Fluvial adjustment of the Lower Jordan River to a drop in the Dead Sea level

Marwan A. Hassan a,*, Micha Klein b

a Department of Geography, Hebrew University of Jerusalem, Mount Scopus, Jerusalem 91905, Israel
b Department of Geography, Haifa University, Mount Carmel, Haifa 31905, Israel

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Abstract

Water utilization in the upper part of the Jordan Basin has led to a significant reduction in inflow to the Dead Sea. Over the last 70 years, a drop of about 22 m in mean sea level has occurred and has resulted in a continual adjustment of the Lower Jordan River. The impacts of this lowering on the channel morphology of the Lower Jordan River were examined using aerial photographs. Until the late 1970s, the drop in the sea level was small but still led to channel extension. Since the early 1980s, a rapid drop in sea level took place leading to major changes in channel morphology and deep incisions. The greatest change in channel width was recorded near the river mouth. Between 1850 and 1980, there were only insignificant changes in channel sinuosity, but subsequently, a 25% increase of channel sinuosity has been recorded. Most of changes in the channel sinuosity were recorded in the newly exposed area. Over the last 30 years, the active channel width has narrowed by almost four times. Until the late 1980s, the channel was relatively stable with minor bank collapses and only one bar detected near the Jisr Abdallah. During the 1990s, a number of bars developed along the channel. The downcutting is in parallel with the sea level drop resulting in the development of terraces along the lower part of the study reach. In 1983, the channel incision reached 8 km upstream and by 1993 it was about 11 km. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Both geomorphologists and geologists have long recognized the relatively important role that base level changes play in controlling the behaviour of alluvial channels. Rivers are expected to respond to base level changes by degradation, aggradation, changes in channel pattern and geometry or a combination of these. Lowering the base level can cause the initiation of gullies and degradation, development of channel terraces, knickpoint migration and acceleration of bank erosion (e.g., Begin et al., 1981). Adjustment will begin at the mouth of the stream and propagate upstream through the stream system (Bonneau and Snow, 1992).

The response of a river to a change in base level is complex and difficult to forecast. The complexity of the river response to base level changes is due to the large number of controls on the fluvial system. Variables that seem to be significant can be lumped into three groups (Schumm, 1993): (1) base level controls
(e.g., magnitude, direction, rate, duration), (2) geological controls (e.g., lithology, structure) and (3) geomorphic controls (e.g., river morphology, valley morphology, surface gradient).

A relative fall in the base level will increase drainage basin relief and increase the potential energy available in the landscape (Summerfield, 1991). A fall in the base level can also lead to erosion and incision of a fluvial system. However, this will usually depend on the inclination of the “newly exposed area.” Three different cases have been distinguished: (1) deposition occurring when the slope of the “new” area is lower than that of the channel, (2) no change when the slope of the “new” area is similar to that of the channel and (3) downcutting, knickpoint migration and development of terraces when the slope of the “new” area is steeper than that of the channel (Summerfield, 1991).

Our knowledge of the impact of base level lowering on fluvial systems is derived largely from flume experiments (e.g., Begin et al., 1980, 1981; Gardner, 1983) and simulation models (e.g., Van der Pool, 1982; Begin, 1987; Slingerland and Snow, 1988; Bonneau and Snow, 1992). Based on flume experiments, Begin et al. (1981) examined the impact of base level lowering on the development of the longitudinal profile of the channel, the sediment discharge at the outlet and the rate of knickpoint migration. All three aspects of the process were then integrated through a basic diffusion model. His flume experiments suggest that the final profile of a stream will tend to be parallel to the original one. However, the final bed gradient may be steeper in the case of heterogeneous material when an armouring process accompanies the incision (Begin et al., 1981). Brush and Wolman (1960) observed a steeper final gradient in flume experiments in which artificial knickpoints were created in the mid-flume locations. An exponential decrease in erosion in the upstream direction was suggested by Hamblin et al. (1981).

A review of the literature indicates that there are few field studies that have examined the impact of base level lowering on a fluvial system or have determined the rate at which disturbance following the lowering of base level moves through the fluvial system (e.g., Whitten and Patrick, 1981; Robbins and Simon, 1983; Rockwell et al., 1984; Schumm et al., 1984; Schumm, 1993; Yodis and Kesel, 1993). A key question is, how much time is needed to reach a new equilibrium following the lowering of base level (see Yodis and Kesel, 1993). Using several field examples, Leopold and Bull (1979) asserted that base level changes affect the vertical position of a river only locally and even then to a minor extent. In addition to gradient adjustment, they argued that parts of the effect of base level changes are absorbed in the adjustments of channel pattern, roughness and shape. The direction of change, the magnitude, rate and duration of change appear to be important variables. Large changes are likely to cause river incision and, in the case of very large changes, they may affect the entire drainage basin. In addition, the amount and type of change in the fluvial system are both affected by the rate and duration of change (Yoxall, 1969; Wood et al., 1992). With rapid incision, flows will cause deep channels resulting in increasing flow energy that, in turn, accelerates the effects of base level lowering (Schumm, 1993). Based on observations made in the southwestern U.S.A., Schumm et al. (1984) stated that, following the initial incision, flows were concentrated in the newly enlarged channel, with the incision moving upstream. In the case of the mouth of a large stream with sufficient discharge, uniform incising is possible, with all of the base level lowering transmitted upstream (Merritts and Vincent, 1989).

Due to water utilization in the upper part of the Jordan basin, inflows to the Dead Sea from the Jordan River have been reduced significantly. As a result, the Dead Sea level dropped from $392$ m in the early 1930s to $414$ m in 1998—a total sea level drop of 22 m, averaging about 32 cm per a year. The purpose of this paper is to examine the effects of base level lowering on the channel morphology of the southern end of the Lower Jordan River. The recent chronology and rate of channel changes through the lower reach of the river caused by the lowering of the base level—changes in the longitudinal profile and channel planform—are documented.

2. The Jordan Basin

The Jordan River is situated along the Jordan Rift Valley and drains an elongated area of 17665 km$^2$ (Schattner, 1962; Fig. 1). The Rift Valley trends north–south and has a 15-km wide depression in which the Dead Sea acts as a regional base level.
The depression is bounded on both sides by normal faults (Freund et al., 1970; Begin, 1974). The basin extends from Mount Hermon in the north to the Dead Sea in the south. The average annual precipitation diminishes from 1600 mm in the north (Mount Hermon) to 250 mm south of the Sea of Galilee and to about 100 mm near the Dead Sea.

Most of the valley bottom south of the Sea of Galilee is covered with Lisan marl, deposited in Lake Lisan, which occupied the region during the last glaciations, 60,000–18,000 years B.P. (Begin, 1974; Begin et al., 1985). In the Lisan marl, laminated deposits are discernable, with alternating thin layers of fine-grained clastic material and layers of aragonite.

The drainage basin is divided into two parts. The upper Jordan River drains into the Sea of Galilee while the Lower Jordan River is situated between the Sea of Galilee and the Dead Sea. Hence, floods occurring in the upper Jordan River have no direct impact on the lower part. The meandering river south of the Sea of Galilee is incised in fine sediment of the Lisan formation. The Sea of Galilee and Yarmouk River are the two main sources of water to the Lower Jordan River. The river floodplain is called Zor and on both sides of the Zor a 30–50-m high slope leads to the ancient elevated valley floor called Ghor. The majority of the tributaries are wadis or seasonal streams that carry water on only a limited number of days each winter.

The flow regime of the river has been altered several times. In 1932, a barrage was built at the exit of the river from the Sea of Galilee to regulate the outflow for hydropower purposes. The main goals of the dam were to reduce the winter flows and to store water for summer release. After 1948, the hydropower station was abandoned and the barrage became part of the irrigation system of the Lower Jordan Valley (Schattner, 1962). In 1964, the Israeli National Water Carrier was completed which diverted water from the Sea of Galilee. In the late 1960s and early 1970s, the Jordanians diverted a large proportion of the base flow from the Yarmouk. Water utilization has a tremendous impact on the Lower Jordan base flow. However, the main source of floods in the Lower Jordan is the Yarmouk River winter floods.

Flow data have been collected for various periods along the Lower Jordan River (Fig. 1). The Daganya station has operated since 1926 and is located near the outlet of the Sea of Galilee. The other stations are Nahrayim (since 1977), Jisr El Majama (1934–1944), Allenby Bridge (1932–1943) and Adasia on the Yarmouk River (since 1988). The Nahrayim and Jisr El Majama stations can be considered for joint analysis because of their proximity (6 km) to each other and because there is no tributary between them. Although the stations cover two different periods of record, they can be used to assess changes in the flow regime of the Lower Jordan River due to water utilization.

Fig. 2 presents the frequency of annual peak flows of the Lower Jordan River and the Yarmouk. Most of the contemporary floods in the Lower Jordan River are due to the contribution only of the Yarmouk River. During years of heavy rainfall the flow from the Upper Jordan River and the Sea of Galilee contributes to increased flooding of the Lower Jordan Valley. Although the largest two floods in the Lower Jordan River were recorded during the 1934–1944 period, the bulk of the data for the two periods overlap (Fig. 2). Both periods yielded about the same mean annual flood of 250 m$^3$ s$^{-1}$. For recurrence intervals of 2 years or more, the two records coincide. The mean annual flood of the Yarmouk River for the observation period, which is rather short, is 90 m$^3$ s$^{-1}$ (Fig. 2). Although the flood magnitudes are lower, the flood analyses of the Yarmouk station revealed a pattern similar to that obtained for Nahrayim. Fig. 2 shows that water diversion did not significantly change the magnitude of the large floods in the Lower Jordan River. However, the effect of water utilization becomes evident for flows with recurrence interval less than 1.8 years, where data from Jisr El Majami station exceed those from Naharayim by a factor of seven.

The mean flow has been altered significantly. Prior to the main water diversion by Israel and Jordan, the yearly discharge of the Lower Jordan River ranged between 648 and 1680 Mm$^3$/year with a mean discharge of 1250 Mm$^3$/year (Schattner, 1962; Klein, 1985). Between 1964 and 1970, Israel diverted about 200 Mm$^3$/year out of the basin from the Sea of Galilee. Since 1971, the amount has increased to about 350 Mm$^3$/year (Klein, 1998) and some 60 Mm$^3$/year pumped for local use. As a result, the annual discharge from the Sea of Galilee at the Daganya gauge station has decreased from 480 to about 70 Mm$^3$/year (Klein, 1985, 1998). The mean annual discharge of the Yar-
Fig. 1. The Jordan River system and the study area.
mouk is estimated at 445 Mm³/year, of which Jordan initially diverted about 70 Mm³/year in the mid 1960s subsequently increased during the 1970s to about 200 Mm³/year. In addition, about 150 Mm³/year has been diverted by Syria (Klein, 1998, 1999). Overall, flow in the Lower Jordan River dropped from 1250 Mm³/year prior to the water diversion in the early 1960s to 213 Mm³/year by the end of the 1980s and then to 150 Mm³/year by 1998 (Klein, 1998). In the last 21 years, there are only eight occasions when the gates of the Daganya dams have been opened for water release to the Dead Sea as a result of lack of storage in the Sea of Galilee.

3. Methodology

Fieldwork in the area is not possible because the river course forms the border between Jordan and Israel. In addition, on both sides of the border, a large number of land mines were carried by the river floods and are scattered throughout the floodplain area. Accordingly, assessment of changes in the southern end of the Lower Jordan channel is based on analyses of aerial photographs from the years 1946, 1971, 1980, 1983, 1991, 1992, 1993 and 1995 obtained from the Survey of Israel. Prior to 1946, channel pattern was determined using a map prepared in 1850 by Lynch (1850, 1852; see also Schattner, 1962). The aerial photographs have a scale of 1:15,000 except those of 1971 (1:50,000) and 1991 (1:45,000). The channel profile was determined photogrammetrically by taking very frequent height readings along the water surface during low flows. The photogrammetric work was completed using a stereoplotter at the Israel Mapping Centre. It is assumed that a low flow water surface provides a good approximation of the bed profile. In some places the vegetation was very dense and an accurate reading was difficult to obtain. The estimated error of the longitudinal profile readings at the 1:15,000

Fig. 2. Annual flood frequency analyses of the Lower Jordan River and Yarmouk River at different gauge stations (MAF = mean annual flood).
scale is in the order of few cm (up to 10 cm) while it could reach a few tens of cm (up to 70 cm) in the case of the 1:50,000 scale. On average, at least 50 measurements were taken for every kilometre of channel length. To reduce the effect of errors in our measurements, the water surface profile was determined by using a running average of 10 readings.

4. Observations

4.1. Dead sea: sea level and bathymetry

The Dead Sea monthly level data were obtained from the Israel Hydrological Service. Fig. 3 presents changes in sea level over time. Between 1930 and 1937, the sea level dropped by 4 m and then remained essentially constant between 1938 and 1956. A drop of 3 m was recorded between 1956 and 1962 and no change in the sea level was observed during the years 1963–1972. Since 1973, a rapid drop of about 15 m in the sea level has been observed. The bathymetry of the Dead Sea coastal area was determined by surveying a cross-section at the Lido, about 4 km west of the contemporary river mouth (Fig. 4; for cross-section location, see Fig. 5). It is assumed that the cross-section represents the frontal part of the river’s delta. The surveyed cross-section was matched with the sea level using the 1946 benchmark. Up to the late 1980s, the rapid decline in the Dead Sea level resulted in the exposure of a wide area with a relatively low slope of 1.7%. In addition, the slope of the river in the exposed area is about that of the sea floor (about 2%). Since then, further falls in base level have exposed a narrow, relatively steep area with an average sea-floor slope of 14%. The rapid decline in sea level has resulted in upstream progressing incision of the channel beds of most wadis that drain into the Dead Sea (Schechnovitz-Pirtel, 1999). In the Jordan mouth, the slope of the newly exposed area is steeper than that of the river, leading to possible downcutting along the main channel.

4.2. Longitudinal profiles

Fig. 6 shows the longitudinal profiles of the river toward the river mouth between 1946 and 1993. Distance in Fig. 6 is measured along the water line. In addition, the bankfull profile of 1932 and the Dead Sea level are shown (Schattner, 1962). In 1932, the distal bankfull level was 392 m below mean sea level. The figure shows a clear trend of downcutting. Between 1946 and 1980, an upstream cutting of about 7 km along the main channel is evident. The response was very rapid because the channel is incised in relatively fine and highly erodible material. Up to 1983, the
Fig. 5. View of the Jordan River between Nahal Perat and the Dead Sea (photo taken in 1995). Points 1, 2 and 3 in Fig. 8 are indicated. Measured channel widths (River Mouth, Middle Point and Jisr Abdallah in Fig. 6) and the Lido cross-section (in Fig. 4) are indicated.
channel headward incision reached about 8 km upstream from the river mouth. By 1993 the headward incision had reached about 11 km (Fig. 6).

Using the 1973 and 1981 aerial photographs, a cross-section 1.5 km upstream of the river mouth was carried out. During the same period, the sea level dropped by 4 m. In 1973, the low water level depth relative to the bankfull level was 6.1 m at the east bank and 6.5 m at the west bank. The measured values for 1981 were 10.6 and 10.6 m, respectively. This implies a downcutting of 4 m over the period, which is identical to the rate of sea level fall during the same period.

4.3. Channel width

Changes in bankfull channel width were examined using aerial photographs taken between 1968 and 1995. Since all examined photographs were taken in the dry summer season, errors associated with the river level are expected to be minimal. The bankfull width was measured in three locations along the river channel; near the river mouth, midway between the mouth and the Jisr Abdallah and near the Jisr Abdallah (Fig. 5). Bankfull was measured as the distance between vegetation found on both banks. Changes in the channel width are presented in Fig. 7. The greatest change in channel width is recorded near the river mouth. During the study period, a general decline in channel width was evident. A similar trend in channel width was recorded in the other two sites, although with less severity than near the river mouth. The variation in channel width between stations was initially high due to degradation of the recently exposed area. Variation in the width is significantly lower in the later time periods since the channel has become progressively incised.

4.4. Channel morphology

Channel bars, bank stability and sediment supplies from banks to the main channel were examined using all available aerial photographs. Two examples, 1968 and 1995, of channel morphology are shown in Fig. 8. For clarity, only the lowermost 350 m is displayed. The other reaches are similar. Both the 1946 and 1968 photographs show relatively vertical banks with no evidence of bank collapse. In addition, no bars were identified along the active channel. North of the Jisr Abdallah (Fig. 5), a 10-m long mid-channel bar is evident in the 1970 photograph. However, this bar was destroyed between 1970 and 1975. No significant changes in channel morphology and bank stability were noted between 1975 and 1981.

During the 1990s, major changes in bar density and size were observed. In addition, large number of bank collapses were noted (Fig. 8). A summary of bar characteristics in 1992 and 1995 is presented in Table 1. The average bar spacing in 1992 and 1995 was 79 and...
Fig. 8. Successive maps of channel and bar morphology of the Lower Jordan River as derived from aerial photographs.
92 m, respectively. Comparing bar locations between 1992 and 1995 shows that a significant number of bars were destroyed or merged with others to form larger ones (Table 1). This implies a relatively active channel during the 1990s in comparison to the 1960s and 1970s. The 1992 photograph shows that some of the bars are found immediately downstream of a meander that was cut during the 1992 flood event (Fig. 2). It appears that the sediment eroded from the meander was the main source for forming these bars. In 1995, new bars were formed near the river mouth.

4.5. River sinuosity

Changes in channel planform over the study period are presented in Fig. 9. Between 1946 and 1971, a new meander developed around Point 1 near Jisr Abdallah (Fig. 5), while the rest of the reach showed very little change in channel planform (Fig. 9). Overall, the study reach was planimetrically stable. In fact, the channel around Point 1 shifted laterally between the examined years. During the 1990s, two major changes occurred, a meander cut near Points 1 and 2, and the development of a new meander near Point 3 (Fig. 9). Both points 1 and 2 are located downstream of two small alluvial fans deposited by small tributaries. We attribute the meander cuts to the record high rainfall in 1991–1992.

Channel sinuosity was examined over the last 150 years. For the period pre-1946, the sinuosity was determined based on maps by Lynch (1850, 1852) and Schattner (1962), whereas aerial photographs were used for the post-1946 period. Fig. 10 presents changes in channel sinuosity with time. Most of the changes in channel sinuosity were found in the newly exposed area. Until the 1960s, the channel sinuosity did not change, implying that the channel was relatively stable, and even into the 1980s no major change in the river sinuosity was recorded. Apart from the meander cut near point 2 (see Figs. 5 and 9), the river course upstream of the 1946 shoreline did not change. Therefore, the sinuosity for that reach hardly changed.

<table>
<thead>
<tr>
<th>Year</th>
<th>1992</th>
<th>1995</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of bars</td>
<td>24</td>
<td>16</td>
</tr>
<tr>
<td>Mean length (m)</td>
<td>8</td>
<td>22</td>
</tr>
<tr>
<td>Total length of bars (m)</td>
<td>192</td>
<td>344</td>
</tr>
<tr>
<td>Mean spacing (m)</td>
<td>79</td>
<td>92</td>
</tr>
<tr>
<td>Total bar length to channel length (%)</td>
<td>11</td>
<td>20</td>
</tr>
</tbody>
</table>

Fig. 9. Successive channel planforms between 1946 and 1995. Points 1–3 indicate locations along the channel referred to in the text and located on Fig. 5.
Since the 1980s, the sinuosity has increased with time and reached a maximum in 1995. Most of the changes took place in newly exposed steep areas.

5. Discussion

The adjustment of a river channel to a base level lowering is complex, with periods of incision followed by sediment storage and renewed incision (Schumm et al., 1987). The rate and extent of channel adjustment varies from one fluvial system to another and depends on a large set of variables. However, most of our knowledge of the impact of a base level lowering on the fluvial system comes from flume experiments. Due to scale and material differences, the applicability of the experimental results to natural rivers is very limited.

Water utilization in the upper part of the Jordan River reduced the annual flow in the Lower Jordan River from 1250 to about 150 Mm$^3$/year by the year 1998. The water diversion resulted in the lowering of the Dead Sea level by about 22 m in the last 68 years (0.32 m/year). Frequency analysis of the annual flood indicated that the impact of the water diversion on the flood magnitude is limited to relatively low flows. However, large floods in the river are the result of the combined contribution of both the Upper Jordan River and the Yarmouk River. Over the last 21 years, only eight floods had flows that exceeded the mean annual flood. On average, once every 3 years a large flood occurs such that it can erode and transport sediment along the river.

The response of the Jordan River to the lowering of the Dead Sea base level is controlled by a large number of variables. These variables include the rate of base level drop, flow characteristics (frequency and magnitude of floods), bed and bank material of the river and slope of the newly exposed area relative to that of the river. Since the decline in the sea level is an ongoing process, it is very difficult to determine the relaxation time of the fluvial system. In this sense, our analysis is at an intermediate stage and a final assessment cannot be made as long as the sea level continues to drop.

In our analysis, we discerned two periods of Jordan River response to the lowering of sea level: 1930–1980 and 1980–1997. However, the second stage is an ongoing process and, therefore, the final response of the river has not yet been achieved. During the first period, the sea level dropped by 0.17 m/year and a relatively gentle and wide foreshore was exposed. The rate of sea level drop exceeded 0.50 m/year during the second period and exposed a relatively steep foreshore. The response of the river during the first period was by incision and a gradual decrease in the active channel width. Few changes, if any, were recorded in the channel pattern and channel morphology. Even though in the newly exposed area the river flows

![Graph showing changes in channel sinuosity with time.](image)

Fig. 10. Changes in channel sinuosity with time as derived from maps and aerial photographs. The sinuosity between 1850 and 1946 was based on Lynch (1850) and Schattner (1962) maps.
through soft, fine sediment over a gentle slope, the reaction was more of vertical incision than of lateral shifting as one would expect (for example, see Schumm, 1993). However, the river is incised in a relatively confined floodplain and, therefore, the vertical adjustment along the incised channel is the main option for the river to deal with base level lowering. Between the 1930s and early 1980s, about 8 km of headward incision was recorded and therefore the average upstream migration of the knickpoint was about 200 m/year. Put in another way, for each 1 m of sea level drop the upstream migration was about 1 km.

Between 1983 and 1995, within the second period, the slope of the shelf was much steeper than that of the river. The channel response was a significant change in channel morphology and pattern. The channel sinuosity increased from an almost straight channel to that of a meandering channel. The streambed lowering, during both periods, led to bank heights that were unstable, excessive bank erosion and the release of relatively large amounts of sediment. This sediment moved through the fluvial system and was stored in the form of bars. Such bars did not exist in the lower part of the river before the 1980s. The existence of bars will probably reduce further degradation until they have been flushed out of the system. In the case of the channel width, the 1990s results indicate a slowing in the decrease of active width.

The upstream incision rate obtained for the Jordan River is comparable to values reported in the literature. The knickpoint migration along the Lower Jordan River averaged about 0.27 km/year for the last 70 years. Values obtained for Mississippi tributaries ranged between 0.06 and 0.37 km/year (Yodis and Kesel, 1993). However, all of the Mississippi tributaries have a smaller drainage area than that of the Jordan River. According to the reported relation between back channel erosion and drainage basin area developed for the Mississippi tributaries (Yodis and Kesel, 1993, Fig. 14), the rate of back erosion by the Jordan River should be at least one order of magnitude higher than the measured value. It seems that the Yodis and Kesel function is suitable only in basins similar to the Mississippi Basin (for which the function was developed). The differences between the Mississippi case and ours could be attributed to differences in flow regime, morphology and lithology.

6. Conclusions

Over the last 70 years, water diversion from the upper part of the Jordan River reduced flows into the Dead Sea. As a result, the Dead Sea level dropped by 0.32 m/year. The drop in the sea level was not evenly distributed over the period and most of it occurred since the early 1980s. During the first period (1930–1980), the base level drop was relatively small (slow) and the river responded by incising, upstream migration of the knickpoint and narrowing its width. The greatest changes in the channel width were recorded near the river’s mouth. Since the 1980s, the rapid drop in the base level resulted in upstream incision, bank collapses, development of mid channel bars, increase in channel sinuosity, development of terraces and narrowing of the channel width. However, most of the increase in the channel sinuosity was limited to the newly exposed area.

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