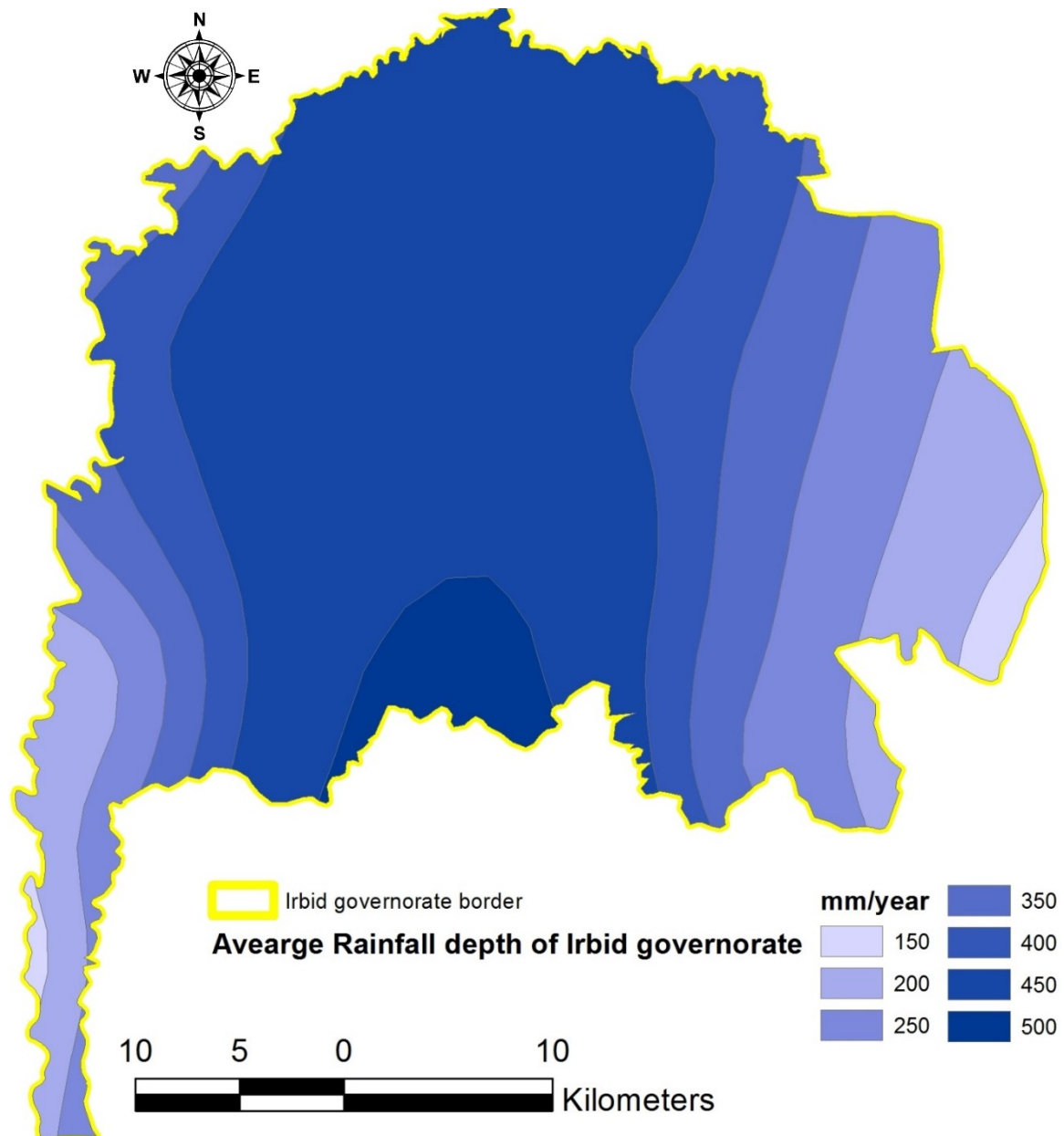
108

109   **Fig.** 2: The topography of the study area. The western part is the lowest elevation that is a part from
110   the Jordan valley. The southern part has the highest elevation that is a part form Ajloun mountains.

Fig. 3: Rainfall quantity spatial distributions of the study area (average of 40 years 1984 – 2014). Meteorological Department 2014 open data source. The amount of rainfall is over the highest topographical elevation at Ajloun mountains.

Irbid governorate is located in the north-western part of Jordan. Two major rivers pass through the governorate, Al Yarmouk River in the north and the Jordan River in the west; nevertheless the major source of water supply is it groundwater resources [3; 4; 15; 17]. This is because the discharges of the two mentioned rivers is limited (Al Yarmouk River 14.5 m³/s, Jordan River 16 m³/s) and because they are both of transboundary nature, hence Jordan needs to respect the bilateral treaties signed about the uses of these rivers [6; 15].

The groundwater of Irbid governorate comes mainly from a hydrogeological basin called Al Yarmouk. It is shared with Syria and has an area of about 1426 Km² [16; 20]. The basin is composed mainly from shallow unconfined unsaturated aquifers. The rock matrix of the aquifers is mainly of tertiary chalks and limestone and basaltic rocks [16]. However, alluvial deposits are found in the wadis especially in the west of the basin. The average hydraulic conductivity of the basin varies from 1×10^{-4} to 1×10^{-6} m/s. The maximum groundwater level is in the south of the study area and reach up to 1000 m absl. While the minimum the groundwater level is the eastern side of the study area and

128   ==reach down to about – 239 meter absl. [6; 15]. The groundwater flow from the south to north mostly==
129   ==but in the eastern side of the study it moves from east to west. The average groundwater recharge is==
130   ==about 8% to 10% from the annual rainfall and he safe yield of the basin is estimated to be 40 Million==
131   ==Cubic Meter (MCM) [21].==
132   Irbid governorate received several migrations waves during recent history [22] (Fig. 4).   The
133   first wave was in 1948 after the first Arab–Israeli war, when Palestinian refugees came to Irbid
134   governorate. The second wave was after the Arab-Israeli Six Days War in 1967. After the war
135   thousands of Palestinian refugees came to Jordan, settling also in the Irbid governorate. Moreover,
136   other two migration waves came after the first and second gulf war in 1991 and 2003 respectively.
137   Hundred thousands of Jordanians and Palestinians moved from Kuwait to Jordan following the first
138   Gulf War. In 2011 the civil war in Syria started, and about half a million Syrian refugees came to
139   Irbid governorate. Furthermore, Irbid governorate with 3.2% has one of the highest population
140   growth rates in the region. Both the increased number of refugees and the natural high population
141   growth rate play a major role for increasing the number of inhabitants rapidly in Irbid governorate
142   [22; 19]
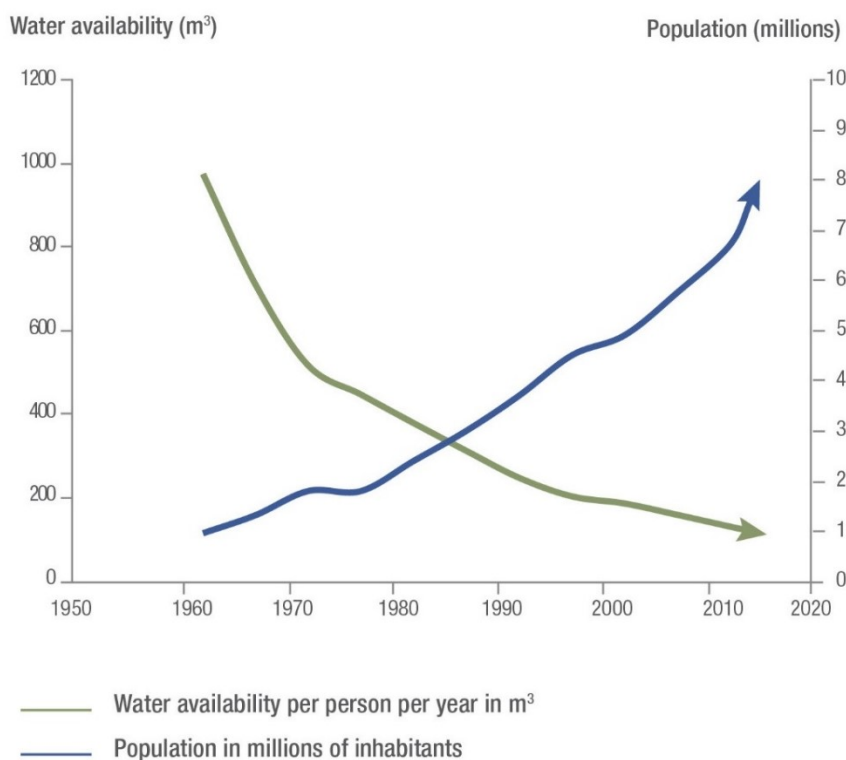
Note: 85% of Jordan's population lives in cities.
Source: FAO Aquastat (2014).

144   **Fig.** 4: The population growth in Jordan [23]. The water availability per person is decreeing while the
145   number of the inhabitant is increasing.

146   The first and main reason of extension of the urban area is the increases population [24].
147   Naturally, the increased number of habitant and the extended urbanized area would consume more
148   water in order to supply the drinking water and construction water respectively [25]; nevertheless, it
149   has been shown in recent literature that most water supply in Jordan goes to the agricultural sector
150   rather than for domestic uses [4; 10]. Nevertheless, population growth and extension of the urban
151   area in Irbid governorate had an impact on the groundwater level and salinity. This impact was due
152   to increasing groundwater abstraction way beyond the safe yield. This study aims at shading light
153   on this exact relationship.
154

155

Methodology

The integrated approach Remote Sensing (RS) and the Geographic Information Systems (GIS) have been recently widely used in order to analyze, store, and display land surface data [26; 27]. However, RS could produce the land surface data of the land cover in form of satellite images, but those images have to be classified in order to generate the land cover classes [28]. The images and their classifications could be stored in form of raster, which is a major type of GIS data (geo-data). GIS is a useful tool for spatial analyzing raster data. Hence, RS and GIS are integrated in a useful approach for land surface data generating [26-29].

Landsat represents the world's longest continuously acquired collection of space-based moderate-resolution land remote sensing data. Four decades of imagery provides a unique data resource for scientists in deferent fields. These data are in form of raster data that is crucial to GIS analysis. It has capacity to provide repetitive and synoptic observations of the land surface that makes it powerful tool in giving information on how land cover changes over a span of time. We used Land sat 5 images for the years of 1984, 1994 and 2004 since it has data record for these years while for the year of 2014 Landsat 7 image was used. Any Landsat image has at least 7 spectral bands with a spatial resolution of 30 meters for Bands 1-5, and 7. For our classifications we used the visible bands that have a resolution of thirty meter and available in for all the landsat images. However, all the landsat images that were used in our study were downloaded from the landsat data access (https://landsat.usgs.gov/landsat-data-access).

ENVI 6 is an image analysis software that is used by GIS professionals, remote sensing scientists, and image analysts to extract meaningful information about the land surface class from the satellite Images [26-27]. ENVI 6 software have a many automated data analysis tools that could access spatial algorithms to rapidly, swiftly, and precisely analyze imagery, such as estimate image geostatistics, measure area and distance features and image supervised classification [26]. Therefore, we used ENVI 6 software as a remote sensing software. The objective from that was to carry out a supervised classification for Landsat images in order to understand the classes of the land surface. However, there are four major methods for supervised classification in ENVI 6 software: Maximum Likelihood, Minimum Distance, Mahalanobis Distance and Spectral Angle Mapper. The minimum distance method gave the best overall accuracy (Tab. 1) therefore we consider it for the classification. Parts of the study area has remote sensing investigations by other studies such Al-Kofahi et al 2017 [30] and Sawalhah [31] were they explained and discussed in details that approach.

However, we categorize the land surface area into only four classes, which have a major influence on the groundwater recharge, as follows: A) Soil units, B) Rock unit, C) Urban land and D) agricultural land. However, we carry out the supervised classification, for the visible bands, to generate these four land cover classes for the Landsat 7 of the time periods of 1984, 1994, 2004 and 2014. These time periods are on constancy with the time periods of the hdrogeologyical data that we would compare the land surface classes changes detections with it (Fig. 5). The validation of the classifications was according to filed work visits for the landsat image of 2014 and Google earths imageries for 2004, 1994 and 1984 landsat images.

196
197
198
199
200
201
202
203
204
205

206　　Tab. 1: Confusion matrix table. It represents the accuracy assessment for the classifying process of
207　　landsat images.
208

Irbid governorate Land sat Image			Reference data				Summations	Users' accuracy
			Soil units	Urban land	Agricultural land	Rock unit		
2014	Classifications	Soil units	30	1	9	2	42	0.71
		Urban land	3	28	2	5	38	0.74
		Agricultural land	5	3	27	2	37	0.73
		Rock unit	2	8	2	31	43	0.72
	Summations		40	40	40	40	160	
	Producers' accuracy		0.75	0.70	0.68	0.78		0.73
2004	Classifications	Soil units	31	1	6	3	41	0.76
		Urban land	2	29	1	4	36	0.81
		Agricultural land	4	1	32	3	40	0.80
		Rock unit	3	8	1	30	42	0.71
	Summations		40	40	40	40	160	
	Producers' accuracy		0.78	0.73	0.80	0.75		0.76
1994	Classifications	Soil units	32	2	2	1	37	0.86
		Urban land	1	28	1	3	33	0.85
		Agricultural land	3	1	35	1	40	0.88
		Rock unit	6	7	1	33	47	0.70
	Summations		40	40	40	40	160	
	Producers' accuracy		0.80	0.70	0.88	0.83		0.80
1984	Classifications	Soil units	33	1	3	1	38	0.87
		Urban land	1	30	1	4	36	0.83
		Agricultural land	8	1	34	1	44	0.77
		Rock unit	1	8	1	34	44	0.77
	Summations		40	40	40	40	160	
	Producers' accuracy		0.83	0.75	0.85	0.85		0.82

209
210
211
212

213
214
215
216
217
218
219
220
221
222

224
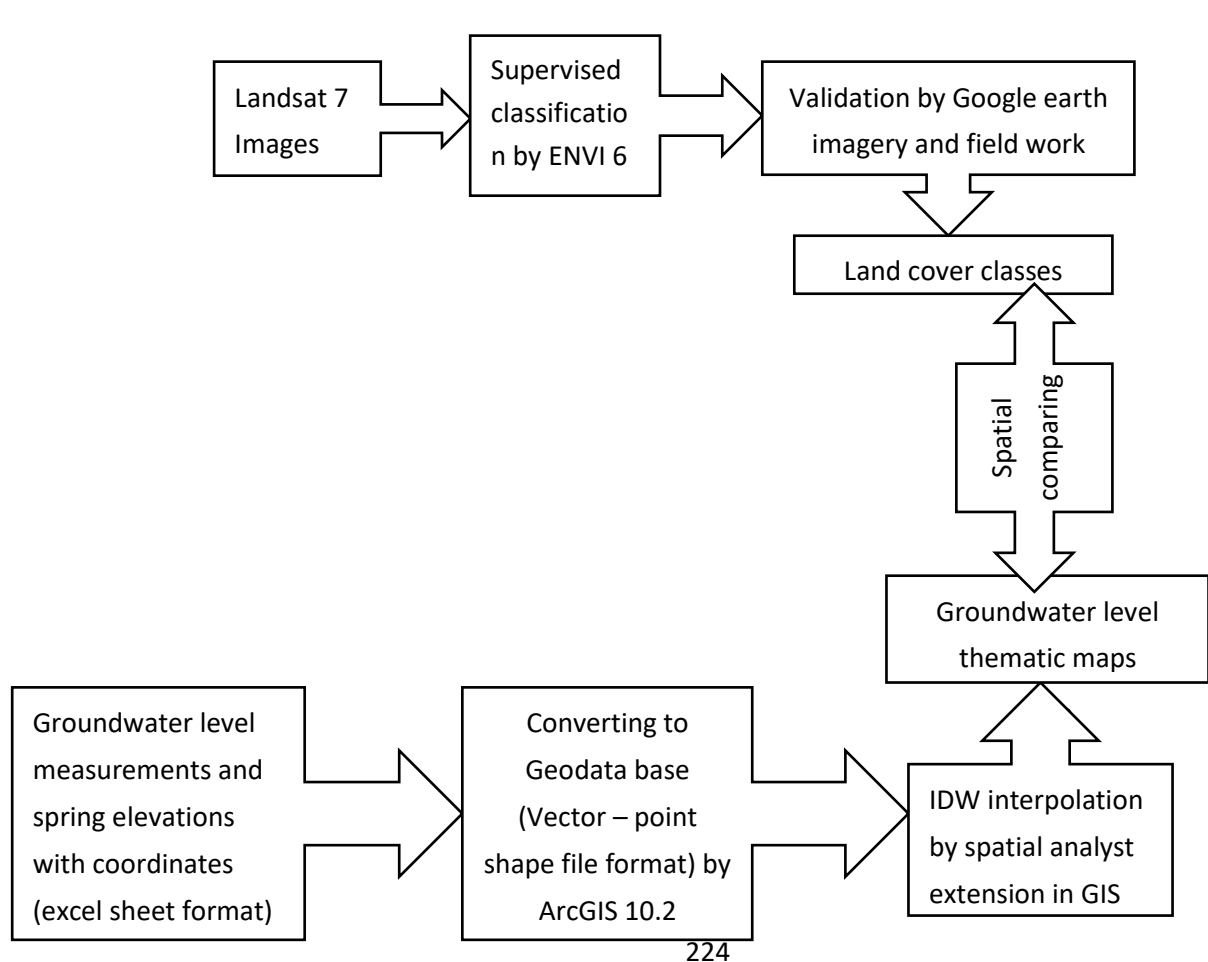
225 **Fig.** 5: A flow chart for a conceptual model of land cover – groundwater level changes detection.
226 comparing groundwater level and land cover class. Both of the groundwater level and the land cover
227 class are in form of raster.

228   The supervised classifications by minimum distance method of all our satellite images has
229 overall accuracy greater than 70% that is applicable according to smith et al 2002 [32]. Thematic
230 maps are one of the most common tools that could be used in order to understand the spatial
231 distributions of specific phenomena [28]. GIS is a powerful tool to achieve that. ArcGIS 10.2 software
232 with its spatial analyst extension is widely used currently for thematic map generating because of its
233 useful interface [33]. Therefore, we used it to generate a thematic map for the groundwater level
234 during time periods of the available groundwater data of Ministry of Water and Irrigation (MWI) in
235 Jordan which are: 1984, 1994, 2004 and 2014.
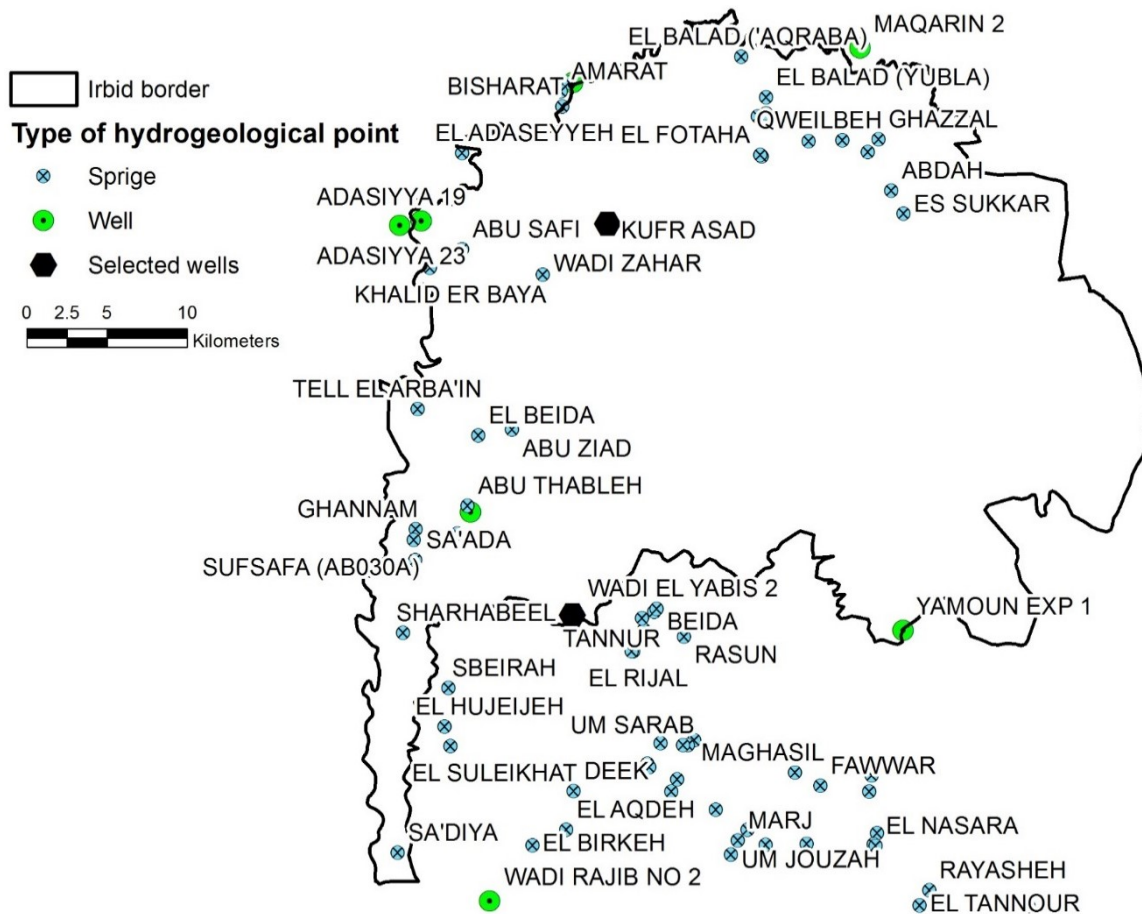236   However, the first step was converting the excel data of the groundwater level of the wells and
237 spring elevations and their coordinates into a vector – points (shapefile namely) by ArcGIS 10.2. The
238 spatial analyst extension in ArcGIS 10.3 could interpolate groundwater levels into thematic maps by
239 the Inverse Distance Weighted (IDW) method. The IDW method includes an estimated weighted
240 average method where the weights of the measured data points, $Z(u_i)$, i = 1, 2, …, M, is set inversely
241 proportional to their distances, h_i, from an interpolated un measured point, $Z(u_x)$. It is could be
242 calculated as follow:
243

$$Z(ux) = \frac{\sum_{i=1}^{M}\left[\dfrac{1}{h_i{}^P} \times Z(u_i)\right]}{\sum_{i=1}^{M}\dfrac{1}{h_i^P}} \tag{1}$$

244
245
246
247
248
249   The values that is in gray shadow represents the overall classification accuracy.
250   where p > 0 is a power parameter. However, the IDW method has several advantages for
251   interpolation such as: could calculate changes in terrain such as cliffs and faults line in addition to it
252   could increase or decrease the number of the sample points to influence cell values [34]. Therefore,
253   we used it as a method for interpolate the thematic maps of the groundwater levels. For that purpose
254   we used 76 hydrogeological points (Fig. 6) that are in and around our case study. The
255   hydrogeological points are the available wells and spring that have hydrogeological record in the
256   ministry of water and irrigation. However, in general, because of data discontinuity/scarcity, not all
257   the wells and springs have a full hydrogeological record [35]. We chose four time periods for
258   interpolation. These time periods are near to the time periods of the migration waves in order to
259   evaluate how the increasing in the inhabitant effects the groundwater level and hence the
260   groundwater salinity. These time periods are: 19984, 1994, 2004 and 2014. They are the exact time
261   periods of the classified Landsat 7 images in order to compare the land classes detection with the
262   groundwater level changes.
263
264
265
266
267
268
269
270
271
272
273
274
275
276
277
278
279
280
281
282
283
284
285
286

Fig. 6: Available hydrogeological points in the study area. The groundwater levels of these points were interpolated to generate a conceptual model for the groundwater level spatial changes. Not all the wells have complete data record about the water level and salinity for forty years therefor tow well only were selected to detect the changes of water level and salinity.

Results and discussion

Figure 7 shows that the land cover of Irbid governorate was changing unregularly during the last forty years. It also shows that the urbanized area was growing rapidly during the same time, as a result of the growing population [24; 19]. It also shows that the agricultural area decreased in the first ten years (1984 – 1994). This is due to the fact that youth whom were working in the agricultural sector started moving toward the main cities to take up jobs in the governmental sector, which was expanding and employing in that time period [36; 22; 19]. However, the following ten years (1994-2014) the agricultural area started to increase because the governmental sector was almost

saturated, stopping expanding and hiring new people, and the people therefore preferred moving toward the agricultural jobs again [22; 19]. In this period many businessmen were investing in land and agribusinesses in this part of the country, expanding agricultural activities and job opportunities in the area [4].
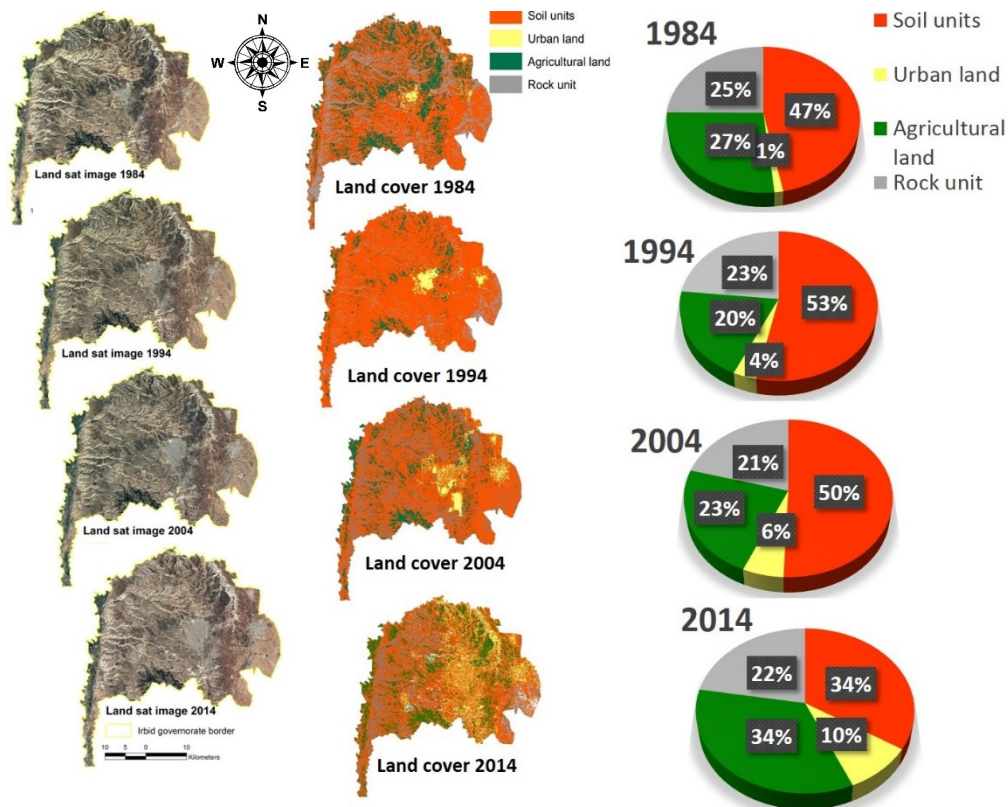
Fig. 7: Land cover changes detections of the study area. During the last forty years the urbanized area were extended rapidly. Land sat 5 images were used for the years of 1984, 1994 and 2004 while for the year of 2014 Landsat 7 image was used to generate a conceptual model for the land cover spatial changes.

From a geological perspective, the area of the soil is associated with the area of agricultural land [37]. When the area of the agricultural land decreased in the first ten year the area of the soil increased [37; 38]. Moreover, in the following thirty years people started moving back toward the agricultural activity, therefore, the agricultural land area increased [18; 19; 22].

The area of rock unit was decreasing during the first thirty years since people prefer to construct the basement of houses, which is the major part of the urbanized area, on that unit in order to reduce the cost of construction by not digging the soil [38; 39; 19]. The houses basements have to be on rock layer so they do not crack during the winter as a result of soil liquefaction [34]. However, in the last ten years the rock unit shows a slight increase up to 1% as a result of the soil erosion that increased in the last 10 years [33].

Figure 8 shows the groundwater level spatial distributions of the study area. It shows where the groundwater level changed as a result of the land cover changes during the last forty years. However, land cover effects the groundwater level in two ways: 1) Reducing the groundwater

recharge by increasing the runoff water that is increasing urban area span and/or 2) Consuming more groundwater in order to meet the high demands for irrigation and drinking purposes when the agricultural land extended and the inhabitant increased respectively [40]. Both these ways impacted the spatial distributions of groundwater level on the study area but the effects were not spatially homogeneous.
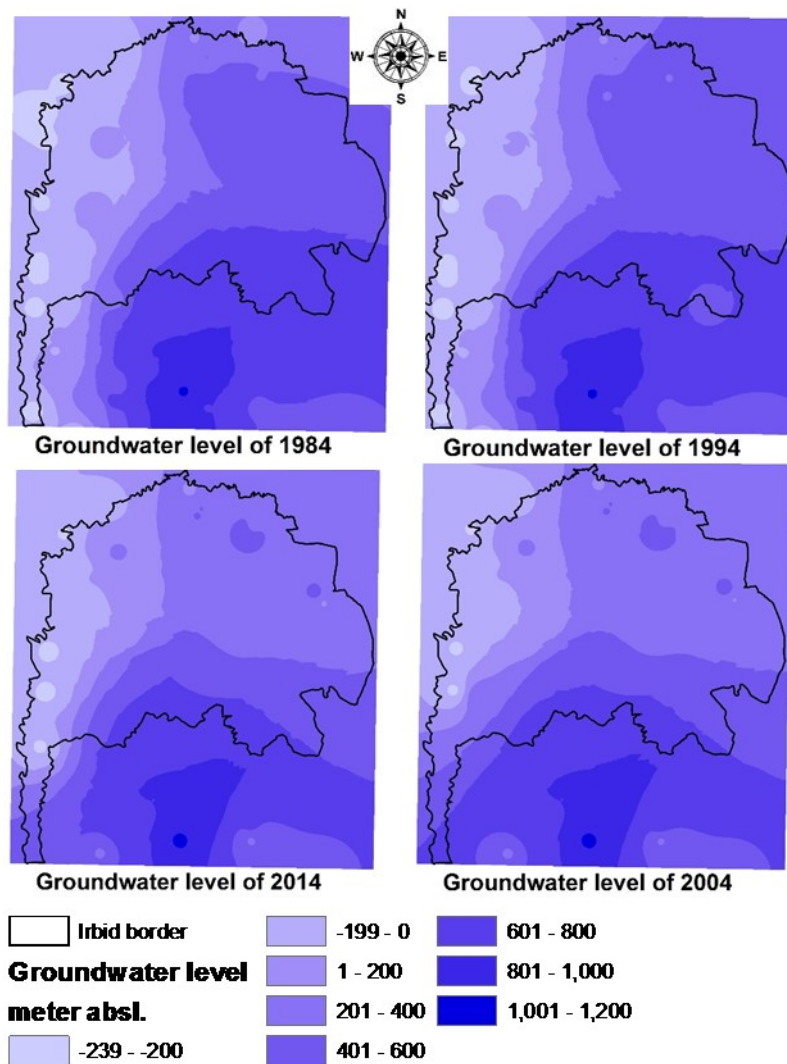
Fig. 8: The conceptual model of the groundwater level changes spatial detections of thirty years duration. In the first ten years (1984 – 1994) the groundwater level was rising in the north west of the study area. After 1994 the groundwater level decrease in the same area as a result of the extended urbanization.

From 1984 to 1994 the groundwater level increased in the north and northeast part of the study area as a result of the decrease in agricultural activities during that time period, which meant decreasing in pumped irrigated water [17]. However, in the south-eastern part of the study area a zone of groundwater over-pumping was generated as result of heavy groundwater mining to supply the increased number of inhabitants in that area, which saw a strong increase in urbanization.

From 1994 to 2004 the groundwater depletion strongly impacted the north and northwestern part of the study area as a result of the extending agricultural and urbanized area. Limestone

352   sinkholes started to be an obvious landscape phenomenon in that area as a result of the groundwater
353   depletion [41; 30]. However, the southern part of the study area has the highest elevation and
354   received the highest amount of rainfall so it has the highest amount of groundwater recharge.
355   From 2004 to 2014 the groundwater depletion impacted the east and the southeastern part of
356   the study area since the urbanization extended more intensively and the population increased as a
357   result of the latest wave of migration [19; 22] (Fig. 9). Hence, it is clear that groundwater depletion is
358   associated with the land cover detection in the study area.
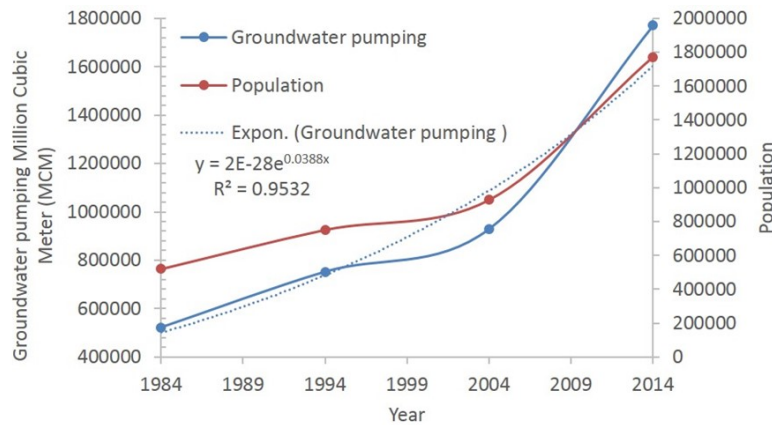
359

360   **Fig.** 9: Population growth and Groundwater pumping increasing in Irbid governorate. They are both
361   in Exponential increasing.

362   The available hydrogeological data record of the study area received from the MWI were also
363   examined and this study found that only two wells have data about the groundwater level and
364   salinity for forty years. The objective of that was to correlate the decreasing level of groundwater
365   with its increasing salinity. Previous studies confirmed that in Jordan salinity increases with
366   groundwater level decreasing [42]. This is due to the fact that deeper waters have more retention
367   times to accumulate dissolved salts than the higher water. Figure 10 shows that the groundwater
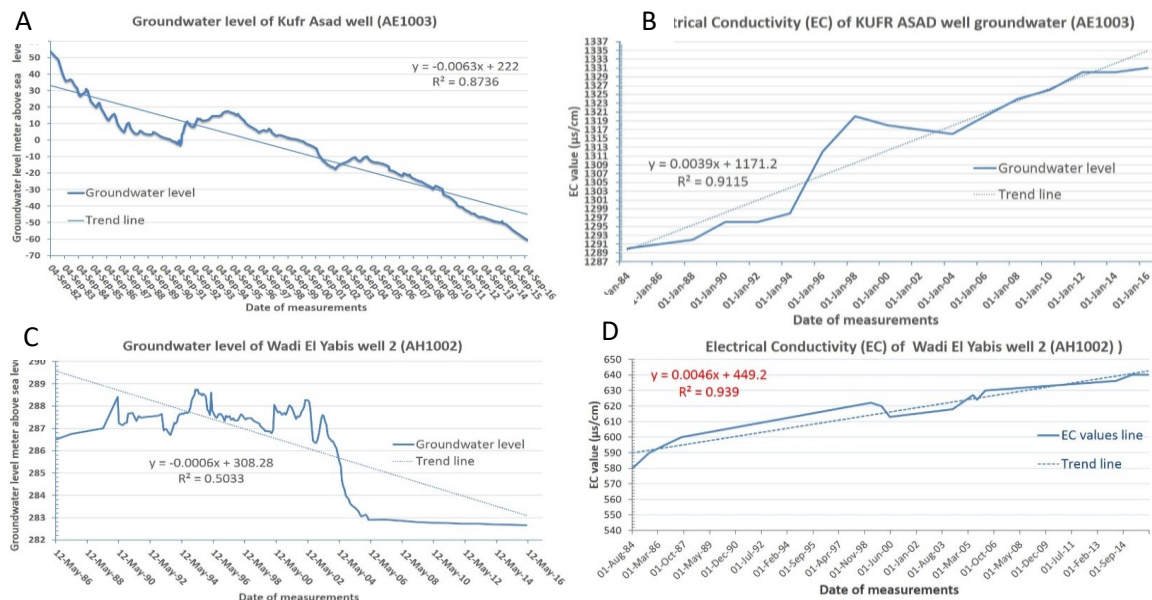
368   level in the

369   **Fig.** 10: Groundwater level changes (A and D) and groundwater salinity changes (B and C) in the two
370   selected wells. Kufr Asad well locates in the north of the study area while Wadi El Yabis well locates
371   in the south of the study area.

372   northern part of the study area decreased more rapidly than the groundwater level in the southern
373   part and that the salinity of the groundwater in the north was increasing faster than in the south.
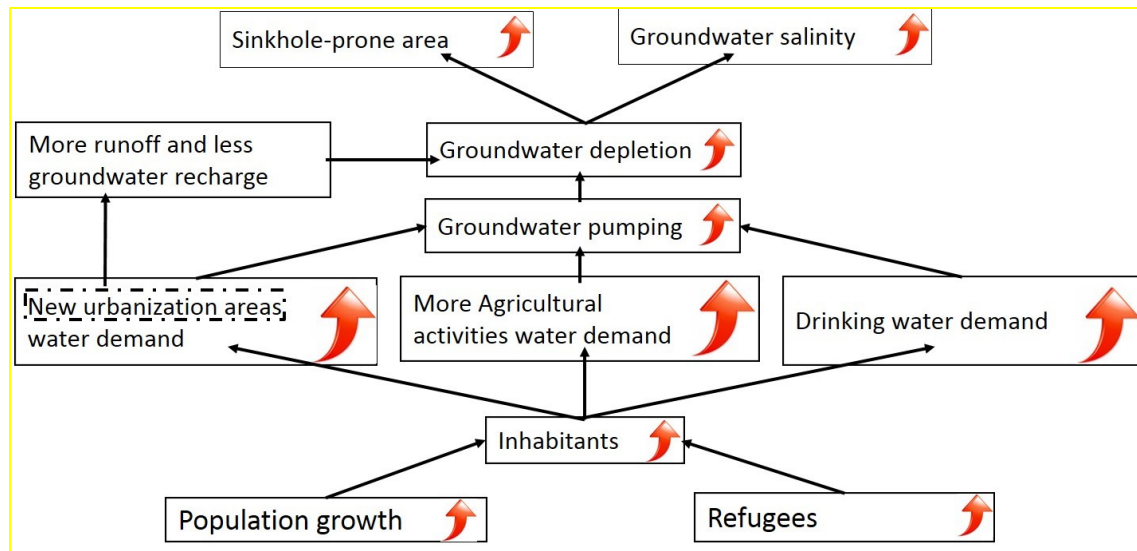
374   Figure 11 shows our conceptual model in form of flow chart. It indicates that the repaid increased

375   Fig. 11: A conceptual model for the mechanism of the increased inhabitants effects on groundwater.
376   When the groundwater level is decreased the groundwater salinity is increased and sinkhole-prone
377   area would increase too.

378   The number of inhabitants increased the groundwater demands which generate more groundwater
379   pumping. The annual groundwater pumping is much more than the annual ground recharge
380   therefore groundwater level decrease characterize a typical case of over-pumping. Our model
381   indicates that that the over-pumping in our case study doesn't only increase the groundwater
382   salinity but it creates sinkhole prone area.

383

384

385   **Conclusions**

386   There is a strong positive correlation between the groundwater depletion and extending
387   urbanization and agricultural activities. Unsurprisingly, population growth is linked to extending
388   urbanization and urban areas, as well as agricultural activities and agricultural investments.
389   Drilling pumping wells has to consider the zonation of surface rainfall and the zonation of
390   groundwater recharge. The area of highest amount of rainfall is usually the area of highest amount
391   of groundwater recharge and it is more resistant and resilient to groundwater depletion. This study
392   also found a positive correlation between the groundwater level and groundwater salinity, therefore
393   population growth, urbanization, and agricultural activities do not threat only groundwater
394   quantity (when over-pumped, such as in the case of northern Jordan), but also groundwater quality.
395
396   In the case of limestone aquifers, sinkholes are natural risks that impact the area of groundwater
397   depletion zone. In the study area, sinkholes and the groundwater zones are extended rapidly and
398   intensively where the groundwater depletion is found. Sinkholes have a direct negative impact on
399   the urbanization areas because of its ability to destroy houses, buildings, and roads. Thus, the effects
400   of groundwater depletion are not only negative on the water quality but also on the urban safety too.

401
402 Conceptual hydrogeological models are very important in order to conduct a sustainable
403 management of the groundwater resources. They describe the elements of the water conflicts and
404 prerequisite for solid numerical groundwater models. Our conceptual model for the water crisis in
405 Irbid governorate indicates that groundwater is the major water resource and its abstraction
406 quantities is rapidly increased in order to supply the increased number of inhabitants and their
407 activities. However, our model indicates the abstraction rate is much more than the groundwater
408 recharge rate, therefore the groundwater level decrease. We do recommend a numerical
409 groundwater modelling for the study area in order to determine the optimized quantity of
410 groundwater pumping. Furthermore, alternative water resources in the study area must be
411 generated in order to reduce the pressure on the groundwater resource.
412
413

416 **References**

417 [1] Jasem A, Raggad M (2010) Assessing groundwater vulnerability in Azraq basin area by a modified
418   DRASTIC index J. Water Resource and Protection, 2010, 2, 944-951doi:
419   https://doi.org/10.4236/jwarp.2010.211112 (http://www.SciRP.org/journal/jwarp)

420 [2] Mohammad AH, Almomani T, Alhejoj I (2015) Groundwater vulnerability for the surface outcropping
421   aquifers in Jordan. J Environ Prot 6: 250–258. https://doi.org/10.4236/jep.2015.63025

422 [3] Hussein, H. (2018a), Yarmouk, Jordan, and Disi basins: Examining the impact of the discourse of water
423   scarcity in Jordan on transboundary water governance. *Mediterranean Politics*, 1-21, DOI:
424   10.1080/13629395.2017.1418941

425 [4] Hussein, H. (2018b), Tomatoes, tribes, bananas, and businessmen: An analysis of the shadow state and of
426   the politics of water in Jordan. Environmental Science & Policy,84, 170-176, DOI:
427   10.1016/j.envsci.2018.03.018

428 [5] Hussein, H. (2018c), Lifting the veil: Unpacking the discourse of water scarcity in Jordan. *Environmental
429   Science & Policy*, *89*, 385-392.

430 [6] Hussein, H. (2017a), Whose 'reality'? Discourses and hydropolitics along the Yarmouk
431   River. *Contemporary Levant*, 2 (2), 103-115, DOI:10.1080/20581831.2017.1379493

432 [7] Hussein, H. (2017b), Politics of the Dead Sea canal: a historical review of the evolving discourses, interests,
433   and plans. Water Int 42(5):527– 542. https://doi.org/10.1080/02508060.2017.1344817

434 [8] Hussein H. (2017c) A critique of water scarcity discourses in educational policy and textbooks in Jordan. J
435   Environ Educ 1–12. https://doi.org/10.1080/00958964.2017.1373620

436 [9] Haddadin MJ (Ed.). (2006). Water resources in Jordan: evolving policies for development, the
437   environment, and conflict resolution. Resources for the Future

438 [10] Hussein, H. (2016). An analysis of the discourse of water scarcity and hydropolitical dynamics in the case
439   of Jordan (Doctoral dissertation, University of East Anglia).

440 [11] Salameh, E., Shteiwi, M., & Al Raggad, M. (2018). *Water Resources of Jordan: Political, Social and Economic
441   Implications of Scarce Water Resources* (Vol. 1). Springer.

442 [12] Al-Bakri, J. T., Shawash, S., Ghanim, A., & Abdelkhaleq, R. (2016). Geospatial techniques for improved
443   water management in Jordan. *Water*, *8*(4), 132.

444 [13] Witheetrirong, Y., Tripathi, N. K., Tipdecho, T., & Parkpian, P. (2011). Estimation of the effect of soil
445   texture on nitrate-nitrogen content in groundwater using optical remote sensing. *International journal of
446   environmental research and public health*, *8*(8), 3416-3436.

447 [14] Dogrul, E. C., Brush, C. F., & Kadir, T. N. (2016). Groundwater modeling in support of water resources
448   management and planning under complex climate, regulatory, and economic stresses. *Water*, *8*(12), 592.

449   [15] Mohammad, A. H., Jung, H. C., Odeh, T., Bhuiyan, C., & Hussein, H. (2018). Understanding the impact of

450   droughts in the Yarmouk Basin, Jordan: monitoring droughts through meteorological and hydrological

451   drought indices. *Arabian Journal of Geosciences*, *11*(5), 103.

452   [16] Bender F (1974) Geology of Jordan. Contribution of the regional geology of the earth. Borntraeger, Berlin

453   [17] Salameh E, Bannayan H (1993) Water Resources of Jordan—Present Status and Future Potentials. Friedrich
454   Ebert Stiftung, Amman, p183.

455   [18] Moshrik H.R., Abu-Allaban M, Al-Shayeb A. (2009) Climate change in Jordan: A comprehensive
456   examination approach. Am. J. Environ. Sci. 5: 58–68.

457   [19] Department of Statistics (2014) Statistical Yearbook; Government publication: Amman, Jordan, 2014; p.
458   200.

459   [20] Abu-Jaber N, Kimberley M, Cavaroc V (1989) Mesozoic-Palaeogene basin development within the Eastern
460   Mediterranean borderland. J. Petrol. Geol. 4: 419–436.

461   [21] Ministry of water and irrigation 2017 open data source.

462   [22] Perdew L (2014) Understanding Jordan Today; Mitchell Lane Publishers, Inc.: Newark, DE, USA, pp. 17–
463   18.

464   [23] FAO Food and Agriculture Organization of the United Nations (2014) open data source. ((this reference
465   for figure 4))

466   [24] Butler D, Davies J (2000) Urban Drainage. Spon Press, USA, p 483.

467   [25] Stephenson D (2003) Water resources management. Taylor and Francis, The Netherlands, p 323.

468   [26] Saraf K, Choudhury R, Roy B, Sarma B, Vijay S, Choudhury S (2004) GIS based surface hydrological
469   modelling in identification of groundwater recharge zones. Int J Remote Sens 25:5759–5770.

470   [27] Odeh T, Rödiger T, Geyer S, Schirmer M (2015) Hydrological modelling of a heterogeneous catchment
471   using an integrated approach of remote sensing, a geographic information system and hydrologic
472   response units: the case study of Wadi Zerka Ma'in catchment area, north east of the Dead Sea. Environ
473   Earth Sci 73:3309–3326.

474   [28] Chou Y (1997) Exploring Spatial Analysis in GIS; Onword Press: New York, NY, USA, p. 500.

475   [29] Berndtsson R, Larson M (1987) Spatial variability of infiltration in a semi-arid environment. J Hydrol
476   90:117–133.

477   [30] Al-Kofahi S , Jamhawi M, Hajahjah Z, (2017) Investigating the current status of geospatial data and urban
478   growth indicators in Jordan and Irbid municipality: implications for urban and environmental planning.
479   Environment, Development and Sustainability Journal. https://doi.org/10.1007/s10668-017-9923-y.

480   [31] Sawalhah M., Al-Kofahi S, Othman Y, Andres F. Cibils (2018) Assessing rangeland cover conversion in
481   Jordan after the Arab spring using a remote sensing approach, Journal of Arid Environments 157:97-102.

482   [32] Smith A, Wooster M, Powell A, Usher D (2002) Texture based feature extraction: application to burn scar
483   detection in Earth observation satellite sensor imagery. Int. J. Rem. Sens. 23:1733–1739.

484   [33] Odeh T, Boulad N, Abed O, Abu Yahya A, Khries N, Abu-Jaber N 2017 The Influence of Geology on
485   Landscape Typology in Jordan: Theoretical Understanding and Planning Implications. *Land 6*: 51.

486   [34] Wang Y , Akeju O, Zhao T (2017) Interpolation of spatially varying but sparsely measured geo-data:
487   Acomparative study. Engineering Geology 231: 200–2017.

488   [35] Wu Y, Wang W, Toll M, Alkhoury W, Sauter M, Kolditz O (2011) Development of a 3D groundwater
489   model based on scarce data: the Wadi Kafrein catchment/Jordan. Environ Earth Sci 64: 771-785.

490   [36] US Department of agriculture (USDA) (1993) Soil Survey Manual, Soil Survey Staff, Natural Resource
491   Conservation Service, Handbook No. 18, U.S. Government Printing Office, Washington; p 437.

492   [37] Zube E, Sell J, Taylor J (1982) Landscape perception: Research, application and theory. Landsc. Plan. 9: 1–
493   33.

494   [38] Bouraoui F, Vachaud G, Treut L, Chen T (1999) Evaluation of the impact of climate changes on water
495   storage and groundwater recharge at the watershed scale. Clim Dyn 15:153–161.

496   [39] Potter R.B, Darmame K, Barham, N., Nortcliff S. (2009) "Ever-growing Amman", Jordan: Urban
497   expansion, social polarisation and contemporary urban planning issues. Habitat Int. 33: 81–92.

498   [40] Jyrkama M, Sykes J, Normani S (2005) Recharge Estimation for Transient Ground Water Modeling.
499   Ground Water 40:638–648.

500   [41] Horowitz A (2001) The Jordan Rift Valley; Ballkema: Rotterdam, The Netherlands, p. 730.

501   [42] Odeh T, Geyer S, Rödiger T, Siebert C, Schirmer M (2013) Groundwater chemistry of strike slip faulted
502   aquifers: the case study of Wadi Zerka Ma'in aquifers, north east of the Dead Sea. Environ Earth Sci
503   70:393–406.