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Tracking Morphological Change Trends along Nile River in Egypt Using Hydrological Data Analysis

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Abstract

Riverbed morphological changes occur due to water flows. The flow energy dislocates riverbed sediment particles and transports them downstream. Such transport changes the riverbed shape over time causing unrecognized bed degradation and aggradation. Therefore, this study aims to track morphological change trends along Nile River 4th reach over past 50 years using hydrological data analysis to identify the future trends, especially in light of the constantly repeated annual discharge cycle. The 4th reach starts at Assuit Barrages and ends at Delta barrages. Data of 10 years between 1962 and 2010 of daily discharges and corresponding water stages at eight gage stations along the study reach were collected. Another additional annual flow to the reach amounting to 7.5 % of the original flow was considered. Seventy-five stage-discharge rating curves were established for the gage stations. Regression quadratic polynomial formulae were established for the curves and used to determine the water stage "WS" values at the eight gage stations for discharges of 37, 70, 100, 140, and 181 Mm^3/d over the ten years. Considering 1962 as a reference year, the WS profiles due to the discharge cases were computed and compared. The WS rise and fall were interpreted as possible riverbed morphological changes. The study revealed aggradation through the reach upstream segment between Maabda and Sheikh Fadl Gages, then severe degradation at the middle segment between Beba and Bani Sweif, then aggradation at the downstream segment between Koraymat and Leithy. Finally, the results were verified by comparison of past and present bathymetries.

Keywords: Morphological Changes; Degradation; Aggradation; Stage-Discharge Rating Curves; Lag Time.

Abbreviations:
D.S = Downstream;
GS = Gage Station;
HAD = High Aswan Dam;
Mm^3/d = Million cubic meters/day;
+MSL = Above Mean Sea Level;
NRI = Nile Research Institute;
PPM = Particle Per Million;
OAD = Old Aswan Dam;
U.S = Upstream; and
WS = Water Stage.

1. Introduction

Riverbed morphological changes (aggradation/degradation) usually occur as a result of flow fluctuations and/or external human interventions. These changes create unstable/unbalanced stream channels that can negatively impact infrastructure, property, water quality, and ecosystems (**Johnson, 2016**) **[1]**. Moreover, they may have severe impacts on river activities such as river storage capacity, inland navigation, water intakes, berths, bridge piers, bank protection, crossing of cables and pipelines underneath the riverbed. Therefore, it is of paramount importance to track and monitor such changes closely and study the resulting river regime periodically to be able to cope with the negative impacts before they worsen. In order to understand and identify the present and future river regime trends, it is necessary to investigate the river morphology over past long periods of time. This can be done by the analysis of the historical hydrologic and bathymetric situations and data records.

As the flow D.S the Old Aswan Dam "OAD" was completely controlled after the High Aswan Dam (HAD) operation, the daily discharge releases and corresponding water levels were regulated to meet various requirements D.S "OAD". As a result, most of the annual sediment load was deposited within the HAD reservoir. This caused the suspended sediment through the river to enormously drop from 4000 PPM before "HAD" to 40 PPM **(Ismail, 1990) [2]**. Accordingly, the river channel responded by trying to establish a new regime that can cope with the drastic changes in the inflow water and sediment rates. These eventually forced the river to change its plan form, meandering pattern, sinuosity and even the cross section geometry at several locations. Moreover, the analysis of the historical records of the daily discharges released D.S the Nile River main barrages before and after "HAD" construction revealed a sharp decline in water stages. **Fig. 1**

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shows an example of the condition D.S Old Assuit barrages (the location is shown in **Fig. 2**) before and after the dam construction. The daily flows that used to be released through the branched irrigation canals U.S those barrages were accordingly reduced. Accordingly, the water levels U.S the barrages had to be raised to maintain an adequate flow discharge. On the other hand, the bathymetric surveys conducted along the Nile River by the Nile Research Institute "NRI" revealed bed degradation and local scour D.S the existing barrages. To mitigate such morphological conditions as well as to generate hydropower, new barrages were constructed D.S each set of the existing ones. Accordingly, the new Esna, Naga-Hammady and Assuit barrages were constructed in years 1994, 2008 and 2018 respectively.

The present study aims to track the morphological change trends that occurred along the Nile River 4th reach by analyzing the hydrological data of past 49 years (between years 1962 and 2010). This may help recognize the future trends, especially in light of the constantly repeated annual discharge cycle. It is worth mentioning that tracking morphological changes is of great importance for navigation as it tells about the locations that may experience river aggradation that causes navigation bottlenecks which obstruct and disrupt the navigation traffic. Also, riverbed aggradation (sediment deposition) near canal entrances may hinder or stop water from flowing into canals.

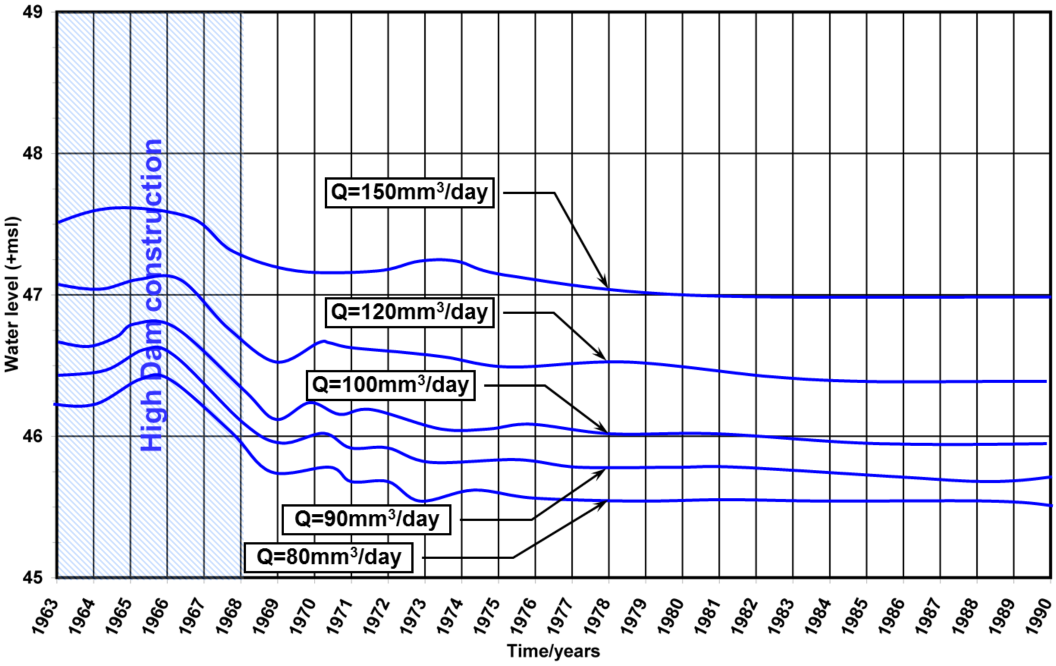

Fig. 1: Water Stage Decline D.S Assuit Barrages directly after HAD Construction (**Source: NRI Data Base, 2022 [3]**).

Another major HAD side effect was detected at the river banks D.S OAD due to the annual reduction in suspended sediment. Bank erosion at some vulnerable locations along the river had occurred causing large scale bank failure. In order to cope with such a condition, a comprehensive field survey from Aswan to Cairo was carried out by NRI in 1981 and 1988 with the aid of 1:10000 topographic maps. The eroded locations and lengths along the river were spotted and the needed river protection works such as revetments or spur dikes were constructed. The bank erosion data collected were utilized to protect about 250 Km length of the eroded banks between year 1988 and 1999. This was funded by the Nile River Protection and Development Project "**RNPD**" in (**1989**) **[4]** and the Social Fund for Development Project "SFD". Selection of the protection works was based on the erosion degree and the environmental impacts on the national income which led to saving a lot of valuable fertile lands.

The extensive field measurements along the various Nile River reaches at the time revealed the existence of significant morphological changes along the fourth reach. This was attributed to its long extension (about 408.250 Km) and the extensive human interventions that took place throughout after HAD operation because of the sense of security that was felt by the dam **(Nasr Hekal, 2003) [5]**. The maximum recorded flow release D.S Assuit barrages was tremendously reduced from 910 Mm^3/d prior to HAD in year 1963 to only 181 Mm^3/d after HAD construction.

Several attempts to estimate the morphological changes that were likely to take place along the Nile River after HAD construction were carried out. They mainly focused on the conditions just U.S and D.S the main barrages. They were arbitrarily conducted due to the shortage of real data and field measurements under different flow conditions D.S HAD.

Applying the tractive force equation, **Fathy (1956) [6]** used his own experience about the ultimate Nile River slope and concluded that the river bed would drop from 14 to 16 m below OAD and D.S each main barrage. **Mustafa (1957) [7]** used another theoretical approach that expected the drop in river bed would be 8.5, 9.0, 7.0 and 6.5 m D.S OAD, Esna, Naga-Hammady and Assiut barrages by years 1986, 1991, 2006 and 2036 respectively.

Another attempt was carried out by the Swedish consultant for the Ministry of Water Resources and Irrigation "**VBB**" in **(1960) [8]** which expected that the maximum degradation D.S OAD and the main barrages would be in the range of 3.0 to 4.0 m. Moreover, two studies conducted by (**Shalash 1965 [9] and 1988) [10])** revealed an empirical sediment transport formula which was applied to estimate the degradation rate as a few centimeters per year. The ultimate drop in bed and water levels was estimated to reach between 1.0 and 2.0 m after years ranging between 100 and 300 D.S each water structure (barrages).

The ultimate degradation D.S OAD was estimated by **Simons (1965) [11]** as 3.0 to 4.0 m. Also, the Hydro-projects **USSR (1975) [12]** estimated the ultimate degradation in bed and water levels D.S the hydraulic structures to vary between 3.5 and 11.0 m during a period ranging between 100 and 700 years.

El-Ansary (1976) [13] used the "Critical Tractive Stress Theory" under the condition that the river after HAD construction would be fed with clear water. Knowing the critical tractive stress and the hydraulic relationships for any river reach, the ultimate stable slope in that reach - under any anticipated condition - can be worked out. Therefore, the corresponding bed decline D.S each main barrage was worked out. The achieved results by **El-nsary (1976) [13]** for the estimated degradation D.S the main river barrages in 1974 and the ultimate values as well as the corresponding affected distance D.S each barrage are listed in **Table 1**.

Table 1: Estimated Degradation after HAD Construction (**Source: Ahmed, 2015 [15]**).

No.	Location	Estimated bed lowering (m)		Affected distance (km)	
		1974	Future	1974	Future
1	D.S Esna barrages	0.60	5.20	43	193
2	D.S Naga-Hammady barrages	0.45	5.20	50	180
3	D.S Assiut barrages	0.75	7.80	185	190

In **Table 1**, the word "future" refers to the ultimate values that might be achieved after an indefinite number of years after HAD operation. Knowing the total lengths of the 2^{nd}, 3^{rd}, and 4^{th} Nile River reaches, this means that the estimated ultimate degradation by **El-Ansary (1976) [13]** would cover 100%, 100% and 46% of the three mentioned Nile River reaches respectively. However, the studies conducted by **(Ahmed 2014 [14] and 2015 [15])** for the first and second Nile River reaches respectively after half century of HAD construction revealed the occurrence of general aggradation along the two river reaches. Therefore, El-Ansary's estimation seems to be unrealistic with respect to the actual conditions.

Although the above studies were conducted to predict the HAD side effects regarding bed degradation and aggradation especially D.S the main hydraulic structures (barrages), no detailed results for specific periods and locations have been determined so far along any of the Nile River reaches. This may be due to the fact that those studies didn't utilize enough real hydrological data of several years before and after HAD. Therefore, the present study is carried out to use the available hydrological data to explicate the corresponding morphological conditions that may have taken place along the 4^{th} reach of the Nile River after HAD.

2. Materials and Methods

2.1. Study Reach

Reach "4" of the Nile River was taken as a study reach. It extends for 408.250 Km from D.S the new Assuit barrages at Km 545.250 D.S OAD to U.S Delta barrages at km 953.500. It is the longest reach among the river reaches. **Fig. 2** shows the map of Egypt and the Nile River reaches.

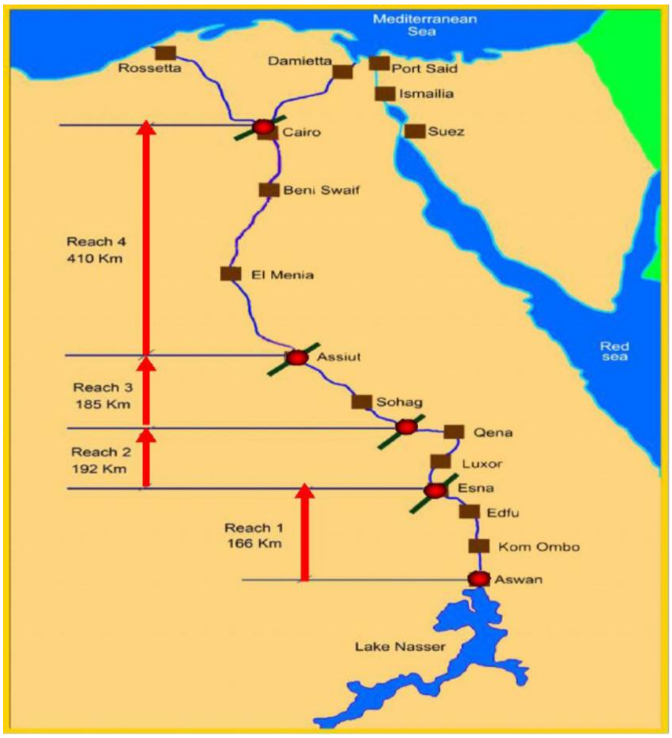

Fig. 2: Reach (4) of the Nile River and the Main Waterway.

2.2. Data Collection

The collected hydrological data consists of 10 sporadic years of the daily water discharges released D.S Assuit barrages and their corresponding water stage records at eight gage stations between years 1962 and 2010. The data is tabulated as given in **Table 2**. The data partially cover about 50 years in steps started in year 1962 before "HAD" construction till year 2010. The hydrological condition at years 1962 - 1963 was considered as a reference, while the condition at every 10-year interval starting from years 1979 - 1980 till years 2009 - 2010 represented the situation after "HAD" construction. The hydrological data was employed in such a way as to give an average value for each two successive years. This procedure was decided due to the unavailability of complete hydrological data of other years.

Table 2: Daily Hydrological Data (Q & WS) D.S Assuit Barrages.

Year	Daily Inflow (Q) D.S Assuit Barrages	Daily water stages at gage stations D.S "OAD" (Km)							
		El-Maabda Km 576.20	El-Mandara Km 612.10	El-Menya Km 687.55	Sheikh Fadl Km 735.25	Beba Km 789.0	Beni Sweif Km 808.60	El-Koraymat Km 839.15	El-Leithy Km 873.70
1962	Y/D	Y/D	Y/D	Y/D	N/A	Y/D	Y/D	Y/D	Y/D
1963	Y/D	Y/D	Y/D	Y/D	Y/D	Y/D	Y/D	Y/D	Y/D
1979	Y/D	Y/D	Y/D	Y/D	Y/D	Y/D	Y/D	Y/D	Y/D
1980	Y/D	Y/D	Y/D	Y/D	Y/D	Y/D	Y/D	Y/D	Y/D
1989	Y/D	Y/D	Y/D	Y/D	Y/D	Y/D	Y/D	Y/D	Y/D
1990	Y/D	Y/D	Y/D	Y/D	Y/D	Y/D	Y/D	Y/D	Y/D
1999	Y/D	Y/D	Y/D	Y/D	Y/D	Y/D	Y/D	Y/D	Y/D
2000	Y/D	N/A	Y/D	Y/D	Y/D	Y/D	Y/D	Y/D	Y/D
2009	Y/D	N/A	N/A	Y/D	Y/D	Y/D	Y/D	Y/D	Y/D
2010	Y/D	N/A	Y/D	Y/D	Y/D	Y/D	Y/D	Y/D	Y/D

Where: **Y/D** Available Data for the whole year
N/A Unavailable Data

The used gage stations cover a total distance of 297.50 Km which represents 72.8 % of the study reach length with intervals ranging between 19.60 and 75.45 km. Selection of the used gages was assigned in such a way as not to be influenced by the generated flow turbulence D.S Assuit barrages and the backwater curve U.S Delta barrages. In order to establish the water surface profile along the study reach, the corresponding hydrological data at the case of minimum and maximum discharge releases D.S Assuit barrages were utilized. 2-D numerical model **HEC-RAS**

(USACE, 2016 [16]) was used to calculate the water stages corresponding to the two provided flow conditions as shown in **Fig. 3**. The D.S boundary condition for the applied model was the water stages U.S Delta barrages corresponding to the two cases of the maximum and minimum flow releases (181 and 25 Mm^3/day respectively).

Fig. 3 reveals that the backwater curve extends for about 52 km U.S Delta barrages at releasing the minimum flow discharge D.S Assuit barrages. This means that El-Leithy gage station which is situated at km 873.70 D.S "OAD" [79.3 km U.S Delta barrages] is not affected.

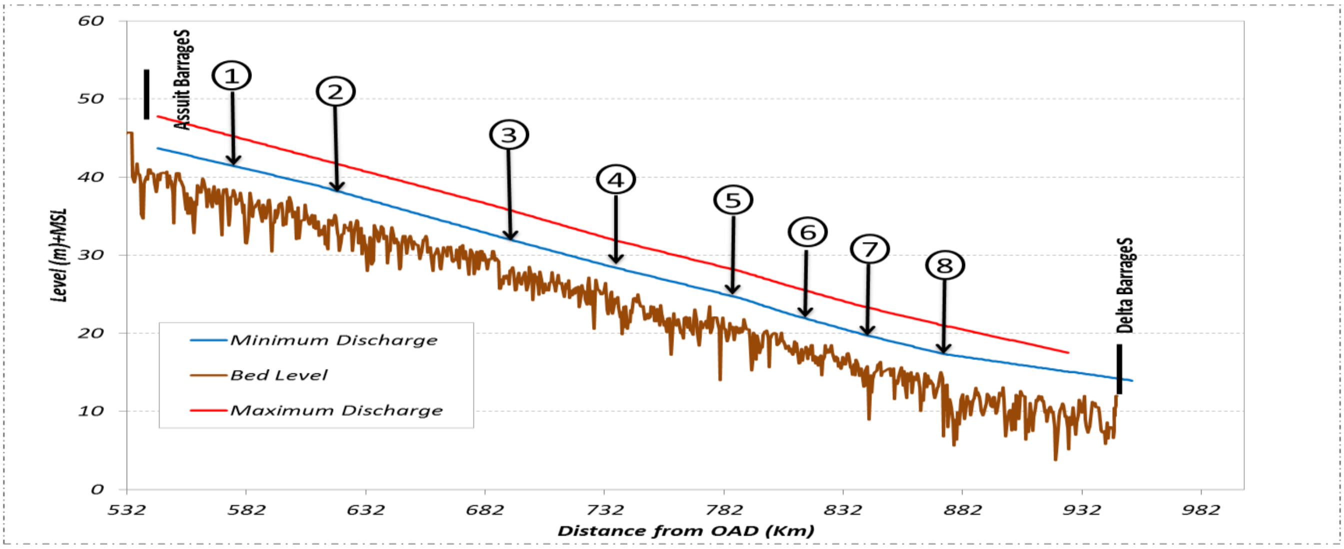

Fig. 3: Locations of the used gage stations along the study reach.

2.3. Proposed Methodology

In order to achieve the paper objective which is tracking the morphological changes along Nile River reach 4 over past 49 years between 1962 and 2010, **Fig. 4** shows a flow chart for the proposed methodology

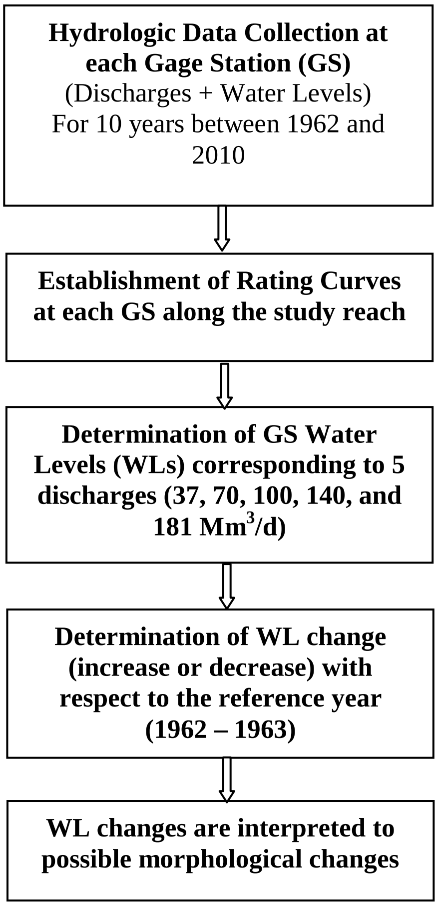

Fig. 4: Proposed methodology for tracking the morphological changes along Nile River reach 4.

Moreover, the applied procedure considered the following points:

1. The hydrological flow situation at years 1962 and 1963 is taken as a reference for the river condition before HAD construction;
2. The post-HAD hydrological condition is analyzed every 10-year interval from years (1979 – 1980) to (2009 – 2010);
3. The percent increase in flow discharge U.S Delta barrages (the end of the study reach) compared with the discharge released D.S Assuit barrages is separately estimated on an annual basis. Then, the corresponding increase at any location along the reach is determined as a percentage of the reach total length;
4. As the study reach extends for 408.250 Km, the lag time - which is the time required for the flow discharge released D.S Assuit barrages to reach Delta barrages – is considered in calculations. Knowing that the lag time through the fourth reach varies from 4 to 8 days during high and low releases respectively, a 6-day lag time period is adopted as an average value according to the Water Distribution Sector of the Egyptian Ministry of

Water Resources and Irrigation "MWRI". Consequently, the corresponding lag time to any location along the reach is first assigned as a percentage of the total lag time at the end of the study reach; and

5. Locations of the gage stations considered in the study should cover a considerable length of the study reach. The stations selected are within the gradually varied flow zone U.S the backwater curve of Delta barrages. In this way, the start and end of the study reach will be lying in a region that will not be influenced by the generated flow turbulence D.S Assuit barrages or the backwater curve U.S Delta barrages.

2.4. Estimation of the Additional Discharge Flowing into the Study Reach

According to a Nile River Water Quality Management study **(NAWQAM, 2003) [17]**, the Nile River main waterway (see **Fig. 2**) receives additional waste water discharges from 67 agricultural drains. Only eleven of which pour their waste water into the study reach. In addition, the reach receives other additional daily amounts of water from several tributary outfalls and El-Ibrahemia canal tail. It is worth mentioning that El Ibrahemia canal branches off the River main waterway directly U.S Assuit Barrages at the west bank and dispose of the remaining water into the study reach at somewhere U.S El Ekhsas gage station. Therefore, the average annual additional inflow to the study reach is first determined and then, added to the study reach original discharge that is released D.S Assuit Barrages.

In order to determine the annual percentage of the additional discharge released into the study reach, three hydrological data sets were analyzed. The daily flow discharge records D.S Assuit barrages were used as an upstream boundary for the three sets, while the corresponding downstream records were measured at two gage stations namely; El Ekhsas and U.S Delta Barrages as illustrated in **Fig. 5**. These data sets were as follows:

1. The daily measured flow discharges within some selective days during 17 years from 1973 to 1989 at El-Ekhsas site which is located at Km 857.00 D.S OAD [at Km 96.500 U.S Delta barrages]. These field measurements were carried out by the "General Directorate for Nile River Degradation and Evaporation" which was established in 1970, then renamed to the High Aswan Dam Side Effects Research Institute "HADSERI" in 1975, then to the current Nile Research Institute "NRI" in 1990;
2. The daily flow records at El-Ekhsas during 1976, 1981, 1989 and 1990; and
3. The daily flow records U.S Delta barrages during 1979, 1989, 1999 and 2009.

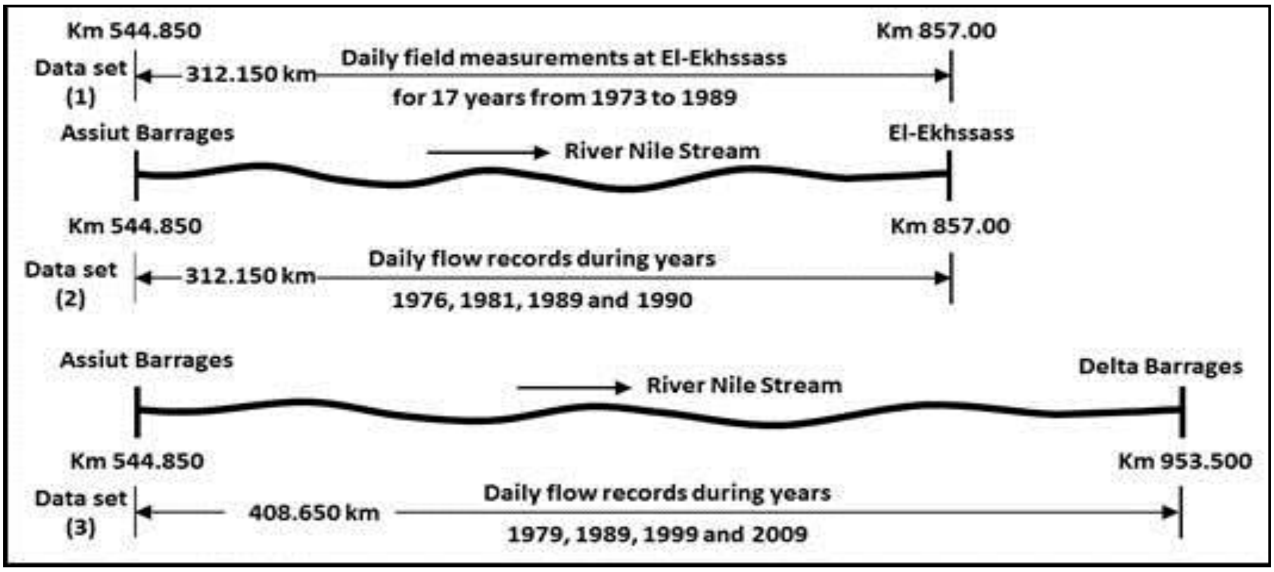

Fig. 5: Downstream boundaries for the three hydrological data sets.

It is worth mentioning that the lag time was considered during the calculation of the annual percentage of the additional flow for the three data sets as listed in **Table 3**. The table reveals an average additional flow value of 7.5 % of the released flow D.S Assuit Barrages. This percent value was distributed linearly along the study reach as shown in **Fig. 6** and **Table 4**.

Table 3. Annual additional discharge value for the three data sets.

No.	Year	Number of annual field discharge measurements (days)	Total discharge release D.S Assuit Barrages (10^6 m^3)	Total discharge measurements at El-Ekhsas (10^6 m^3)	Resulting Additional Discharge (10^6 m^3)	Percent additional discharge (%)
Data Set (1)						
1	1973	46	4633.4	4867.86	234.46	5.06
2	1974	49	4927.4	5191.60	264.20	5.36
3	1975	36	3492.0	3863.29	371.29	10.63
4	1976	35	3293.0	3538.25	245.25	7.45
5	1977	19	1961.0	2130.71	169.71	8.65
6	1978	42	4636.0	5086.37	450.37	9.71
7	1979	43	4643.0	4914.43	271.43	5.85
8	1980	37	3550.0	3724.70	174.70	4.92
9	1981	25	2560.0	2626.47	66.47	2.60
10	1982	30	3242.0	3448.31	206.31	6.36
11	1983	34	3675.0	3807.22	132.22	3.60
12	1984	8	858.5	896.83	38.33	4.46
13	1985	46	4134.5	4584.73	450.23	10.89
14	1986	36	3595.5	3887.83	292.33	8.13
15	1987	36	3106.0	3784.75	678.75	21.85
16	1988	31	2771.0	3225.05	454.05	16.39
17	1989	18	1653.0	1722.30	69.30	4.19
Average annual value			3337.14	3605.92	268.78	**8.05**
Data Set (2)						
1	1976	366	34516.3	36978.0	2461.7	7.13
2	1981	365	37954.0	39824.0	1870.0	4.93
3	1989	365	32075.8	34472.1	2396.3	7.47
4	1990	365	31041.2	33871.5	2830.3	9.12
Average annual value			33896.82	36286.4	2389.58	**7.05**
Data Set (3) at Delta Barrages						
1	1979	365	39685.00	42166.37	2481.37	6.25
2	1989	365	32048.30	34805.30	2757.00	8.60
3	1999	365	46126.20	49356.63	3230.43	7.00
4	2009	365	39773.93	42852.30	3078.37	7.74
Average annual value			39408.36	42295.15	2886.79	**7.33**

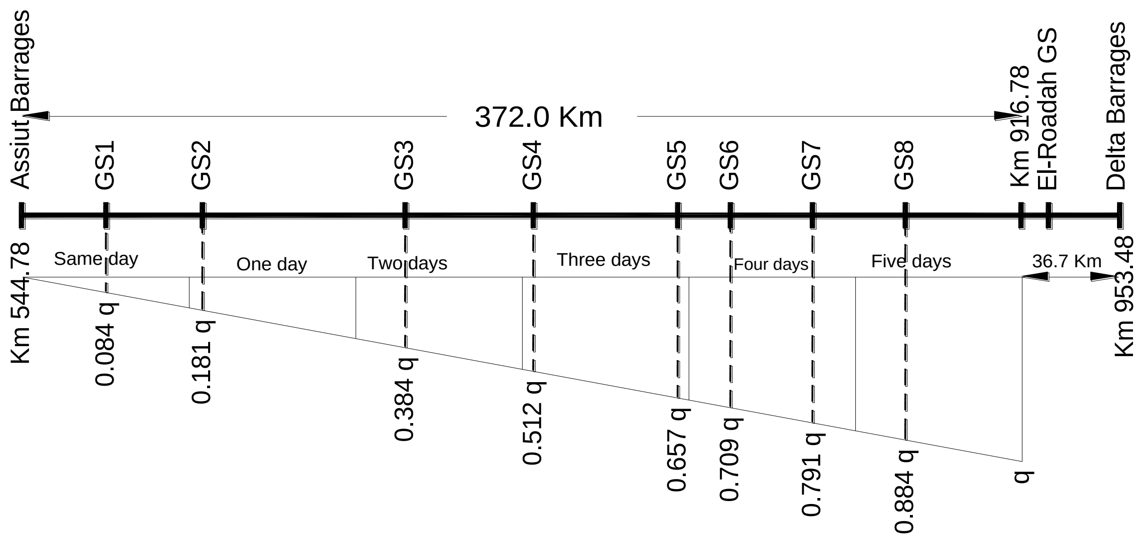

Fig. 6: Lag time and annual percent additional discharge at various gage stations.

Table 4. Annual percent additional discharge and lag time at various gage stations along the study reach.

Gage Station	Name	Location D.S "OAD" (Km)	Lag time (day)	Distance D.S Assuit Barrages. (Km)	Percent additional discharge (I_q)	Percent increase (%)
GS1	El-Maabda	576.20	No lag	31.42	0.084 q	0.63 %
GS2	El-Mandara	612.10	One day	67.32	0.181 q	1.36 %
GS3	El-Menya	687.55	Two days	142.77	0.384 q	2.88 %
GS4	El-Sheikh Fadl	735.25	Three days	190.47	0.512 q	3.84 %
GS5	Beba	789.00	Three days	244.22	0.657 q	4.93 %
GS6	Beni Sweif	808.60	Four days	263.82	0.709 q	5.32 %
GS7	El-Koraymat	839.15	Four days	294.37	0.791 q	5.93 %
GS8	El-Leithy	873.70	Five days	328.92	0.884 q	6.63 %

It should be noted that "q" is the annual percent additional discharge at the D.S end of the study reach (36.70 km U.S Delta Barrages GS). This additional discharge was taken as an average of the average annual additional discharge values of the three data sets shown in **Table 3**. It was found to be equal to 7.5 % of the discharge released D.S Assuit Barrages. As an illustrative example to show how this percentage is distributed along the study reach, suppose that a discharge of 140 Mm^3/day is released D.S Assuit Barrages. This discharge will arrive at the end of the Study Reach (El Roda GS) equal to 149.282 Mm^3/day. Now, the additional discharge "q" of 9.282 Mm^3/day will be distributed along the Reach at the various gage stations in different (portions) shares depending on the distance intervals between the stations. For example, the percent discharge addition at El Maabda GS will be equal to [(31.42/372) * q] which is [0.084 * q] and so on as shown in **Table 4**. This additional discharge is supposed to arrive at El Maabda on the same day assuming a flow velocity ranging between 0.40 to 0.80 m/s. So, there is no lag time. In the same way, the percent discharge addition at El Mandara GS will be equal to [(67.32/372) * q] which is [0.181 * q]. This will arrive after one day and so on.

3. Analysis and Results

Using the historical annual hydrologic data (Q and WS) of the selected ten past years between 1962 and 2010 as well as the estimated additional discharge value (I_q), seventy-five rating curves were plotted for the gage stations along the study reach. **Fig. 7** shows a sample rating curve at El Menya gage station in 1990. Then, the data of each rating curve were used to create a good-fit regression line (a trend line) with an R-squared value and a mathematical formula. It is worth remembering that the R-squared value is defined as a statistical measure of how close the data are to the fitted regression line. This value varies between zero and one. The bigger the R^2 is, the better the data fit is. The resulting mathematical formula is a correlation of Q_{total} and WS. These formulas were used to determine the WS value corresponding to any Q_{total}, where $Q_{total} = Q + I_q$. **Table 5** displays sample mathematical formulas obtained at two gage stations at different years, as well as the WS values calculated using these formulas and corresponding to five different discharge values released D.S Assuit Barrages (37, 70, 100, 140, 181) Mm3/day. The aim of selecting these values was to examine the water stage trends (rise and/or fall) at every gage station round the year and over the selected ten years. This helps to identify the general trends of the water surface profiles along the study reach and hence, interpret the general trends of the riverbed morphological changes.

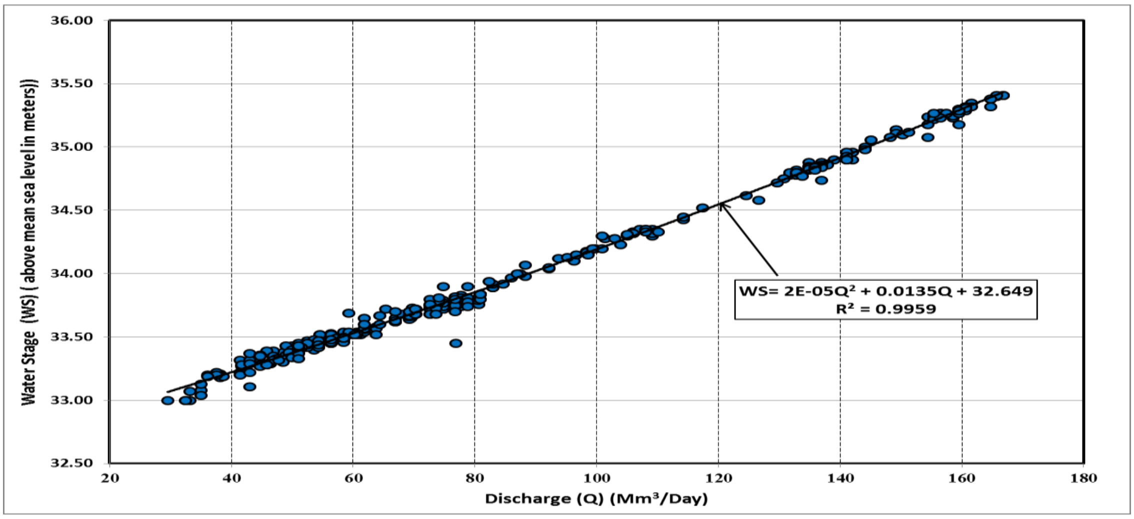

Fig. 7: A sample rating curve at El Menya gage station in 1990

Table (5): Sample obtained WS Results at some Gage Stations**.**

GS & Year		Eq. No.	Mathematical formula of fitted regression line	R^2	Q = 37		Q = 70		Q = 100		Q = 140		Q = 181	
					Q_{total} = Q + I_q (Mm³/d)	WS (m)	Q_{total} = Q + I_q (Mm³/d)	WS (m)	Q_{total} = Q + I_q (Mm³/d)	WS (m)	Q_{total} = Q + I_q (Mm³/d)	WS (m)	Q_{total} = Q + I_q (Mm³/d)	WS (m)
El-Maabda	1962	1	WL = -1.044E-05Q^2 + 1.827E-02Q + 4.194E+01	0.994		42.61		43.18		43.67		44.31		44.93
	1963	2	WL = -1.131E-05Q^2 + 1.912E-02Q + 4.160E+01	0.981		42.30		42.89		43.41		44.07		44.71
	1979	3	WL = -1.622E-04Q^2 + 5.975E-02Q+ 3.902E+01	0.928		41.02		42.43		43.41		44.22		44.59
	1980	4	WL = 3.696E-05Q2 + 9.969E-03Q + 4.201E+01	0.946	37.233	42.43	70.441	42.89	100.630	43.38	140.882	44.15	182.140	45.04
	1989	5	WL= 5.799E-05Q2 - 2.295E-03Q + 4.360E+01	0.912		43.59		43.72		43.95		44.43		45.08
	1990	6	WL = 1.666E-04Q2 - 8.296E-03Q + 4.256E+01	0.951		42.48		42.79		43.39		44.70		46.51
	1999	7	WL = 7.096E-05Q2 - 2.228E-03Q + 4.338E+01	0.803		43.39		43.57		43.87		44.47		45.30
El-Mandara	1962	11	WL= -1.342E-05 Q2 + 1.994E-02Q + 3.878E+01	0.961		39.51		40.13		40.67		41.34		42.00
	1963	12	WL = -1.454E-05 Q^2 + 2.131E-02Q + 3.834E+01	0.979		39.12		39.78		40.35		41.36		41.77
	1979	13	WL = -1.279E-04 Q^2 + 4.636E-02Q + 3.729E+01	0.951		38.85		39.95		40.71		41.29		41.60
	1980	14	WL = 4.058E-05 Q^2+ 5.289E-03Q + 3.966E+01	0.95	37.502	39.91	70.950	40.23	101.358	40.60	141.904	41.23	183.457	41.96
	1989	15	WL = 1.325E-05 Q^2+ 1.393E-02Q + 3.899E+01	0.976		39.53		40.04		40.53		41.23		41.98
	1990	16	WL = 3.443E-05 Q^2 + 1.164E-02Q + 3.906E+01	0.983		39.54		40.05		40.58		41.41		42.32
	1999	17	WL = 4.393E-05 Q^2+ 1.074E-02Q + 3.885E+01	0.943		38.98		39.19		39.47		41.26		40.61
	2000	18	WL = 9.913E-05 Q^2 - 1.166E-03Q +	0.94		39.50		39.81		40.28		41.24		42.44

			3.941E+01											
	2010	20	WL = 5.339E-06 Q^2 + 9.426E-03Q + 3.970E+01	0.873		40.06		40.39		40.71		41.15		41.60

The above calculated WSs at the selected gage stations were utilized to determine the average WS values for every two consecutive years as listed in **Table 6**. The average WS of years (1962-1963) at each gage station, for the different discharge cases, was, then, considered as the condition before HAD construction (the reference WS). As for the average values for each two other consecutive years (1979-1980, 1989-1990, 1999-2000, 2009-2010) at each gage station, they were computed to demonstrate the average WS after HAD construction.

Table 6. Average water stages at every two consecutive years.

GS	Year	Different discharges (Mm^3/day)				
		37	70	100	140	181
Maabda	1962-1963	42.45	43.03	43.54	44.19	44.82
	1979-1980	41.73	42.66	43.40	44.19	44.81
	1989-1990	43.04	43.26	43.67	44.57	45.79
	1990	43.39	43.57	43.87	44.47	45.30
Mandra	1962-1963	39.31	39.95	40.51	41.35	41.89
	1979-1980	39.38	40.09	40.66	41.26	41.78
	1989-1990	39.54	40.05	40.56	41.32	42.15
	1999-2000	39.24	39.50	39.87	41.25	41.53
	2010	40.06	40.39	40.71	41.15	41.60
El Menya	1962-1963	32.62	33.27	33.84	34.55	35.25
	1979-1980	32.77	33.60	34.27	34.95	35.59
	1989-1990	33.17	33.71	34.22	34.94	35.68
	1999-2000	33.08	33.56	34.09	35.01	36.00
	2009-2010	32.66	33.37	34.04	34.96	35.90
Sheikh Fadl	1963	28.50	29.11	29.65	30.31	30.98
	1979-1980	28.44	29.30	29.98	30.67	31.35
	1989-1990	29.05	29.55	30.02	30.70	31.40
	1999-2000	28.97	29.50	30.05	30.92	31.83
	2009-2010	28.77	29.45	30.09	30.99	31.90
Beba	1962-1963	25.39	25.79	26.15	26.62	27.08
	1979-1980	24.29	25.12	25.78	26.54	27.16
	1989-1990	24.92	25.40	25.86	26.52	27.23
	1999-2000	24.87	25.24	25.70	26.47	27.46
	2009-2010	24.36	25.05	25.70	26.59	27.52
Bani Sweif	1962-1963	23.55	24.00	24.39	24.90	25.39
	1979-1980	22.32	23.36	24.15	24.98	25.56
	1989-1990	22.93	23.59	24.16	24.90	25.62
	1999-2000	23.18	23.63	24.13	24.92	25.87
	2009-2010	22.91	23.62	24.26	25.09	25.93
Koraymat	1962-1963	19.72	20.34	20.88	21.56	22.23
	1979-1980	19.80	20.76	21.51	22.32	22.94
	1989-1990	20.42	20.91	21.39	22.08	22.84
	1999-2000	20.49	20.94	21.45	22.25	23.24
	2009-2010	20.29	20.98	21.63	22.50	23.43
Leithy	1962-1963	17.20	17.79	18.31	18.97	19.61
	1979-1980	17.26	18.16	18.87	19.65	20.26
	1989-1990	18.15	18.50	18.86	19.42	20.06
	1999-2000	18.09	18.49	18.96	19.74	20.72
	2009-2010	17.93	18.58	19.19	20.06	21.00

In order to obtain the fluctuation values in WSs at the different gage stations at the selected different discharges, the previous WSs computed at the reference year (1962-1963) were subtracted from those of each of the other two consecutive years as shown in **Table 7**. It is worth noting that the negative and positive values in **Table 7** indicate fall and rise of water stage respectively with respect to the WS condition in 1962-1963 before HAD construction. And as an illustrative example for the water surface condition that occurred in (1979-1980, 1989-1990, 1999-2000, and 2009-2010), **Fig. 8** shows the water surface profile fluctuations at each gage station that correspond to the five discharge cases released D.S Assuit Barrages.

Table 7. WS fluctuations with reference to year (1962-1963) at gage stations for five different discharges.

GS	Year	Different cases of discharges (Q) released D.S Assuit Barrages					Remarks
		37	70	100	140	181	
Maabda	1962-1963	0.00	0.00	0.00	0.00	0.00	Ref., Year
	1979-1980	-0.72	-0.37	-0.15	0.00	-0.01	
	1989-1990	0.59	0.22	0.13	0.38	0.98	
	1990	0.94	0.54	0.32	0.28	0.48	
Mandara	1962-1963	0.00	0.00	0.00	0.00	0.00	Ref., Year
	1979-1980	0.07	0.14	0.15	-0.09	-0.10	
	1989-1990	0.22	0.09	0.05	-0.03	0.27	
	1999-2000	-0.08	-0.45	-0.64	-0.10	-0.36	
	2010	0.75	0.44	0.20	-0.20	-0.28	
El-Menya	1962-1963	0.00	0.00	0.00	0.00	0.00	Ref., Year
	1979-1980	0.15	0.33	0.43	0.40	0.33	
	1989-1990	0.55	0.44	0.38	0.39	0.43	
	1999-2000	0.46	0.29	0.25	0.47	0.75	
	2009-2010	0.04	0.10	0.20	0.41	0.65	
Sheikh Fadl	1963	0.00	0.00	0.00	0.00	0.00	Ref., Year
	1979-1980	-0.06	0.19	0.34	0.36	0.36	
	1989-1990	0.55	0.44	0.38	0.39	0.41	
	1999-2000	0.47	0.39	0.40	0.61	0.84	
	2009-2010	0.27	0.34	0.44	0.68	0.92	
Beba	1962-1963	0.00	0.00	0.00	0.00	0.00	Ref., Year
	1979-1980	-1.10	-0.68	-0.37	-0.08	0.07	
	1989-1990	-0.47	-0.39	-0.29	-0.10	0.15	
	1999-2000	-0.52	-0.55	-0.46	-0.15	0.38	
	2009-2010	-1.03	-0.74	-0.45	-0.03	0.44	
Beni Sweif	1962-1963	0.00	0.00	0.00	0.00	0.00	Ref., Year
	1979-1980	-1.23	-0.64	-0.24	0.08	0.16	
	1989-1990	-0.62	-0.41	-0.23	0.00	0.22	
	1999-2000	0.25	0.05	-0.03	0.02	0.26	
	2009-2010	-0.64	-0.38	-0.13	0.20	0.54	
Koraymat	1962-1963	0.00	0.00	0.00	0.00	0.00	Ref., Year
	1979-1980	0.08	0.42	0.63	0.76	0.71	
	1989-1990	0.69	0.57	0.52	0.52	0.61	
	1999-2000	0.77	0.61	0.57	0.69	1.01	
	2009-2010	0.57	0.65	0.75	0.94	1.20	
Leithy	1962-1963	0.00	0.00	0.00	0.00	0.00	Ref., Year
	1979-1980	0.06	0.37	0.56	0.68	0.65	
	1989-1990	0.95	0.71	0.55	0.45	0.45	
	1999-2000	0.89	0.70	0.65	0.77	1.11	
	2009-2010	0.73	0.79	0.89	1.09	1.39	

By careful consideration of **Fig. 8**, you can observe the following:

1. The general trend of the water stage fluctuations along the study reach is almost sinuous with respect to the situation in 1962-1963 for the five selected discharge cases.
2. For the discharge cases, the water fluctuations rise at Maabda then fall at Mandara then rise at El Menya then rise again at sheikh Fadl then fall at Beba then fall again at Bani Sweif then rise at Koraymat and again at El Leithy. This trend occurred during the comparison years 1989-1990, 1999-2000, and 2009-2010 except year 1979-1980 where the fluctuations start with fall then rise at Mandara, El Menya, and Sheikh Fadl then fall at Beba and Bani Sweif then rise again at Koraymat and El Leithy.
3. The trends of the WS fluctuations are almost similar in all discharge cases;
4. It is clear that the river segment between El Menya and El Shekh Fadl and the segment between Koraymat and El Leithy experience a WS rise, while the segment between Beba and Bani Sweif has a WS fall. This means that the U.S and D.S river segments experience a WS rise while the middle segment has a WS fall;
5. The maximum WS rise occurred in 2009-2010 during the release of discharge 181 Mm3/d at El Lethy gage station and was equal to 1.39 m, while the minimum WS fall took place in 1979-1980 during the release of discharge 37 Mm^3/d at Bani Sweif and was equal to 1.23 m;

The above WS fluctuations can be interpreted to possible riverbed morphological changes assuming that the WS slope is the same as that of the riverbed. Accordingly, it can be said that the U.S segment of the study reach extending from D.S Assuit barrages until Sheikh Fadl may have experienced river bed aggradation that reached a maximum value of 0.92 m at Sheikh Fadl during the release of the maximum discharge 181 Mm3/d. As for the middle segment between Beba and Bani Sweif, it is clear that it had severe degradation that reached a maximum value of 1.23 m at Bani Sweif during the release of the Minimum discharge 37 Mm3/d. Regarding the D.S segment between Koraymat and El Leithy, it is also clear that the riverbed had aggradation thicker than that occurred in the U.S segment. The value of this aggradation reached 1.39 m during the maximum water discharge (181 Mm3/d).

4. Result Verification

In order to verify the above interpretation of the results, the riverbed situations at El Mandara, El Menya, Beba and El-Leithy gage stations were investigated in years 1982 and 2003. Using the bathymetric maps produced by "NRI" in those two years, two cross sections at each location were extracted and compared as shown in **Fig. 9**. The results revealed that the cross section of year 2003 at El Mandara, and Beba had undergone degradation, while those of the same year had experienced aggradation at El Menya and El Leithy. These results support the result interpretation obtained above and shown in **Fig. 8** considering the closeness of years 1980 and 2000 to years 1982 and 2003 respectively.

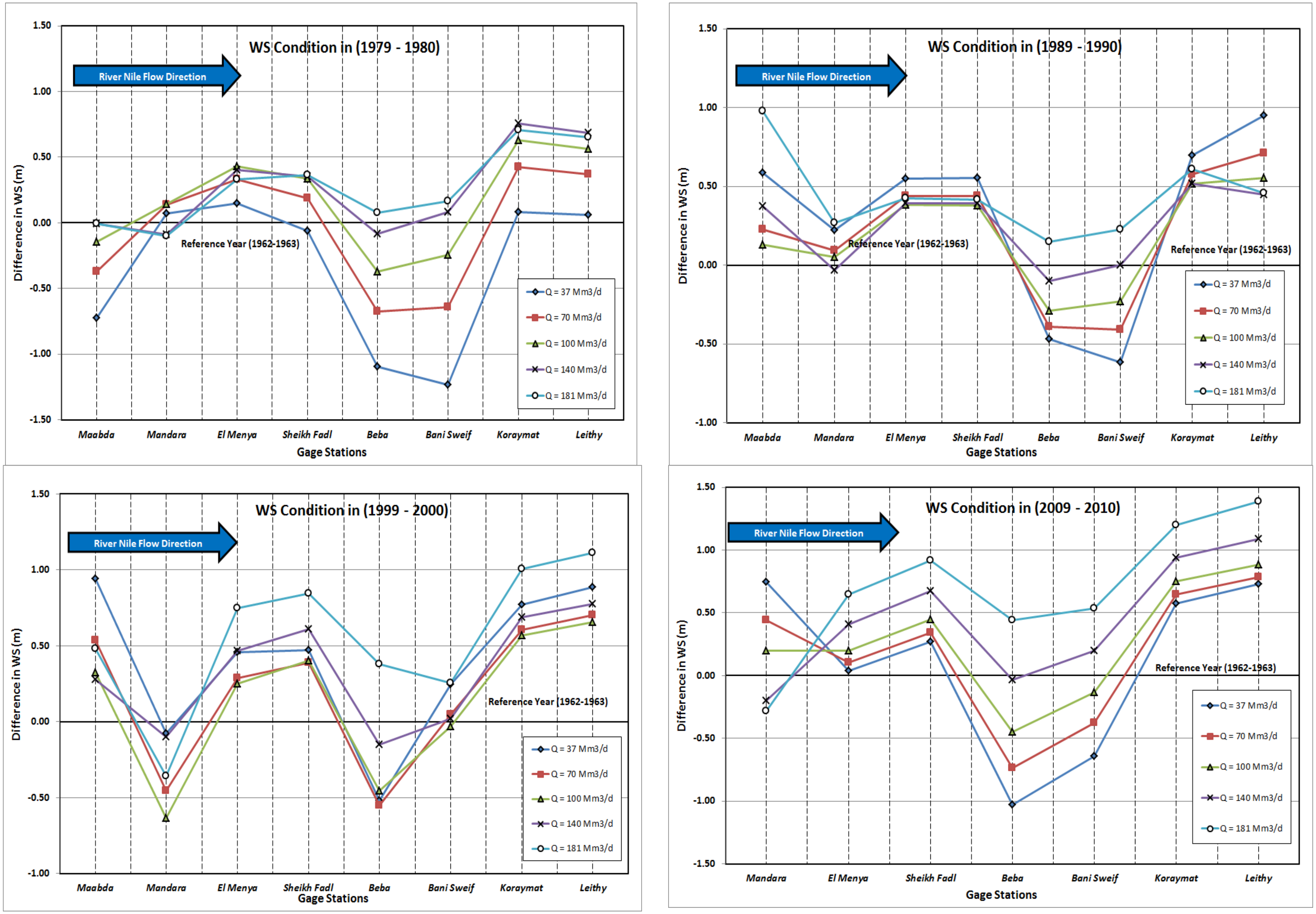

Fig. 8. Development of Water surface profile fluctuations between Years 1979 and 2010 for the five discharge cases compared with 1962-1963.

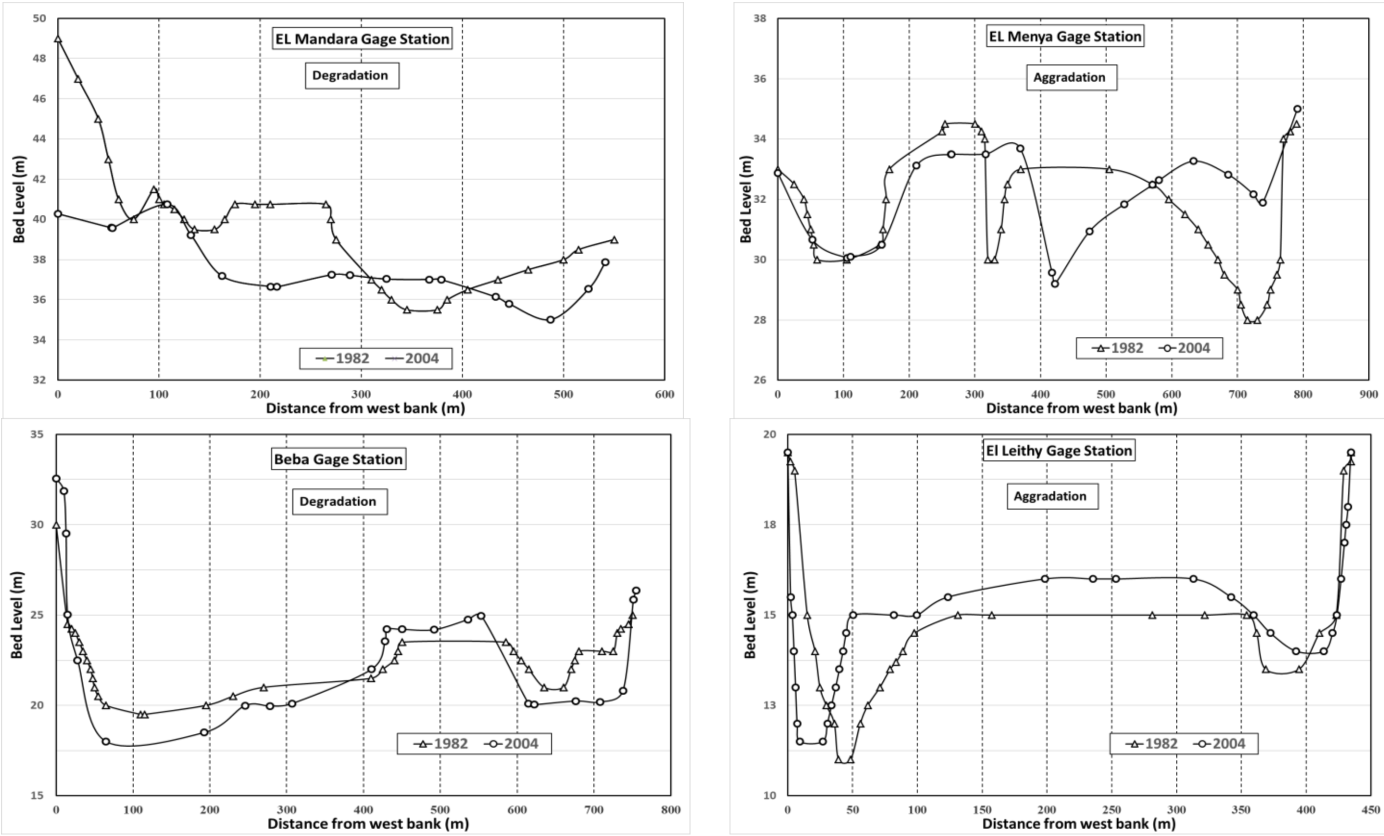

Fig 9. Comparison of four cross sections of years 1982 and 2003 at Mandara, Menya, Beba and El-Leithy Gage Stations**.**

5. Conclusion

The present study used a statistical analysis of the hydrological data of the Nile River fourth reach over past 49 years (between 1962 and 2010) to infer the river regime trends especially after HAD construction. It focused on investigating the water surface profile trends along the study reach during the release of a number of different flow discharges of values (37, 70, 100, 140, and 181 Mm3/d) D.S Assuit Barrages which are located at the beginning of the reach. The main aim was to track the changes that occurred to the Water Stages until 2010 compared to the condition in 1962. Accordingly, the study translated such changes to possible riverbed morphological changes and verified that by comparing riverbed cross sections of years 1982 and 2004 at Mandara, Menya, Beba and El Leithy gage stations for instance. Finally, the study concluded the following points:

1. The general trend of the water stage fluctuations (rise and fall) along the study reach is almost sinuous with respect to the situation in 1962-1963 for the five selected discharge cases;
2. For the different discharge cases, the water fluctuations rise at El Maabda then fall at El Mandara then rise at El Menya then rise again at El Sheikh Fadl then fall at Beba then fall again at Bani Sweif then rise at El Koraymat and again at El Leithy. This trend occurred during the comparison years 1989-1990, 1999-2000, and 2009-2010 except year 1979-1980 where the fluctuations start with fall then rise at Mandara, El Menya, and Sheikh Fadl then fall at Beba and Bani Sweif then rise again at Koraymat and El Leithy. It might be interpreted as this period was closer to the HAD operation time where most of the sediment load was detained behind the dam and accordingly the flow current downstream was still able to erode the riverbed more strongly;
3. The trends of the WS fluctuations are almost similar in all discharge cases.;
4. It is clear that the river segment between El Menya and El Sheikh Fadl and the segment between Koraymat and El Leithy experienced a WS rise, while the segment between Beba and Bani Sweif had a WS fall. This means that part of the U.S river segment and the D.S segment experienced a WS rise while the middle segment had a WS fall. This means that the study reach has been seeking a state of equilibrium;
5. The maximum WS rise occurred in 2009-2010 during the release of discharge 181 Mm3/d at El Leithy gage station and was equal to 1.39 m, while the minimum WS fall took place in 1979-1980 during the release of discharge 37 Mm^3/d at Bani Sweif and was equal to 1.23 m;

6. The above WS fluctuation values could be interpreted to possible riverbed morphological changes assuming that the WS slope is parallel to that of the riverbed along the study reach. Accordingly, the U.S segment of the study reach extending from Maabda until Sheikh Fadl may have experienced river bed aggradation that reached a maximum value of 0.92 m at Sheikh Fadl during the release of the maximum discharge 181 Mm^3/d. As for the middle segment between Beba and Bani Sweif, it is clear that it had severe degradation of a maximum value of 1.23 m at Bani Sweif which appeared during the release of the Minimum discharge 37 Mm^3/d. Regarding the D.S segment between Koraymat and El Leithy, it is also clear that the riverbed might have had aggradation thicker than that occurred in the U.S segment. The value of this aggradation reached 1.39 m during the maximum water discharge (181 Mm^3/d); and
7. The river segment between D.S Assuit Barrages and Maabda GS is about 31 km long and is not included in the study. However, it is known that the morphological changes in this part should be degradation as it is always subject to turbulence due to the rushing flow D.S the barrages.

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Conflict of Interests

The authors declare that there is no conflict of interests.

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تتبع اتجاهات التغير المورفولوجي على طول نهر النيل في مصر باستخدام تحليل البيانات الهيدرولوجية

المستخلص

يهدف هذا البحث إلى تتبع اتجاهات التغير المورفولوجي على امتداد الحبس الرابع لنهر النيل داخل جمهورية مصر العربية على مدار الخمسين عامًا الماضية باستخدام تحليل البيانات الهيدرولوجية ، حيث يساعد هذا التتبع في التعرف على الاتجاهات المستقبلية المحتملة ، خاصة في ضوء دورة االتصرفات والمناسيب المتكررة سنوياً. ويمتد االحبس الرابع لنهر النيل من خلف قناطر أسيوط وينتهي أمام قناطر دلتا. وقد تم تجميع بيانات ١٠ سنوات سابقة بين عامي ١٩٦٢ و ٢٠١٠ للتصريفات اليومية ومناسيب المياه المقابلة عند ثمان محطات قياس على امتداد حبس الدراسة. ثم تم الأخذ في الإعتبار تصرف سنوي إضافي آخر للحبس يساوي حوالي ٧.٥ ٪ من التدفق الأصلي. ثم تم إنشاء خمسة وسبعين منحنى علاقة التصرف ومنسوب سطح المياه لمحطات القياس المختلفة. بعد ذلك ، تم إنشاء معادلات التراجع التربيعية متعددة الحدود للمنحنيات واستخدمت لتحديد قيم منسوب المياه في المحطات الثمانية للقياس عند تصرفات ٣٧ ، ٧٠ ، ١٠٠ ، ١٤٠ ، ١٨١ مليون متر مكعب / يوم على مدى السنوات العشر المختارة. وباعتبار عام ١٩٦٢ مرجعاً للمقارنة ، تم حساب ومقارنة القطاعات الطولية الجانبية لسطح المياه المقابلة لحالات التصرف المختلفة. ثم تم تفسير صعود وهبوط سطح المياه على أنه تغيرات مورفولوجية لقاع مجرى النهر. وأخيراً ، كشفت الدراسة عن حدوث ترسيب خلال الجزء الأمامي لحبس الدراسة من مقياس المعابدة وحتى مقياس الشيخ فضل ، ثم حدوث نحر في الجزء الأوسط بين مقياسي ببا وبني سويف ثم ترسيب مرة أخرى خلال الجزء الخلفي للحبس بين مقياسي الكريمات والليثي. ثم تم التحقق من هذا التفسير بتقديم مقارنة بين قطاعين عرضيين لسنتي ١٩٨٢ و ٢٠٠٣ عند محطتي قياس ببا والليثي مستخرجين من الخرائط الكونتورية لقاع مجرى نهر النيل والمنتجة بواسطة معهد بحوث النيل خلال هاتين السنتين.