ESTIMATION OF BED AND BANK LEVELS OF AN IRRIGATION CANAL NETWORK TOWARDS ACCURATE GROUNDWATER MODELING OF THE NILE DELTA AQUIFER

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ABSTRACT

An integrated groundwater modelling in Nile Delta (ND) region requires the bed and water levels of the irrigation canals to properly describe groundwater recharge, groundwater–surface-water interaction, and seawater intrusion. The main objective of this study is to present a new methodology to estimate the bed and bank levels of the irrigation canals within the ND by using Global Mapper (GM) and Google Earth Pro (GEP). GM was used to estimate bed levels based on the available digital elevation model and then GEP was integrated with available Landsat imagery of ND to estimate the bank levels at the cross sections same as for bed-level. The results exhibited that the difference between the measured and estimated bed levels of Damietta Branch ranged from 0.03 to 0.70 m and from 0.01 to 0.80 m for bank levels. Overall coefficient of determination of the estimated and measured bed bathymetry along ten cross sections ranged from 0.79 to 0.98 and the Root Mean Square Error (RMSE) for ten cross sections were between 0.61 and 1.37 m with an average 0.88 m indicating a reasonable performance. The application results of the proposed method are useful for accurate groundwater simulation of the ND aquifer.

Keywords: Irrigation canals; Nile Delta, Bed level, Bank level, Global Mapper, Google Earth Pro.
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1 INTRODUCTION

The Nile Delta (ND) canals receive about 35.5 billion m^3 of surface water annually, which is used for agriculture, industrial activities, and water supply. The intensive irrigation canal networks recharge the aquifer in two ways: infiltration of excess irrigation water and seepage from canals and drains (Anon, 1980; El Kashef, 1983). The main source of recharge of the ND aquifer is percolation from agriculture and infiltration from irrigation and drainage network canals (Wahaab and Badawy, 2004). (Mabrouk et al. 2013) stated that the water levels of the irrigation canals have significant influence on the groundwater recharge of the ND aquifer system.

The major portion of annual overall groundwater recharge of ND aquifer is provided by the direct seepage from the Nile River, the huge network of irrigation canals and from excess irrigation water (Kashef, 1983). In that study, water budget concept was applied, despite of the lack of irrigation canals bed and bank levels, to estimate recharge from irrigation canals and irrigation water, which was about

6.4 km^3/year. The annual seepage of surface water to groundwater system in the ND aquifer was estimated to equal to 2.5 km^3/year (Dahab, 1993). The effect of freshwater recharge on seawater intrusion in the ND aquifer is also observed in the upper layer around the Nile River and its branches (Sherif, 2012). The seawater intruded towards the ND aquifer with the decrease of water levels of canals (Abdelaty et al., 2014). However, those previous studies considered groundwater recharge based up to ten canals in groundwater modelling despite of the high density of irrigation network in ND region that consists of more than 200 canals (MWRI, 1954). There was obviously a shortage in the data of bed and water levels of the ND canals, although this data of bed, bank level and bed slope is necessary for more accurate representation, simulation of groundwater modelling to understand interaction between surface water and groundwater in the ND aquifer system.

Determination of water level in canals requires information of bed and banks levels which are not available for irrigation canals network of the ND in the previous studies. Nowadays, many different tools are available to estimate bed level and bank levels of rivers. GM is a geographic information system (GIS) software package developed by Blue Marble Geographics Company (Poirier, 2014). Global Mapper was used by different authors to determine the longitudinal bed slope of streams also to draw cross section of canals. Abdul-Hameed et al. (2014) used Global Mapper to create cross sections along Upper Euphrattes River (In Iraq) to calculate the optimal height and number of small dams. Saher et al. (2015) used Global Mapper to create different cross section through DEM to select the best site for earthen reservoir to reduce the flash flood hazard of hill torrents; and second, to make use of flood water as a source of irrigation by conserving flood water in an earthen reservoir. Ham (2008) also used Global Mapper to estimate the bed level of a catchment area when designing a large-scale spate-irrigation system in Ethiopia. Borkowski et al. (2011) used Global Mapper to estimate the length, elevation, difference and slope angle of selected elements of a local slide within the Zbyszyce landslide. Google Earth uses digital elevation model (DEM) data collected by NASA's Shuttle Radar Topography Mission (SRTM), (Mohammed et al. 2013). The standard error of estimating the SRTM in the ND equals 9.502 m, (Bolten and Waldhoff, 2010). Ssegane and Tollner (2007) used Google Earth to derive elevations in the Nzoia basin (Kenya) and to calculate the differences between Google Earth and GPS.

From the literature review, there was shortage of bed level, bed slope, bank level and upper canal width data for irrigation canals network in the ND, while it was needed for building an integrated groundwater modelling of the ND aquifer and accurate simulation of interaction between surface water and groundwater. Consequently, this paper presents a new method combining GM and GEP to estimate the bed and bank levels of irrigation canals including major rivers by taking the large ND region as a case study. We additionally present the first study using GM to estimate the bathymetry of different cross sections in canals and calibrate the method by comparing its output with the cross sections surveyed on ground.

2 STUDY AREA AND DATA COLLECTION

The ND is located in the northern part of Egypt (30°05'–31°30'N, 29°50'–32°15'E), covering an area of about 25,000 km^2 as shown in Fig. 1. The numbers from 1 to 17 that indicated on Figure 1 refer to the canals with names as given below. The ND is bounded by the Mediterranean Sea to the north, Nile River to the south, Suez and Ismailia canals to the east, and El Nobaria Canal to the west (MWRI, 2013). The names and directions of the irrigation canal networks in the central part of the ND were identified based on maps from National Water Research Centre NWRC (RIGW, 2015) and (NWRP, 2005), and those in western and eastern regions of the ND were based on (Roest, 1998). The bed and bank levels used in the calibration are available for the Damietta Branch and Mareis El Gamal Canal from Hydraulic Research Institute, National Water Research Centre of Egypt, (HRI, 2000) and (HRI, 2004). (Zaghloul, 2006) studied the morphological changes of (Damietta and Rosetta Branch) in the Delta Barrages area to show the degradation in the downstream area which extends about 10 km along the two branches. He concluded that there was increasing in Branches width and depth along the study reach. The bed bathymetry points of Damietta Branch changed since 1982 to 2001 in a range from 0.0 to 2.0 for the five cross sections which reflect the bed morphology change, Moussa and Aziz (2007). Increasing the discharge in Damietta Branch from 60 to 80 million m^3/day causes the bed level increase from 1.0 to 3.8m due to morphological changes (Negm et al. 2011). The available high-resolution (30 × 30 m) DEM of the ND was obtained from the ASTER GDEM site. The ASTER GDEM is distinguished with a higher resolution, fewer missing data, and better topographic representation than the SRTM DEM, especially in high steep slopes mountainous areas (Nakano, 2013). The second version of the ASTER GDEM (GDEM2) is scheduled for release by NASA and METI in mid-October, 2011. The improvements in the GDEM2 result from acquiring 260,000 additional scenes to improve coverage, a smaller correlation kernel to yield higher spatial resolution, and improved water masking by variety of sources, including Landsat, the SRTM water body dataset, and images in Google Earth, (ASTER GDEM V2.0 Validation team, 2011). The standard error of the ASTER GDEM estimating in the ND equals 9.101 m and R^2 equals 0.968 (Ebaid, 2014). The bed bathymetry of the cross sections of reaches 1 and 2 of the Damietta Branch were collected from (HRI, 2000) and were used in the calibration of the used method.

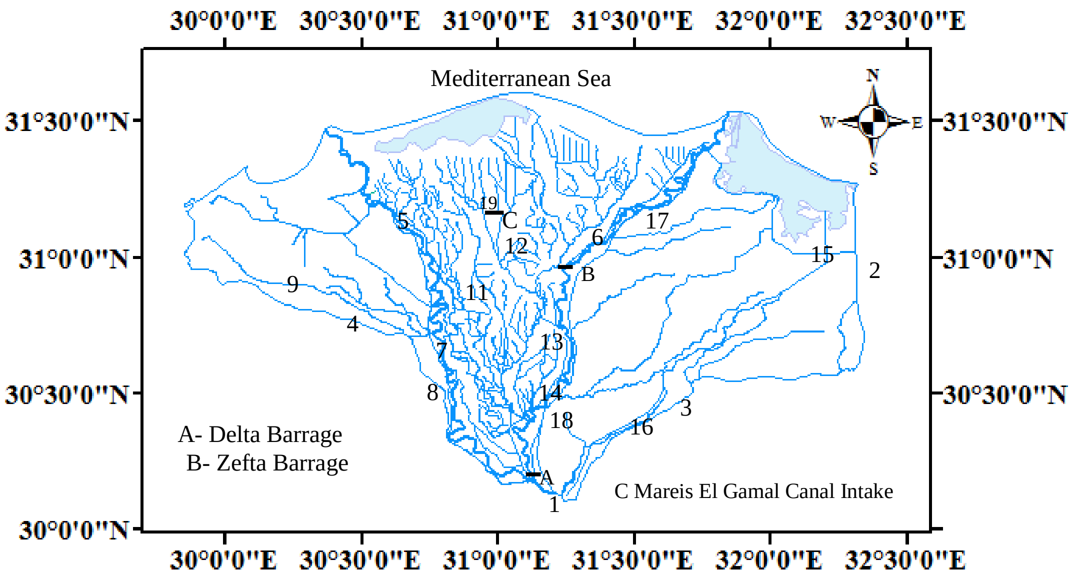

Figure 1. Digitized map of irrigation canal networks in the ND region: Nile River (1), Suez (2), Ismailia (3), El Nobaria (4), Rosetta Branch (5), Damietta Branch (6), EL Rayah-Nasseri (7), El Beheira (8), El Mahmoudia (9), El Menoufia (10), El Baguria (11), El Kasid (12), El Shibin (13) and El Atf (14), El Salam (15), Ismailia, El Sharkawiya (16), El Mansouria (17), El Tawfiki (18) and Mareis El Gamal Canal (19)

3 METHOD

The proposed method follows seven steps to estimate of the bed and bank levels of the irrigation canal networks in the ND, as shown in Fig. 2:

1. The irrigation canal networks were digitized using GEP and the path of each canal saved as a KML file, which was placed within a file of its region. The total number of irrigation canals was 192. Figure 1 shows the irrigation canal networks in the ND.

2. 3D path profile/ line of sight tool through GM software version 16.0 was used with the available high-resolution (30 × 30 m) DEM of the ND (ASTER GDEM) to estimate the bed level of the Damietta Branch at cross sections at 2-km intervals starting at the Delta barrage (Reach 1, 93-km length) and Mareis El Gamal Canal (19) at 1-km interval (12km) starting at its intake.

3. The tool shows elevation profile for a specific untitled path through GEP was used to estimate the bank level of the Damietta Branch at each of the same 2-km intervals and Mareis El Gamal Canal at 1-km interval (12km) using available Landsat imagery.
4. The method for estimating the bed bathymetry, bed level, and bed slope was calibrated by comparison with measured values obtained from (HRI, 2004), NWRC, and those estimated by GM for the same cross sections.
5. The method for estimating the bank level and upper canal width was calibrated by comparison with measured values obtained from (HRI, 2004), NWRC, and those estimated by GEP for the same cross sections.
6. Each canal was divided into small parts according to its length (max. length = 5.0 km for long canals and 2.0 km for short canals).
7. The method was applied to all irrigation canals in the ND region to determine bed level and bank level.

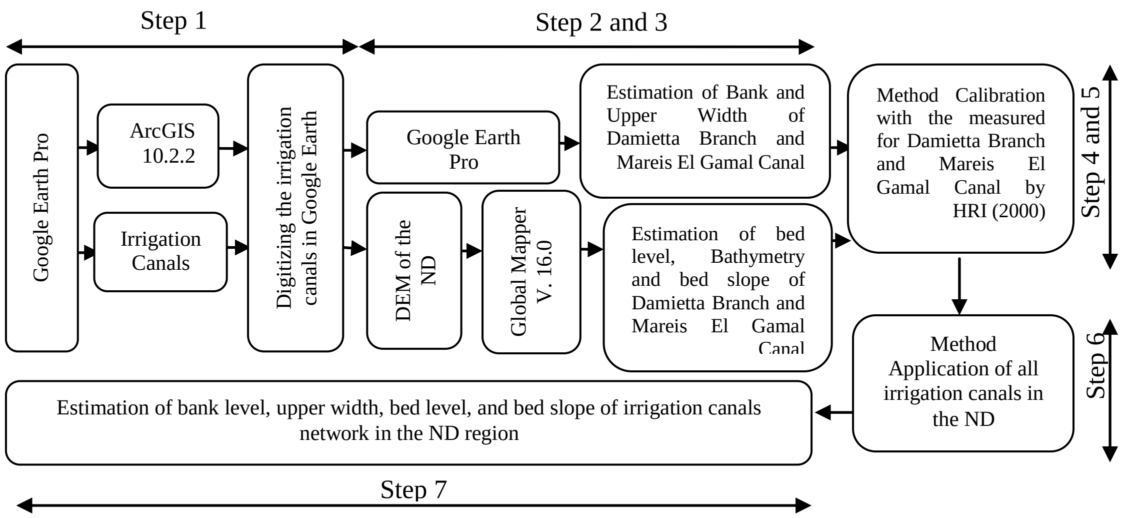

Figure 2. Bathymetry estimation using Global Mapper and Google Earth Pro

4 APPLICATION

The method was calibrated by comparing the estimated values for the bed level, bathymetry of the bed, bank level, upper water width, and bed slope with values obtained in the field for Reach 1 of the Damietta Branch (from Delta Barrage to Zefta Barrage) and Mareis El Gamal Canal based on HRI (2000, 2004). The bathymetry of 10 cross sections of the Damietta Branch was plotted at different points on the bed at 5.0-m intervals from the left bank of the cross section.

In Google Earth, the Damietta branch was divided into 2-km segments and Mareis El Gamal Canal was divided into 1-km interval (12km) At each cross section, a node point was drawn and saved as a KML file. The KML files were input into the GM software to determine the position of each cross section accurately. Through the GM interface, the cross-section tool was used to determine the bed level at the required cross section. The bed slope was calculated for each 2-km segment of Reach 1 of the Damietta Branch (93 km) also was calculated for each 1-km segment for Mareis El Gamal Canal. This was taken as the elevation difference between the start and finish points of the segment divided by the distance (2 km). The average bed slope was calculated for each canal and equals to the average slope for all segments of the canals. The calibrated method was applied to the irrigation canals networks in the ND region. GM software, based on the available DEM 30mx30m of the ND region, was used to estimate the bed level and bed slope of the Nile River, Damietta Branch, Rosetta Branch, main canals, branch canals, and distributed canals. GEP was used to estimate the bank level and upper canal width of irrigation canals networks. Estimation of bathymetry by using GM for small canals having top water width less than 30m need a higher resolution DEM, which is not available for the ND region.

5 RESULTS

The RMSE and R^2 values calculated for all bed bathymetry points of the cross sections are summarized in Table 1. The correlation coefficients between the estimated and measured bed bathymetry points indicate strong correlations (0.79 – 0.96), especially for cross sections 1–7 and 9. The correlation coefficients are 0.96 and 0.95 for C1 and C2 respectively (Figures 3A and B). The values of RMSE are 0.75m and 0.70 m for C1 and C2 respectively.

Table 1. Results of the calibration method for Reach 1 of the Damietta Branch and Mareis El Gamal Canal

NO.	Estimated Item		Distance from Delta Barrage (km)	Tool	Supported images	Measured in the field (2000)	R^2	RMSE
1	Bathymetry of cross section of Damietta branch (at each 5.0 m from the left side of the bank)	C1	4.70	GM	ASTER GDEM Version 2.0 of the ND (used the archived images from 2000 to 2010)	Hydraulic Research Institute of Egypt (HRI, (2000))	0.96	0.75 m
		C2	4.86				0.95	0.70 m
		C3	81.5				0.94	1.22 m
		C4	83.5				0.97	0.61 m
		C5	6.40				0.92	0.83 m
		C6	6.51				0.94	0.93 m
		C7	89.0				0.96	0.77 m
		C8	77.5				0.79	1.37 m
		C9	94.0				0.92	0.89 m
		C10	94.8				0.86	0.76 m
2	Bed level of Damietta branch		At each 2.0 km for reach 1 (93km length)	GM	ASTER GDEM Version 2.0	(HRI, (2000)) and (HRI, (2004))	0.94	0.31 m
	Bed Level of Mareis El Gamal Canal		At each 1.0 km for head regulator (12km)	GM	ASTER GDEM Version 2.0	(HRI, (2000))	0.95	0.71m
3	Average longitudinal bed slope of Damietta branch		For each segment with length 2.0 km for reach 1 (93km length)	GEP	ASTER GDEM Version 2.0	(HRI, (2000)) and (HRI, (2004))	0.94	0.45 cm/km
	Average longitudinal bed slope of Mareis El Gamal Canal		For each segment with length 1.0 km		ASTER GDEM Version 2.0	(HRI, (2000))	0.80	5.5 cm/km
4	Bank level of Damietta branch		At each 2.0 km for reach 1 (93km length)	GEP	Landsat image of the ND 2000	(HRI, (2000))	0.87	0.685 m
	Bank level of Mareis El Gamal Canal		At each 1.0 km for reach		Landsat image of the ND 2000		0.80	0.43m
5	Upper width of Damietta branch		At each 2.0 km for reach 1 (93km length)	GEP	Landsat image of the ND 2000	(HRI, (2000))	0.99	1.02 m
	Upper width of Mareis El Gamal Canal		At each 1.0 km for reach		Landsat image of the ND 2000		0.87	0.74m

Fig. 3A shows that the difference between in bed decreased at canal bed near to the center line of cross sections while it increases moving away from the centre line. In Fig. 3B, the difference decreased in the bottom and right side while increased in the left side of the bathymetry cross section. Results for cross sections 5, 6, 7, 9 and 10 were similar to for cross sections C1 and C2 and show the R^2 equal to 0.92, 0.94, 0.96, 0.92 and 0.86 respectively and RMSE equal to 0.83, 0.93, 0.77, 0.89 and 0.77 m respectively. Fig. 3C shows strong correlation where the R^2 equals 0.94. The RMSE for all points bathymetry in cross section C3 equals 1.22m. The similar result was observed for cross section 8 where the R^2 and RMSE equal 0.94 and 1.22 respectively. Fig. 3D also shows a good matching and strong correlation between the measured and estimated bathymetry where the R^2 and RMSE equal 0.97 and 0.61 m respectively.

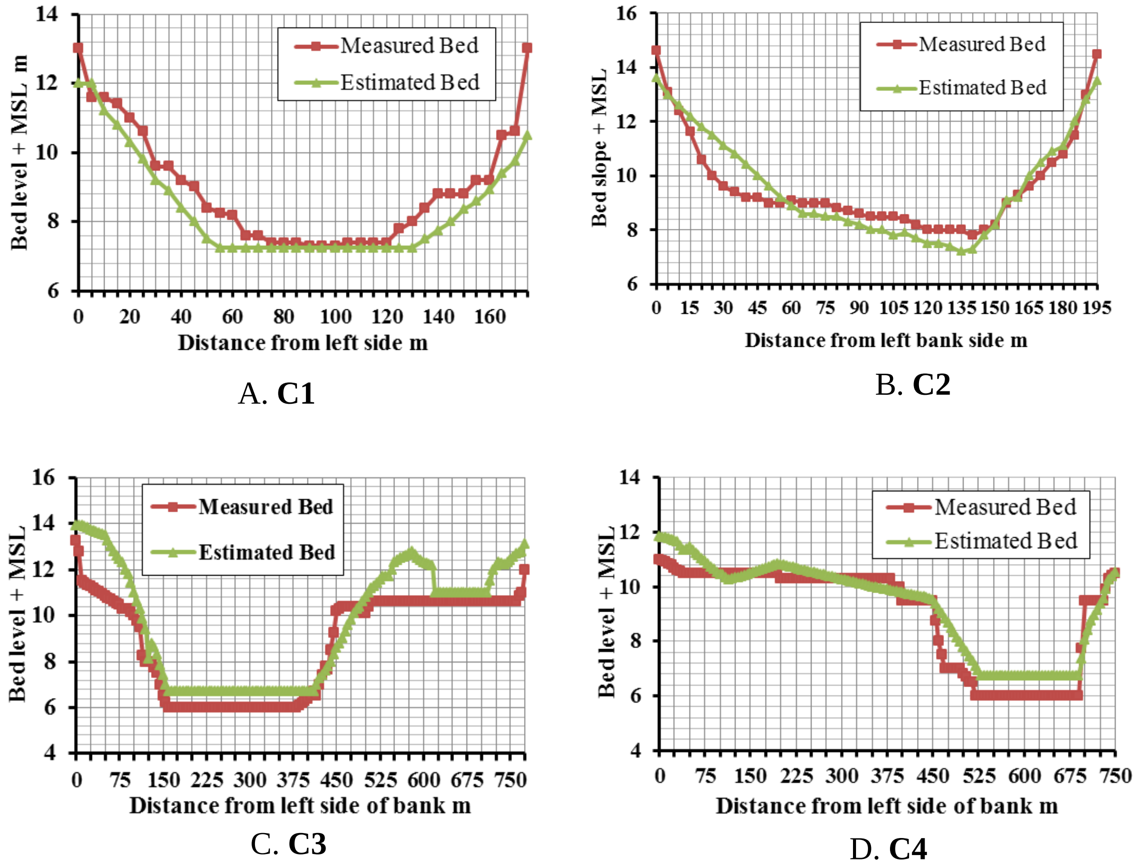

Figure 3. Estimated and measured bathymetry of cross sections (C1, C2, C3 and C4- see Table I)

For Damietta Branch, the maximum and minimum bed differences between the measured values and those estimated by GM were 0.70 and 0.03 m, respectively. The RMSE for the 45 cross sections was 0.31 m and the correlation coefficient was 0.94, as shown in Fig. 4. Fig. 4 also shows the comparison between the measured bank levels and upper width with those estimated by GEP. The maximum and minimum differences between the two values were 0.80 and 0.01 m, respectively. The RMSE between the two values was 0.685 m and the correlation coefficient is 0.87. The correlation coefficient indicates strong correlation between the estimated and measured bank levels. The average estimated and measured bed slopes for Reach 1 of the Damietta Branch were 8.67 and 8.22 cm/km, respectively, with RMSEs of 0.45 cm/km. The upper width and the bed slope of Reach 1 of the Damietta Branch were estimated for the same cross sections measured by (HRI, 2000). The RMSE and R^2 values for upper width were 1.02 m and 0.99, respectively.

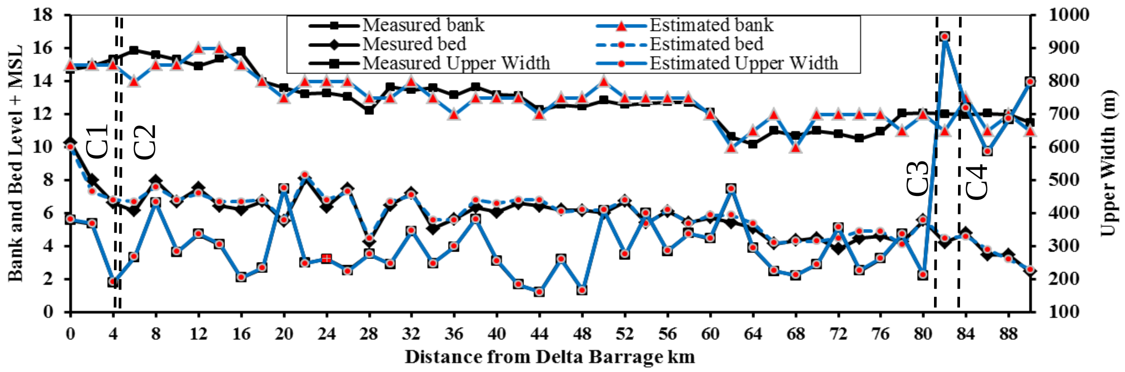

Figure 4. Comparison between measured and estimated values of bank, bed levels and upper width of for Damietta Branch

Fig. 5 presents the comparison between the measured and estimated bed, bank levels and upper width of Mareis El Gamal Canal. The maximum and minimum bed differences between the measured values and those estimated by GM are 1.44m and 0.0 m, respectively where equal 0.77m and 0.03m consequently for bank level estimated by GEP. The RMSE values of 12 cross sections are 0.71m and 0.43m for bed and bank level respectively. R^2 for the same cross sections equal 0.95 and 0.80 for bed and bank level respectively. The average estimated and measured bed slopes for Mareis El Gamal Canal are 15.50 and 10.0 cm/km, respectively, with RMSEs of 5.50 cm/km. The upper width and the bed slope of Mareis El Gamal Canal were estimated for the same cross sections measured by (HRI, 2000). The RMSE and R^2 values for upper width are 0.74m and 0.87, respectively. The correlation coefficient between the measured and estimated values for Damietta and Mareis El Gamal canal indicates strong linear relationship. The RMSE for eight of the cross sections of Damietta Branch was <1.0 m, where as it was 1.22 and 1.37 m for C3 and C8, respectively (Table I). The increase in RMSE for the bed bathymetry of Damietta Branch for these two cross sections is due to differences in the times between the acquisition of the measured data (HRI, 2000) and data of the ASTER GDEM Version 2.0. The ASTER GDEM version 2.0 was released on October 17, 2011 based on archived data from 2000 to August 2010 (Urai et al., 2012).

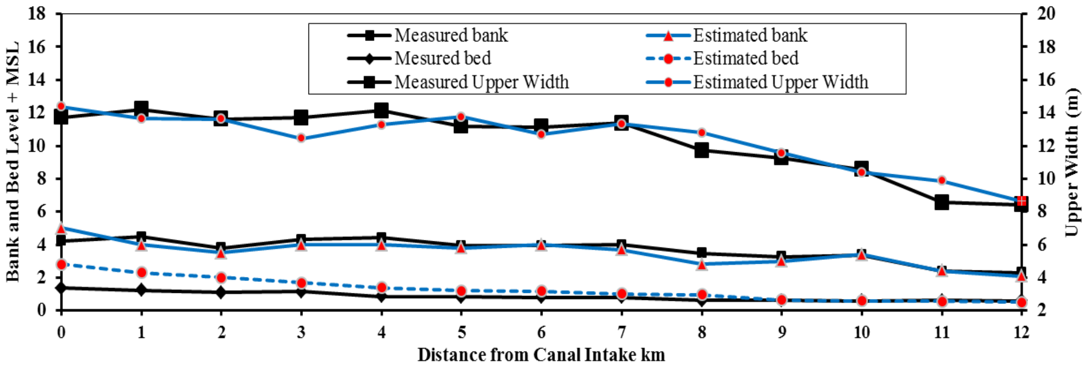

Figure 5. Comparison between measured and estimated values of bank, bed levels and upper width of for Mareis El Gamal Canal

The bed and bank levels of canals decrease towards the north according to the topography of the ND (Table 2). El Raiah El Tawfiq bed level starts with 16.5m above mean sea level and ends with 0.0 m with 9.813 cm/km an average bed slope, while the bank level starts with 20.5 m and ends with 2.0 m + MSL. The bed slope of irrigation canals decreases with the increase of the degree of canals. The results of bed slope were matched with the specifications of Egyptian code of water resources and irrigation works (NWRC, 2003) and (Sakla, 1999) for design of irrigation canals. The bed slope of Bahr Shibin, El Doon and Abou Halal canals equals 5.0, 10.5 and 18.6 cm/km respectively reflecting the canal degree. On the other hand, the length and upper width of irrigation canals increase with the increase of canal degree. The length of El Nobaria, East Kahnat and Hamed meneis canals equal 110, 44 and 14 km respectively, where the upper canals width equal 79, 38 and 9.3 m respectively. Fig. 6 shows the estimated bed and bank levels of the El Bagoria Canal, which lies in the central part of the ND. The bed level starts at 13.1 m and ends at 0.0 m + MSL, and the bank level starts at 16.6 m and ends at 2.0 m above MSL. The longitudinal average bed slope is 8.812 cm/km.

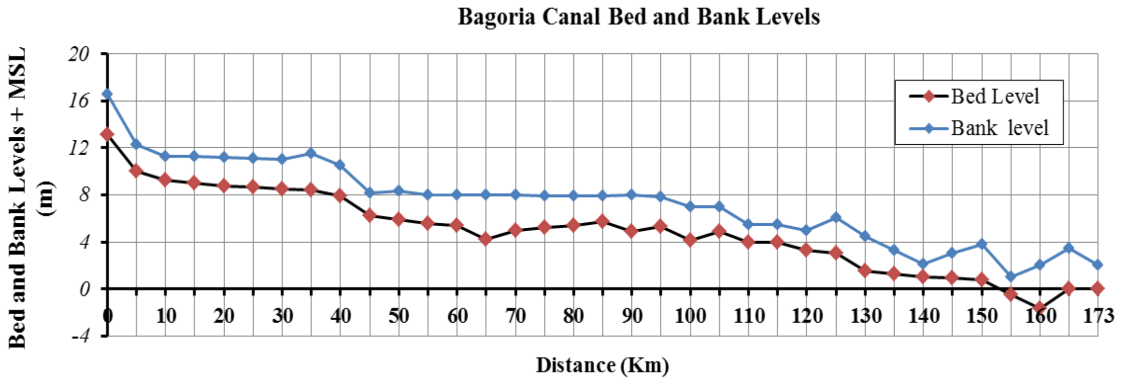

Figure 6. Estimated bed and bank levels of Bagoria canal- central Nile Delta

Table 2. Bed level, bed slope, length, upper canal width, and bank level for samples of irrigation canal networks in the ND region

Name of canals	**Bed level (m) +MSL**	**Bank level (m) +MSL**	**Average bed slope (cm/km)**	**Length of canal (km)**	**Upper canal width (m)**	**Type of canal**
Samples of irrigation canals in the central part of the ND						
Bahr Shebin	4.0,3.5	7.2,7.0	5.00	16.8	49	Main canal
Atf canal	11,8.0	14.2,12.0	10.00	32.2	34.1	Main canal
El Halwanei canal	2.2,0.0	5.0,1.0	11.10	19.50	12.4	Branch canal
El Doon canal	10.4,8.3	2.1,1.2	10.50	18.5	16.4	Branch canal
Abou Halal canal	1.8,0.2	3.8,2.2	18.60	8.6	9.5	Distributed canal
Mansour canal	2.5,1.4	5.4,2.5	13.75	8.00	4.50	Distributed canal
Samples of irrigation canals in the Eastern part of the ND						
EL Raiah El Twafiq	16.5,0.0	20.5,2.0	9.813	160.0	49.0	Raiah
Wadei canal	7.5,0.0	10.4,1.5	7.938	80.0	65.10	Main canal
Bahr Sageir	5.0,0.0	8.5,1.3	7.667	65.0	35.0	Main canal
Boaheia canal	9.8,3.7	12.8,6.0	10.40	50.0	21.50	Main canal
Samples of irrigation canals in the Western part of the ND						
El Raiah El Beheriei	15.2,7.5	19.0,12.5	8.563	80.00	87.0	Raiah
El Nobaria canal	7.0,1.0	11,3.0	6.909	110.0	79.0	Main canal
East Kahnat canal	5.0,2.2	8.6,5.0	6.044	44.0	38.0	Branch canal
canal project Naser	0.9,-1.0	3.4,-2.0	16.923	11.50	19.00	Distributed canal
Hamed meneis canal	1.4,-1.0	4.5,-2.0	17.133	14.00	9.30	Distributed canal

6 DISCUSSION

Notwithstanding the good comparison between the method results and the surveying data in Damietta Branch and Mareis El Gamal Canal by (HRI, 2000), obviously differences of bed, bed slope, upper width and bank level remain. These errors of bed bathymetry, bed slope and bed level estimation can be attributed to four reasons. Firstly the fact that the used DEM was produced for an average data of several years from 2000 to 2010 while the measured data is for a particular year (2000). Secondly, it relates to the corresponding error of the elevation data of ASTER GDEM in the

ND region. Thirdly, the available used ASTER GDEM of the ND has a resolution 30x30m. Finally, it relates to the morphology change of Damietta Branch in the ND. Errors of estimation of bank level and upper canal width in Damietta Branch and Mareis El Gamal Canal were related to morphology change and the corresponding error of STRM DEM used by Google Earth.

The R^2 between the measured and estimated bed level, bed slope, upper width, and bank level of Damietta Branch and Mareis El Gamal Canal showed strong correlation. The discrepancy between the estimated and the measured bed results of Mareis El Gamal canal partially due to the morphological change of bed. The present hydraulic structures was changing the flow regime at it and downstream of the structures. The impact of these structures is lesser towards the tail of the canal for example 5 hydraulic structures out of 12 existed in the first 5.0 km. In spite of the above short coming in the presented method made it possible to estimate the bed and bank levels of irrigation canals network to be available for researchers for further and future research also building an integrated groundwater model of the ND. The maximum difference between the measured and estimated values of bank and bed levels for Damietta Branch equal 0.80m and 0.70m respectively where equal 0.77m and 1.44m for Mareis El Gamal canal. The results of method application for Mareis El Gamal Canal (small canal) based on RMSE and R^2 show its suitability and acceptance for estimation the bank level and upper width, where a higher resolution DEM is recommended to use whenever available of the ND to enhance and increase its suitability and acceptance for estimation the bed level of small canals (with upper width less than 30m) which 113 out of 200 canals. To enhance the method application and results, it is recommended to use a higher resolution and recently produced DEM of the ND whenever available along with recent field data.

7 CONCLUSIONS

The paper presented a new methodology, which combines GM and GEP, to estimate the bed and bank levels of irrigation canals network in the ND, Egypt, to be available for researchers for further and future research, which can also be applied for any other area. The presented method was used also to estimate the bathymetry of canals cross sections. The R^2 values for 10 cross sections of bed bathymetry in the Damietta Branch show strong correlation. The RMSE values for the bathymetry cross sections ranged from 0.61 to 1.37 m, only two cross sections were higher than 1m, which reflects the change in the time of acquisition of the field measurement data by HRI and the data of the ASTER GDEM. The difference in bed level for Damietta Branch ranged from 0.03 to 0.70 m, and from 0.01 to 0.80 m for bank level where ranged from 0.0 to 1.44m and 0.03 to 0.77 m For Mareis El Gamal Canal, respectively. The R^2 values of bed level, bed slope, upper width, and bank level for Damietta Branch and Mareis El Gamal Canal showed strong correlation between the estimated and measured values. The results of the calibration of the method of Damietta Branch and Mareis El Gamal Canal indicated its suitability and acceptance based on RMSE and R^2 of bed, bed slope, upper width and bathymetry cross section. GM and GEP software are proven to be powerful tools for estimating bed and bank levels of irrigation canals. It is recommended that bed and bank levels of irrigation canal networks, estimated using GM and GEP, could be used to include irrigation canal networks when building 3D groundwater models of the ND aquifer.

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