Analysis of non climatic origins of floods in the downstream part of the Kura River, Azerbaijan

R. K. Abbasov · R. N. Mahmudov

Abstract   Over the past century, there is an increased contribution of non climatic factors to the flood formation processes in the Kura River. Non climatic factors of floods refer to factors that are related to reductions in channel capacity and result in floods. More recently, there are numerous non climatic factors occurring in and around the Kura River basin that have increased the frequency of floods. Sediment accumulation in the riverbed over a long period of time has led to the reduction of channel capacity and has raised the elevation of the riverbed above the surrounding territory. It is illustrated that construction of dykes and levees do not actually prevent flooding, where hydrologic connections between ground-water and surface water are high, since infiltrated waters from channel results in raising of ground waters, causing an effect of "underground flood." Since underground floods occur when water going from channels raises the level of ground waters, there is an urgent need to carefully investigate the groundwater–surface water connections. With the purpose of predicting floods, the authors suggest defining maximal acceptable flows (MAFs) rather than channel capacities. Results show that high rates of hydraulic conductivity of soils will decrease MAF rates. MAF computations before high-water season allow for further reg-ulation of outlets further downstream in order to prevent flooding and enable flood forecasting. While the study focuses on a specific region, the overall approach suggested is generic and may be applied elsewhere.

Keywords   Flood · Sedimentation · State–discharge curves · Hydraulic conductivity · Channel capacity · Maximum acceptable flow

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1 Introduction

Floods in all regions of the world are often the main factor restricting local economic development (Simonowic and Carson 2003; Petrow et al. 2006; Ahmad and Ahmed 2003). As stated in the literature, floods in the majority of areas of the world are caused by snowmelts and rains of different duration and intensity as a result of cyclones (Istomina et al. 2005). At the same time, it has been widely accepted that non climatic and non hydrologic impacts can also be major factors causing floods (Yongqiang and Xiqing 2000; Mohapatra and Singh 2003). Riverbed silting can play an important role in the formation of floods when significant volumes of sediment accumulate in a riverbed and reduce the size of the active channel (Dian and Changxing 2001). Therefore, magnitude of peak flow is not the only factor of flood risk: a flood occurs when main channel water levels are sufficient to exceed the local bank height. Thus, flood risk is driven by changes in river channel stage, which may be impacted upon by changes in both flow magnitude and river channel conveyance (Lane et al. 2007).

Flow regulation in downstream of the Kura River, Azerbaijan (Fig. 1) has historically been considered as the most effective method for flood prevention, although large flood events began to occur even in the highly regulated reaches in recent years (Sultanov and Khalilov 2004). Also, while most of the Kura River's flood events have usually occurred during high flow periods, flooding events have been more recently observed even during low flow water periods. Floods in the Kura River occur most often along the alluvial plain of the watershed, where the river frequently meanders and streambed slopes are very shallow. This recent change in the river's flood frequency and magnitude has increased the
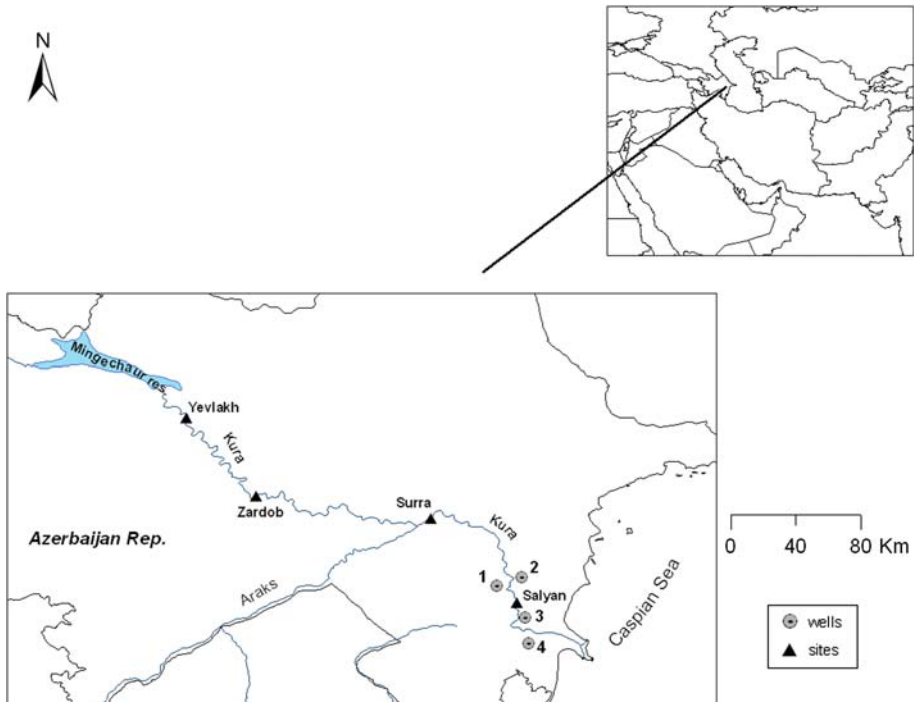

Fig. 1 A map of the Kura River basin and a study area

threat to floodplain residents and the productivity of floodplain agricultural activities. As a result, agricultural lands of the Kura-Araks lowlands are flooded and colossal economic and social damage is caused to municipalities located near the banks.

Larger flood events have the potential to cause massive economic and social damage to municipalities located near the banks of the river by not only flooding the surface of the floodplain, but also by raising local groundwater levels that affect the normal function of households both at the banks and the territories that are located far from the river.

2 Analysis of factors contributing to floods in the Kura River

More recently, there have been numerous additional factors occurring in and around the Kura River basin that have increased flooding in the Kura River. These factors can be divided into two general categories: direct factors that contribute to flooding by contributing to large discharge events, and indirect factors that can either affect the magnitude and timing of water flow (discharge) or which affect the function of the riverbed.

Direct factors have a climatic origin and directly influence the water flow. Climatic patterns that increase intense snowmelt and intense rains during high flow period have increased flood frequency and peak flows. Caspian Sea level fluctuations, significant rainfalls, and intense snowmelts can be considered as direct factors. Indirect factors, which affect a riverbed capacity to effectively convey water, can also cause flooding to occur during normal flood events. Indirect factors can also be defined as non climatic factors. Land use modifications, deforestation, erosion, riverbed silting, and land use have been considered as main indirect factors.

As it has been noted above, the main causes that affected floods in the Kura basin have historically been intense snowmelt events and significant rainfalls, which usually occur within spring time, from late March to early July. Maximal flow discharges that cause major floods have both snow and rainfall origin. During instrumental observations over the past century, notable floods were observed in 1915, 1936, 1942, 1944, 1946, 1952, 1969, 1976, 2002, and 2003. All of these floods were observed in high flow periods having relatively short period, e.g., a major flooding event that was observed in 1969 had a duration of nearly 19 days (Mamedov 1989); however, a flooding event in 2002 continued approximately for 70 days effecting a long-time rise in groundwater level (Abbasov and Kondratyev 2006). In an effort to reduce the frequency and severity of these floods, the Mingechaur reservoir was constructed in 1953. After dam and reservoir construction, the highest peak flows were reduced. Regulated flow from the reservoir altered the annual flow distribution of downstream, and flood events were almost entirely eliminated during the first 15 years after construction.

During the last century, the level of the Caspian Sea fluctuated heavily due to climatic variations and this factor deeply affected the outlet areas of the river (Mikhaylov et al. 2003; Hoogendoorn et al. 2005). The water level of the Caspian Sea is currently positioned at approximately 27 m below the mean sea level and the sea has no surface outlets. Instrumental observations, which were carried out over the period 1830–2005, illustrate rapid level fluctuations of the sea. The last short-term sea-level cycle started with a sea-level fall of 3 m from 1929 to 1977, and again, a sea-level rise of 3 m from 1977 onwards, until a high stand was reached in 1995. Since then, smaller oscillations have taken place. These fluctuations are a result of the interaction among differences in river discharge, evaporation, and precipitation. Extensive information concerning sea level fluctuations is given by Kosarev and Yablonskaya (1994). The sea level fluctuations result in water level

variations in outlet area and, as a consequence contribute to the decreasing in water velocity and, riverbed sedimentation, jamming the main channel. Although impacts of the level fluctuations on the water table of the river are obvious, unfortunately, the data on level fluctuations at hydrological stations in the Kura are insufficient.

The Kura is one of the muddiest rivers in the world. The average annual volume of the alluvium passing through the outlet reaches about 30–35 million tons. The primary source of riverbed silting in the Kura is a denudation from the catchments area which contributes to excessive suspended or dissolved sediments in the flow. After the construction of the Mingechaur reservoir, the river's sediment discharge and suspended bed load decreased for some time, as significant sediment accumulation took place within the reservoir (Belyaev et al. 1967). A more detailed analysis of water and sediment discharge rates of the Kura River for the periods 1930–1952 and 1953–1993 are presented by Mikhaylov et al. (2003). However, since the 1990s, an increase in suspended sediment in the Kura River has been observed. This pattern may be a result of intensive deforestation occurring in the catchment area, which began during the energy crisis after the collapse of the Soviet Union, when forests were the only heating source for provincial areas of Azerbaijan. It is widely recognized that the mass removal of vegetation decreases infiltration and evapotranspiration, leaving a larger percent of incoming precipitation to generate surface runoff (Mohapatra and Singh 2003). The removal of vegetation also makes steep slopes much more susceptible to sheet erosion and mass failure by removing roots that otherwise stabilizes the soil column (Balyuk and Kondratyev 2004). Deforestation and the mass removal of vegetation in the Kura basin increased the rate of denudation, which subsequently affected rates of sheet and rill erosion via surface runoff. Consequently, this increases the speed and intensity of soil erosion in the catchment areas of small rivers belonging to the Kura basin. Eventually, the sediment is transported through the channel of the Kura, where the most accumulation takes place as a result of reduced velocities in the highly meandering lowlands (Abbasov and Kondratyev 2006).

3 Materials and methods

3.1 Study area

For this study, downstream of the Kura River in Azerbaijan was selected as the study area. Observations on climatic, hydrologic, geomorphologic, and irrigation characteristics over the past 100 years were used to evaluate the long-term changes in hydrologic conditions over the downstream. The Kura River, together with the Araks River, forms the largest transboundary river system of the South Caucasus region. The origins of the Kura can be found in east Turkey, and it flows across the Ardakhan plateau through Georgia and enters Azerbaijan. In Azerbaijan, the Kura crosses the Kura-Araks plain, where it joins with the Araks and finally flows out into the Caspian Sea. The length of the river is 1,364 km; the basin is 188,000 km^2 The source of the river is located at a height of 2,740 m, while the outlet is at −27 m below the sea level. The slope of the upper basin is equal to 4.2%, while the slope of the lower basin is very low and equal to 0.09%. The average slope of the basin is equal to 2.03%.

About 45% of the basin is plains' territory, and the rest of consists of high and low mountains. The Kura River plays a vital role in both local and regional economies and has been used to generate energy, irrigation, and water supply in Azerbaijan and Georgia (Fig. 1).

Geologic characteristics of the Kura basin are rather varied, and there are rocks of different age and origin. The upper basin in the west consists of ancient crystal rocks such as gneiss, slates, and granite. The central part of the upper basin consists of comparatively friable rocks: limestone, marlstone, and gneiss. The lower basin almost completely consists of alluvium (Hoogendoorn et al. 2005). There are different types of soils in the Kura basin. The upper basin area mainly consists of light chestnut and brown soil types. The lower basin mainly consists of gray and saline soils.

3.2 Data collection

Annual, monthly, and daily values of water and sediment discharge data from 1933 to 2005 from four hydrological sites (Fig. 1) located downstream of the Kura were collected. In order to construct granulometric curves, results of analyses relating to granulometric structure of bed loads were taken from the periodicals of the Hydrometeorological Survey of USSR (Water Resources of USSR 1967, 1987, 1990) and from the periodicals of the Hydrometeorological Department of Azerbaijan (Water Resources of Azerbaijan 2007). For simply defining modifications in the granulometric structure of deposited solids over the past 70 years, cumulative granulometric curves of the different years were constructed and compared. Samples represent periods of "before regulation," "after regulation," and the following years, and all of them had been taken after high flow periods. Samples of all deposited solids were analyzed by pipette and fractional methods. Fractional method is used for separating fractions with diameters <1 mm. Fractions <0.001 and >0.05 mm were defined by pipette method (Water Resources of USSR 1967; Water Resources of Azerbaijan 2007).

3.3 Long-term changes in sediment discharges

In order to detect the chronological changes in hydrological and meteorological characteristics, different trend detection methods are widely applied (McBean and Motiee 2008). In order to detect changes in the time series of suspended sediment discharges for the first time, series of moving averages was constructed as

$$I_1 = N_1; \quad I_2 = N_1 + N_2/2; \quad I_3 = N_1 + N_2 + N_3/3; \tag{1}$$
$$I_n = N_1 + N_2 + N_3 + \ldots N_{n-1} + N_n/n$$

where N_1, N_2, N_3, and N_n are the annual values of sediment discharges and I_1, I_2, I_3, and I_n are the long-term averages for each year (moving averages).

Time series of the moving averages were then divided into two parts: the first part includes the period from 1953 to 1988, and the second one covers the period from 1989 to 2005. The long term changes in the average values of sediment discharges were then analyzed.

3.4 Stage–discharge curves

Stage–discharge curves reflect the relationship between the water discharge and water level, and can appear as an equation:

$$Q = aH^b, \tag{2}$$

where Q is the water discharge for a given time, H is the water level in the channel, and a and b are parameters of the equation.

For identifying changes in the channel capacity, stage–discharge curves for historical periods have been compared, and decreased channel capacity was estimated according to this formula:

$$\Delta Q = aH_2^b - aH_1^b, \qquad (3)$$

where ΔQ is the change in channel capacity, aH_1^b and aH_2^b are the different values of water discharges estimated from different curves for the same level.

Growths in the channel stages over the past 50 years were defined as a difference between channel stages of different periods with same water discharges

$$\Delta H = H_2 - H_1, \qquad (4)$$

where ΔH is the growth in channel stage, H_2 and H_1 are the channel stages of different periods with same water discharge.

3.5 Maximal acceptable flow (MAF)

Some authors consider that flooding occurs when the volume of water passing through a channel per unit of time exceeds the volume of the channel reach or the channel capacity (Andrew 1992; Lane et al. 2007). However, this general definition assumes that the surface channel's streambed is composed of impervious material, inhibiting any hydrologic connection between the surface channel and the nearby alluvial aquifer. This "hydrologic connection" can also be considered as streambed leakage (seepage), a type of groundwater–surface water interaction that occurs when the hydraulic head of the surface channel is greater than the hydraulic head of the nearby alluvial aquifer. In such cases, stream water goes through sediments feeding the ground waters and such open channels are referred to as losing streams. Another way of interaction between ground water and surface water is when groundwater feeds surface water and such type of streams are defined as gaining streams (Kalbus et al. 2006). If there are interactions between the surface channel and groundwater, a flow event that falls under normal high water levels can lead to the rise in groundwater levels, causing "groundwater flooding," which is able to disrupt the normal economic functioning of buildings and households along of coastal areas. This can occur in low-lying areas along the floodplain, where the water table is driven upward by stream discharge and intersects the land surface. Because of the potential for economic damage to be incurred without the need for the Kura River to physically spill over its surface channel banks, it is prudent to use the term "maximal acceptable flow," rather than "channel capacity."

MAF is a threshold discharge value, with any flows below the MAF not causing any danger to households and other establishments. The MAF may also be defined as a maximum amount of water flowing through a cross section in the given unit of time that does not cause danger to floodplain facilities and households during this flow (Abbasov 2007). Water discharges that exceed the MAF can be defined as undesirable discharges. "Undesirable discharges" have been typically considered as flow events that produce surface flooding and have the potential to damage bridges, agricultural lands, and other facilities situated on or near banks and floodplains. However, considering the effects of non-flood events on nearby groundwater levels, an "undesirable discharge" may occur even though the flow may not have spilled over its stream banks.

The MAF can be estimated by simply multiplying the velocity of flow by the maximum area of cross section:

$$Q_{\text{MAF}} = V(H_{\text{ave}} - \Delta H)B \tag{5}$$

where Q_{MAF} is MAF, V is the velocity of flow in the riverbed, H_{ave} is the average depth of maximum area of cross section, ΔH is the difference between maximal water level in cross section and groundwater level, which does not cause underground flooding.

3.6 Groundwater–surface water relationships and hydraulic conductivity

Since groundwater raisings can cause an effect of underground floods, there is an urgent need to investigate the groundwater–surface water relations. There are many methods that exclusively model the interactions between groundwater and surface water and they are based on different approaches. The methods are grouped into direct measurements of water flux, heat tracer methods, methods based on Darcy's Law, and mass balance approaches (Kalbus et al. 2006). The methods based on Darcy's Law typically require measurements of the components of Darcy equation (Darcy 1856). The methods based on the difference in temperatures between groundwater and surface water are has been recognized as "heat tracer methods." These differences can be used to delineate the groundwater discharge or recharge zones and quantify the water fluxes at the groundwater–surface water interface (Winter et al. 1998). Direct measurements of water flux across the groundwater–surface water can be estimated using seepage meters. Bag-type seepage meters are a bottomless cylinder vented to a deflated plastic bag. This cylinder is turned into the sediment, and as water flows from the groundwater to the surface water, it is collected in the plastic bag. According to composed water, the cross-sectional area of the cylinder, the collection period, and the seepage flux can be estimated (Lee 1977; Lee and Cherry 1978).

In order to explore the groundwater–surface water connections, hydraulic conductivity of soils needs to be defined. Hydraulic conductivity defines the rate of movement of water through a porous medium such as a soil or aquifer. It is the constant of proportionality in Darcy's Law and as such is defined as the flow volume per unit cross-sectional area of porous medium under the influence of an unit hydraulic gradient (Oosterbaan and Nijland 1994).

With the purpose of studying surface water–ground water connections and defining hydraulic conductivity, data on the Salyan site area taken from four experimental water wells were used (Fig. 1). For measuring hydraulic heads, piezometers were constructed in all the wells. The depth of each well is 8 m and they are located at different distances from the Salyan site. Measurements were taken every 4 days during high water season, from the end of April until the beginning of May, in 2004.

Hydraulic falls between water level in the channel and water level in the wells were defined by this formula:

$$\text{d}H = h_2 - h_1 \tag{6}$$

where h_2 is the hydraulic head in the channel and h_1 is the hydraulic head in the well for a definite time.

The distances between wells and channel were then divided into the time that is necessary for making h_1 and h_2 values equal, and this ratio is accepted as the hydraulic conductivity:

$$K = L/T \tag{7}$$

where K is hydraulic conductivity, L is the distance between channel and wells, and T is the time required for h_1 level for reaching the fixed level of h_2.

4 Results

4.1 Spatial and temporal distributions OD-suspended solids

Analysis of suspended solids in the Kura for the last 30 years illustrates a sharp increase in transported sediment that occurred between 1992 and 1994, increasing from 500–1,000 to 2,000–4,000 g/m^3 (Fig. 2). This is an attribute of the aforementioned deforestation that occurred during the last decade in the Kura basin. Riparian and floodplain forests along the main channel as well as its tributaries have especially suffered. Increasing capacity of total suspended solids along the length of the river from the Salyan site to the mouth of the river has been observed and also supports intensive accumulation in the mouth area. High rates of sediment runoff and total suspended solids, combined with low flow rates caused sediment accumulation in the river mouth, where the channel slope is low and flow rates are diminished. Sediment accumulation in the riverbed over a long period of time has led to the reduction of channel capacity and raised the elevation of the riverbed above the surrounding territory. The construction of levees and dykes on the river coasts elevates the river even further, creating the effect of an "above-ground river." In some places between the Salyan and the mouth, the riverbed of the Kura lies 2–3 m above the surrounding floodplain.

The results show that deforestation, affecting spatial and temporal distributions of suspended solids, has a marked influence on the granulometric characteristics of sediments transported by overland flow (Fig. 3). As most typical solids in the Kura are observed after floods, only results of samples taken in Salyan site during low flows were used.

Fig. 2 Long-term changes in annual sediment discharges at Salyan (site in the Kura) during the last 30 years
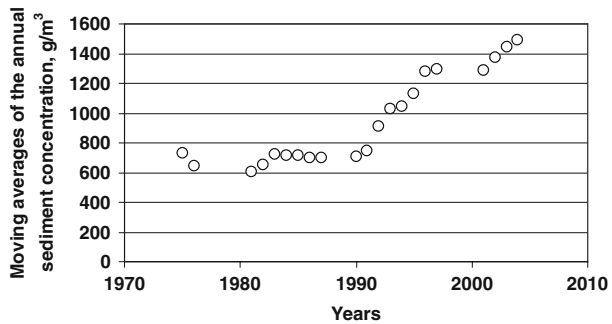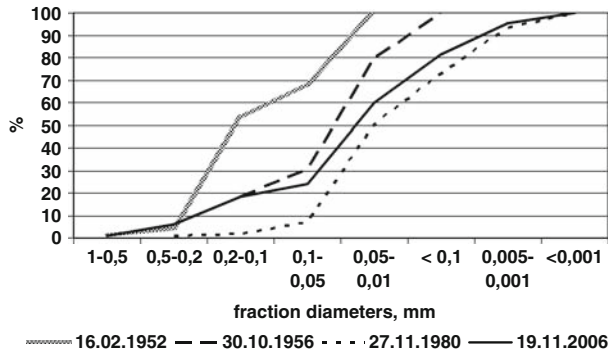
Fig. 3 Cumulative granulometric curves of the different periods near the mouth

Analyses show that there are some changes in the structure of deposited solids. Part of these changes is due to flow regulation, which took place after construction of the Minge-chaur reservoir in 1953. According to the data, fractions with diameters 0.2–0.1 mm were dominated before flow regulation (in 1952), while after regulation the amount of smaller fractions (0.05–0.01 mm) was increased and this increase was observed even later; e.g., results of tests show that in 1980 smaller fraction portions with diameters <0.01 mm formed more than 50% of the deposited sediments. Regardless of this increase, last year's fraction sizes in granulometric structure of the deposited solids have again increased and, the portion of fractions with diameters 0.05–0.01 mm consists of more than 60%. As regards the sub-stance of the deposited solids, it can be said that all of the sediments consist of only fine sand and clay. Since in downstream parts the Kura is a flat river, with smaller fractions in gran-ulometric structure, these changes have not resulted in the roughness of the riverbed, and for such rivers Manning's n value is accepted as 0.030. Simultaneously, there are great changes in the roughness of floodplain areas, since most of the floodplain forests were cut down. In most floodplain areas, n values before deforestation was nearly 0.015; however, after deforestation these values increased to 0.035, which resulted in increasing coastal erosion.

4.2 Changes in channel capacity

Although the changes in granulometric structure have not resulted in modifications of river roughness, during the past 60 years there have been serious changes in the channel capacity of the river. For identifying change in channel capacity as well as assessing sedimentation of the Kura state–discharge curves have been constructed. Curves have been constructed for the sites at Yevlakh, Zardob, Surra, and Salyan, where lengths of obser-vations are enough to evaluate the long-term changes. These state–discharge curves from various periods of time fully illustrate the change in channel capacity for the Kura River and show an overall increase in the riverbed elevation during the last half century (Fig. 4). This can be indirectly linked to intensive sediment accumulation and silting on the riv-erbed. The amount of accumulation in the riverbed increases from the source to the mouth of the river, and is also accompanied by decreasing flow rates. The most intensive period of channel deposition took place in the last decade; for example, at the Yevlakh site, while approximately 50 cm of sediment accumulated in the channel from the 1960s to 1994, twice that amount, 100 cm, had been permanently deposited there during the last 10 years (1994–2003). Channel elevation actively monitored at the Zardob site shows a 120–130 cm rise in the streambed level in some places during the last decade. By comparing the curves of the Salyan at different times, the change in channel elevation has about a 100 cm rise during the last decade, and occurred mainly in the bank areas. An analysis of discharge rating curves for the Salyan for years 1993 and 2003 also supports siltation of the channel with a total of about 100 cm and fully reveals the decrease of channel capacity in the riverbed (Fig. 5). A notable increase in channel elevation occurred at all of the afore-mentioned sites, with the greatest increase in elevation occurring in the banks. This pattern is typical of natural levee development, where the lowest velocities along the banks support higher rates of deposition than in the thalweg of the river.

There are serious changes in channel capacity along the river. Most harmful reductions in channel capacity in the Salyan and Zardob sites are observed. The sedimentation in the Salyan area from 1960 to 2003 makes 750 m³/s of decrease in channel capacity, and in the Zardob site about 450 m³/s. According to the estimations, in Salyan, the MAF value on April 15, 2004 was approximately 1,050 m³/s. Nevertheless, the same value for the cross section of 1993, shown in the Fig. 5, reached 1,300 m³/s.
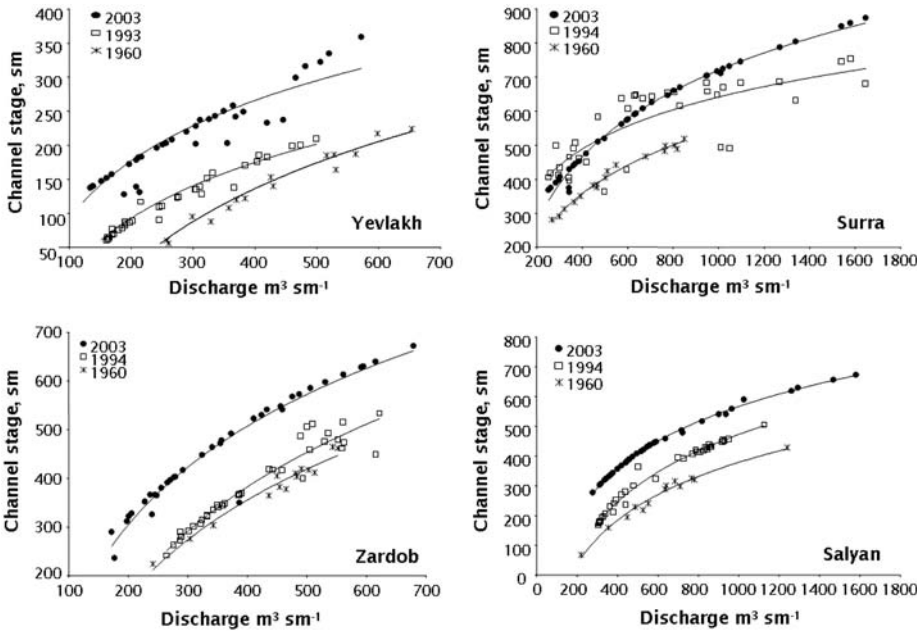
Fig. 4 State–discharge curves in different years for different sites (channel stage above the datum)
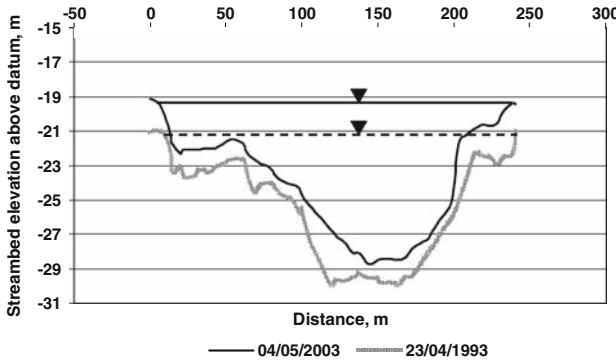

Fig. 5 Rising of the riverbed at Salyan over the period 1993–2003

Changes in channel capacity and construction of dykes may contribute to underground flooding, for example, in 2005, in the Salyan site area, when groundwater levels raised enough to disrupt the agricultural productivity at irrigated fields along the bank, even though the channel itself did not overflow (Fig. 6). This situation occurred after the construction of several dykes on the Kura River that are aimed at eliminating surface channel flooding. Since these dykes are higher than the natural riverbanks, they cause the ground water level to rise and damage the floodplain facilities even though no surface channel flooding occurred. As a result of this, underground flooding is observed long before flooding occurs. This example illustrates how groundwater–surface water interactions between the surface channel and the alluvial aquifer can cause the water table to rise above

Fig. 6 Underground flooding near the outlet in 2005 (right coast)

the ground surface in some fluvial systems. For this situation, the channel's MAF is always less than the channel capacity. Excessive in-stream sedimentation in the lower regions of the Kura River basin can cause not only a diminution in the overall channel capacity but also an increase in surface water elevation, which can drive water through the streambed and into the nearby aquifer. Both these can affect the MAF values to reach the river. This has been observed in the river Kura during the last 10 years, with active sedimentation in the streambed caused by intensive deforestation in the basin.

Figure 7 illustrates the relationship between underground water tables and water level at the Salyan site in 2004 using data from the experimental well 1. Similar relationships have been established for all the four wells. The R^2 for such relationships ranges from 0.92 to 0.96. Such relationships can be used to estimate MAF for any area and can be used to forecast underground flooding using hydrologic forecasts. Hydraulic conductivity of soils between the channel and wells ranges from 0.083 m/h (well #1 and #2) to 0.18 m/h (well #3).

Figure 8 illustrates the channel cross section, surveyed on April 15, 2004, and a $Q = f(\omega)$ curve for the Kura River at Salyan (a site on the Kura) for several flow events that occurred in 2004. As seen in the figure, the area of the maximum cross section for a surface water elevation of -22 (22 m below mean sea level) was computed to be
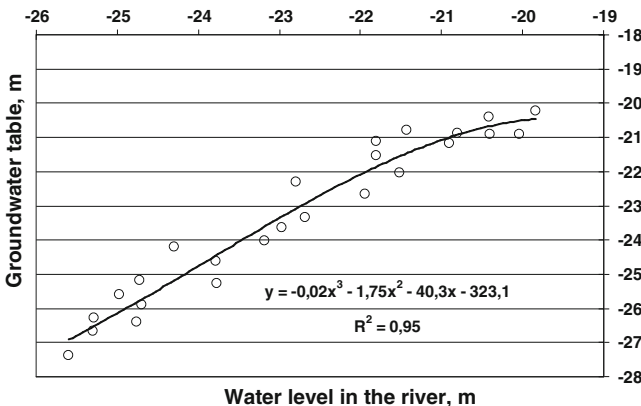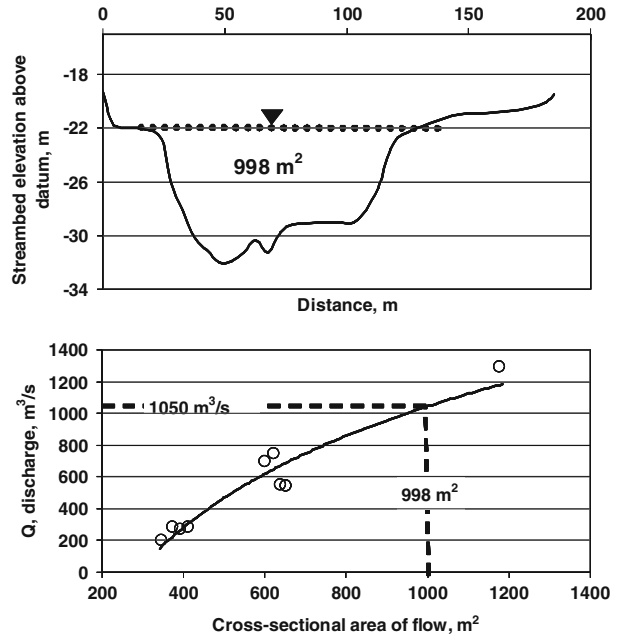

Fig. 7 A relationship between groundwater table and water level at Salyan site, 2004

Fig. 8 Cross section of the Kura
River (*top*) and a $Q = f(\omega)$ curve
at Salyan on April 15, 2004

approximately 998 м². This curve reflects the relationship between the cross-sectional area
and the discharge flows. The site's MAF may be computed for maximum capacity based on
this curve. It was defined that flows no larger than 1,100 m³/s could be conveyed through
the maximum cross-sectional area of 998 м². In other words, it was defined that MAF for
the Salyan was 1,050 m³/s in 2004, and any flows exceeding 1,050 m³/s can be considered
"undesirable discharge" events.

In dry climates where channel levels are consistently low, there is no need to estimate
the MAF for the entire water year. In rivers with intensive in-stream sedimentation, MAF
value may change very rapidly. For such rivers, it may be necessary to compute a new
MAF at the beginning of every high-water season. MAF computations before high-water
season allows for further regulation of outlets further downstream in order to prevent
flooding and enable forecasters to predict floods, including underground ones.

5 Conclusion

The investigations performed in this study have shown that over the past century, flood
formation conditions in the downstream of the Kura have completely changed and there are
growing impacts of non climatic factors. The Kura Basin is experiencing severe erosion
problems as a result of intense deforestation in catchments of small rivers and floodplain
territories. Deforestation also has caused changes in the granulometric structure of sus-
pended and deposited solids. Consequently, high rates of sediment runoff has caused
sediment accumulation in the low parts of the river and, sediment accumulation in the
riverbed over long period of time has led to the reduction of channel capacity, raising the
channel stage above the surrounding territory. The construction of dykes in the river coasts
elevates the riverbed even further, thus creating the effect of an "above-ground river,"
which increases risk of underground flooding where rates of hydraulic conductivity high.

Underground flooding refers to a situation where high levels of ground waters disturb the processes of human activity. Underground floods may occur not only in those cases when ground waters go out of the surface of the land, but also when they stay very close to the surface.

In order to forecast underground flooding, simple solutions have also been proposed for estimation of MAF through regression relationships of underground water table with the surface water level. MAF is defined as a maximum amount of water flowing through a cross section in the given unit of time that does not cause any danger to floodplain facilities and households. Hydraulic conductivity of soils near the channel can also influence MAF rates; accordingly, high rates of hydraulic conductivity will decrease MAF rates.

Results show that construction of dykes cannot increase MAF for rivers such as the Kura, since there are high interactions between the surface water and groundwater, a flow event that falls under normal high water levels can lead to the rise in groundwater levels, causing "groundwater flooding." MAF computations and estimating hydraulic conductivities before high-water season allows for further regulation of outlets further downstream in order to prevent flooding. Moreover, estimating these conductivities facilitates flood prediction, including underground floods.

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