Geocarto International

ISSN: 1010-6049 (Print) 1752-0762 (Online) Journal homepage: http://www.tandfonline.com/loi/tgei20

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To cite this article: Saleh Yousefi, Hamid Reza Moradi, Saskia Keesstra, Hamid Reza Pourghasemi, Oldrich Navratil & Janet Hooke (2017): Effects of urbanization on river morphology of the Talar River, Mazandarn Province, Iran, Geocarto International, DOI: 10.1080/10106049.2017.1386722

To link to this article: http://dx.doi.org/10.1080/10106049.2017.1386722

Publisher: Taylor & Francis
Journal: *Geocarto International*
DOI: http://doi.org/10.1080/10106049.2017.1386722

Effects of urbanization on river morphology of the Talar River, Mazandarn Province, Iran

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Abstract

Rivers are the most important indicators of environmental changes. In the present study, we investigate the effects of urbanization growth on river morphology in the downstream part of Talar River, east of Mazandaran Province, Iran. We analysed aerial photos of the 1955–2013 period. Morphological and morphometric parameters in ten equal sub-reaches were defined along a 11.5 km reach of the Talar River after land cover maps were produced for 1955, 1968, 1994, 2005, and 2013. Land cover types changed extremely during the study period. Residential lands were found to have increased in area by about 1631%, while forest land and riparian vegetation decreased in by approximately 99.9% and 96.2% respectively. The results of morphometric and morphological factors showed that average channel width (W) for all 11.5 km of the study river decreased by 84% during the study period, while the flow length increased by about 2.14%. The River Network Change Index (RNCI), the Braided Index (BI), and the Sinuosity Index (SI) were used as morphological indices to assess the changes over the study period. The RNCI was -4.16 m per year during the entire period, showing that the main processes in this part of the Talar River are sedimentation and river narrowing. The BI decreased at a rate of 1.06 and the SI increased at a rate of 0.02, which is likely due to changes in the hydrological and ecological regime due to human impacts. Residential area development around the fluvial systems played a great role in controlling geomorphological characteristics of the rivers, especially river narrowing.

Keywords: River morphology; River channel change; Land cover; GIS

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1. Introduction

Rivers are one of the major landforms of plain landscapes (Das et al., 2014; Kondolf et al., 2007). The morphology of river reaches and segments (e.g. stretches with a length of 101-103 m bank full channel widths) are determined by interactions between inputs such as water (Chen and Tang, 2012; Frascati and Lanzoni, 2010; Jahani et al., 2013) sediment and organic materials, and the characteristics of their boundaries including geology (Cserkész-Nagy et al., 2010; Gordon and Meentemeyer, 2006), land use (Yousefi et al., 2016) and anthropogenic elements (Blanckaert, 2003; Güneralp et al., 2012; Hooke, 2013; Howard, 2009; Imwangana et al., 2014; Leopold, 1973; Staelens et al., 2006). These river reach morphologies are known as hydro-geomorphological forms. Dynamics in alluvial rivers, because of spatial displacement in floodplains and change in flood risk, are important for human life (Dai et al., 2008; Engel and Rhoads, 2012; Wiliams, 1986; Zaimes et al., 2004). River systems are one of the most important factors for morphological changes of the flood plains (Güneralp et al., 2012; Güneralp and Rhoads, 2009; Spitz et al., 2001; Yousefi et al., 2016). This highly dynamic process, may create major problems in flood plains such as flooding (Hooke, 2016a), sedimentation (Rhoads et al., 2016), incision and bank erosion (Camporeale and Ridolfi, 2010; Dépret et al., 2017; Posner and Duan, 2012; Yousefi et al., 2017). A change in one of the morphological variables of a river, can cause a change in other morphological and ecological characteristics, such as channel depth (Frothingham and Rhoads, 2003), sedimentation and erosion process (Chu et al., 2006; Engel and Rhoads, 2012), restoration projects (Lorenz et al., 2009; Lorenz and Feld, 2013), urbanization development (Alayande and Ogunwamba, 2010), discharge (Camporeale and Ridolfi, 2010; Dépret et al., 2015; Riley and Rhoads, 2012) and land use (Lorenz and Feld, 2013; Yousefi et al., 2016). Therefore, changes to the fluvial system such as morphological changes, are obvious signs changed drivers and characterisitics of the system. The evolution of the river geomorphology can therefore be considered as a tool to assess the impact of the changed drivers of the system (Dai et al., 2008; Keesstra et al., 2005; Kondolf et al., 2007; Kong et al., 2010; Nardi et al., 2012; Yang et al., 1999; Yousefi et al., 2014). Changes in sediment load (Price and Leigh, 2006), slope (Hooke, 1984), climate (Van De Wiel et al., 2011), discharge (Hooke, 2016b; Russell et al., 2016), building dams (Dai et al., 2008; Ma et al., 2012), bridges (Yousefi et al., 2015) large woods (Boivin et al., 2016), human interference (Gregory, 2006; Kiss and Blanka, 2012; Vanacker et al., 2005), land abandonment (Keesstra et al., 2005) and land use in marginal area of rivers (Clark and Wilcock, 2000; Gordon and Meentemeyer, 2006; Kivarz et al., 2014; Yousefi et al., 2017), change the conditions for the river characteristics in the plains.

Historically, alluvial rivers have been a good source for gravel mining (Belletti et al., 2016; Liro, 2015; Rinaldi et al., 2005). In-channel mining is sometimes promoted in alluvial rivers to increase channel flood capacity and prevent flooding (Rinaldi et al., 2005; Russell et al., 2016). Gravel mining then induced changes in hydraulic conditions and bedload transport and associated channel adjustment such as channel incision, widening or narrowing (Belletti et al., 2016; Magliulo et al., 2016; Sanjuán et al., 2016; Surian and Rinaldi, 2003). Such changes has direct effects on human stakes, which is well illustrated by bridge undermining and sometimes collapse or increase in bank erosion and associated infrastructure damages and limitation of uses on adjacent lands developed for residence or agriculture (Kondolf et al., 2007).

Changes in the river parameters over time need to be considered for urban planning, dam and road construction, erosion and sedimentation control (Chin, 2006; Niezgoda and Johnson, 2005; O'Driscoll et al., 2009; Overeem et al., 2013; Paul and Meyer, 2001). Approximately, fifty percent of the world population is currently residing in urban areas, a value that is likely to increase in the near future (Alayande and Ogunwamba, 2010; Cohen, 2003; O'Driscoll et al., 2010, 2009). Many urban centers develop around water resources such as rivers. River systems provide drinking water for the population and irrigation water for agriculture (Alayande and Ogunwamba, 2010; Das et al., 2014; Grischek et al., 2002). Over the past decades, urbanization has altered watershed systems, including the removal of the riparian vegetation (Arnold and Gibbons, 1996; Meybeck and Vörösmarty, 2005; Meyer et al., 2005; Rutherfurd and Price, 2007; Yanan et al., 2011; Zaimes et al., 2004).

The population density is higher in northern Iran than in other regions of the country (Safaripour et al., 2012; Yousefi et al., 2015). The southern shore of the Caspian Sea is the most important agricultural and economical region in Iran and also attracts tourism (Jahani et al., 2013). During the past decades, these areas had to endure high environmental pressure because of the increase in the local population and tourists (Ghadiri Masoum et al., 2014; Yousefi et al., 2015).

Many researchers have studied the consequences of urbanization on the fluvial system in terms of hydrological, geomorphological, and ecological functioning(Das et al., 2014; Kondolf et al., 2007; Kong et al., 2010; Paul and Meyer, 2001). For instance, (Leopold, 1973) reported that during a study period of 20 years in a river in the United States, the channel width decreased because of residential sprawl. However, (Doll et al., 2002) and (O'Driscoll et al., 2010, 2009)found that channel dimensions and channel homogeneity increased due to urban development, while flow length or drainage intensity decreased.

Worldwide, most human communities have developed around rivers, especially in the floodplain part of rivers. Therefore, investigation of the effects of urban sprawl on alluvial rivers in geomorphology of the rivers is essential to inform landscape managers. By knowing pattern changes in fluvial parameters during the urban development, the future of the fluvial systems behavior can be predicted. This can help watershed managers to better understand the effects of land cover changes especially of urban development on fluvial system parameters can be expected to make better management decisions, and help to minimize the damage resulting from river change. Despite the importance of this subject looking into the dynamic interaction between rivers ecosystem and human communities, there are no clear studies that have addressed this issue. Therefore, the main purposes of this study are: i) to investigate the morphological changes during the period 1955-2013 in a braided reach of the Talar River which is one of the most important and largest rivers in the northern Iran, ii) to assess the effects of urban development on the observed changes.

2. Materials and Methods

2.1 Characteristics of the study area

The study area is located in the Talar River basin, one of the largest basins in the Caspian Sea Watershed with a drainage area of 2,845 km^2 (Figure 1). The headwaters of the Talar River are in the Alborz Mountains (Safaripour et al., 2012), and it flows approximately 150 km to the Caspian Sea. For the period 1951-2013, the mean annual precipitation was calculated as 729 mm and there were on average 114 rainy days during a year. The distribution of precipitation is uneven over the seasons, with 8%, 19%, 48%, and 25% falling in spring, summer, fall, and winter, respectively. The annual average temperature for the study area is 17.3ºC (Yousefi et al., 2015).

For the investigation reported in this paper, we focused on a study site located upstream of Ghaemshahr City (320,741 inhabitants) in the Ghaemshahr Township (Mazandaran Province). The site features an alluvial area with gravel sediment and comprises an area of about 8,332 ha, including a reach of the Talar River with a length of 11,551 m. The river has a braided morphology and features a mean discharge of about 14.3 m^{3}s^{-1}. The average channel bed slope is approximately 1.96%.

2.2 Data

In this study, aerial photos were used to extract land cover maps as a main data source (Table 1). All aerial photos were provided by the National Cartographic Center of Iran (NCCI). Aerial photos were scanned at 1200 dpi resolution and have been combined to a mosaic according to the Digital Number (DN) based method using Microsoft ICE (Microsoft Image Composite Editor 1.4.4) (Yousefi et al., 2015). The geometric corrections on the images were carried out using the map-to-image method, using 79 ground control points that were selected on vector layers of roads and residential area (Giriraj et al., 2008). Geometric corrections of the images were carried out by a non-parametric method of polynomials (Yousefi et al., 2015). After removing unidentifiable points (points that were very hard to find in aerial photos), using 68 ground control points (GCPs) geometric correlation was done and an average RMSE of 1.6 pixels was achieved (Hughes et al., 2006; Kivarz et al., 2014).

For this study at the first the supervised image classification methods including the SVM(support vector machine), ML (maximum likelihood) and NN(neural network) were applied to produce land cover types. But regards to the type of our data (old aerial photos) the outputs were not acceptable and for all of theclassificationmethods the overall accuracy was less than 43%. So, land cover maps in 1955, 1968, 1994, 2005, and 2013 were determined by digitizing or visual interpretation of aerial photos in ArcGIS 10.2. Land cover maps were grouped in seven classes:

- Agriculture; including wheat and rice farmlands;
- Garden/orchards; lands that are covered by fruit trees;
- Residential/urban area; any developed area and other human construction;
- Bar; alluvial bars and islands that are created by sediment deposit processes;
- Water body; the area that is covered by water, including irrigation pools and rivers.
- Riparian vegetation/meadows; riparian area is the interface between land and a river or stream, this area includes natural straw, grass, and lawn;
- Forest; the lands that are covered by natural trees including different species viz. *Quercus castaneifolia, Carpinus betulus, Populus caspica,* and *Parrotia persica;*

2.3 Morphometric and morphological parameters

In ArcGIS10.2, the channel body (combining by waterbody and unvegetated bars) was obtained for 1955, 1968, 1994, 2005, and 2013 from the aerial photographs. The study area was determined by creating a 3.5 km buffer from the studied river reach on both sides (Yousefi et al., 2016). The channel area of Talar River was extracted from the land cover maps for each aerial photo set. Active channel area was calculated by summing the area of unvegetated bars and of river water body. It was divided into 10 equal sub-reaches in term of length. Morphometric characteristics including active channel width (W), water flow length (S), section length (L), erosion area (EA), sedimentation area (DA), and alluvial bar length (BL) were calculated for each study period and all ten sub reaches. The erosion area (EA) is the area that by channel variation process during a period, channel turned to be a part of the active channel by the end of the period. DA is the area of active channel that has been changed to other land cover types during a period. In addition, the morphological indices such as the sinuosity index (SI) (Eq. 1), the braided index (BI) (Eq. 2), and the River Network Change Index (RNCI) (Eq. 3) were calculated for all sub reaches in 1955, 1968, 1994, 2005, and 2013 using AUTOCAD2009 and ArcGIS10.2 (Brice, 1960; Grenfell et al., 2013; Wu et al., 2008; Yousefi et al., 2017, 2016).

$$\mathrm{SI} = \frac{\mathrm{S}}{\mathrm{L}} \qquad (1)$$

$$\mathrm{BI} = \frac{\sum \mathrm{BL}}{\mathrm{L}} \qquad (2)$$

$$RNCI = \left(\frac{\sum EA - \sum DA}{L}\right)/Y \qquad (3)$$

where, Y is the number of years between start and the end of a period. Channel width was calculated by 1,155 cross sections in 10 meter intervals along the study reach by Fluvial Corridor 10.1 (Roux et al., 2015). In addition, the length of alluvial bars was calculated using the Longest Line Extension in ArcGIS 10.2. The GIS data was complemented by 20 point field observation performed in summer 2014 (Figure 2).

2.4Hydrological data

The mean annual suspended sediment load, water discharge, and precipitation have been provided for Kiakola hydrometric station located downstream of the study reach from 1955 to 2013, and the maximum annual discharges have been extracted for the study period (Figure 3). The maximum discharge recorded between 1955 and 2013 was 568 m^{3}s^{-1} in 1988, when an unexceptional precipitation was recorded (i.e.

1,067 mm). In the period 1955-2013, the mean annual discharge at Kiakola station is 14.31 m^3s^{-1} for the study period (Yousefi et al., 2015).

3. Results

The generated land cover maps show that during the study period the land cover has changed dramatically (Figure 4). Natural cover (forest and riparian lands) were removed almost completely, especially in the first period (1955-1968), and residential area increased in the study area. In addition, the results of land cover mapping show that during the study period (1955-2013), the study area has endured high variations in land cover types (Figure 5). The area of residential lands or urbanization development has increased significantly, from 1.87% to 32.4% (Figure 6). Riparian vegetation and forest lands observed the contrary, a rapid decrease from 33.3% to 0.09% (Figure 6). During the study period, the active channel area has decreased from 355 ha (4.2%) in 1955 to 77 ha (0.92%) in 2013 (Figure 6). The total area of alluvial bars has decreased from 260 to 33 ha between 1955 and 2013 (3.1% and 0.4%). The observed trend intensified after 1966 (Figure 6). Active channel vector layers have been extracted from land cover maps for all dates (Figure 7). The area covered by the active channel, decreased from 95 to 43 ha between 1955 and 2013.

The population grew from 34000 inhabitants in 1955 to 320000 inhabitants in 2013, which led to an associated large increase in the residential land areas. Developed areas moved closer to the river channel and occupied the floodplain area especially, causing channel narrowing by agricultural and economical activities.

Also, morphometric variables were studied for all ten sub-reaches (Table 2). Average flow length during the 58 years increased by about 278 m (2.14%) and the total length of alluvial bars (BL) decreased by about 12,241 m (70%). The average width of the channel changed from 308 m to 67 m from 1955 to 2013. Monitored morphological indices showed that during the study period, the study reach of the Talar River passed an important stage of evolution and an extreme narrowing process occurred.

The average of RNCI during the study period was about -4.1 m year-1, with the greatest channel change values of -6.12 m $year^{-1}$ recorded for 1966-1994. The negative value of RNCI indicates that sedimentation or narrowing is the main process in the study river (Nelson et al., 2013; Yousefi et al., 2016). Braided index (BI) reached a highest value of 1.9 in 1966 and dropped to 0.4 by 2013. By 2013, the sinuosity index had increased by about 0.02 from a starting value of 1.12 in 1955 (Figure 8). More details about morphological indices are shown in Table 3. Figure 9 shows the bank retreat in river sides that have been occupied with residential area which has increased in the last two periods (1994-2005 and 2005-2013).

4. Discussion

In the study area, forest and riparian vegetation were changed to other land use types. About 99% of the riparian vegetation was removed during the past 58 years. Moreover, channel area during this time decreased by a total of about 276.61 ha, corresponding to 79%.

4.1 Effects of urban development on channel morphology

The geomorphological changed in the area have their root cause in several land use changes in the area. The extensive urbanization in the area has had multiple direct and indirect effects on the rivers´ morphology. First of all the observed change in channel width is a phenomenon that has been observed also by other researchers to be the result of urbanization (Alayande and Ogunwamba, 2010; Cabezas et al., 2008; Chin, 2006; Clark and Wilcock, 2000; Yousefi et al., 2016). During the study period, average channel width decreased about 241 m so the river has been narrowing. In addition, the results showed that the maximum width at 1955 was about 962 m and this value decreased to 153 m in 2013. Lastly, the results show that reach number 2 has the highest variation in channel width during the 58 years (average channel width decreased by approximately 706 m).

Causes identified by other researchers are mainly the depletion of sediment in the channel causing incision. This is on the one hand caused by the changed land use, from largely agricultural land providing sediment to the channel, to urbanized land that is sealed and will provide much less sediment and more water due to the reduced infiltration potential. This causes the river to have higher sediment transport capacity (more water, and less sediment), which causes incision. The decreased channel width which was found in this study as a result of increased residential land area, is in agreement with(Leopold, 1973),(O'Driscoll et al., 2009), and (Kong et al., 2010) who showed the same effects in other parts of the world.

Apart from soil sealing as a result of urbanization in the floodplain and surrounding area, the land cover evolution maps also showed that during the past decades forest lands and riparian cover around the Talar river were removed and agricultural and residential lands have appeared instead of natural covers in the vicinity of the river. In areas where agriculture comes near the river channel, according to the over running to river, the width of the river is reduced and therefore the same amount of discharge in the smaller section is forced to flow down the river more quickly. Increased water velocity caused increased water power, greater incision, and bank erosion and thus increases the water flow length, so that flow length of the section is increasing, as well (Grenfell et al., 2014; Heo et al., 2009; Hooke, 2004; Kondolf et al., 2007; Yousefi et al., 2016).

A last reason for the incision is the practice of sand and gravel mining in the reaches close to the urbanization. The sediments of this part of river have high quality for urban construction. By growth of urban lands, the sand mining of sediments of Talar River has been increased too, especially in the last two decades. The gravel mining causes large changes in the sediment dynamics of the river system. The river is depleted of its sediment, but still has to discharge the same amount of water (or even higher amounts due to the soil sealing effect as described above). Due to the hungry water effect as described by (Kondolf et al., 2007) the river will erode the sediments in the channel and banks to restore the water-sediment balance. Similar effects have been found due to gravel mining by (Brestolani et al., 2015; Calle et al., 2017) and due to land abandonment (Keesstra et al., 2005).

4.2 Effects on alluvial bars and braided index

In 1955, the total alluvial bar length was about 17.4 km and this morphometric factor was about 5.1 km in 2013. However, the number of alluvial bars at the study dates stayed nearly the same (68 and 71, respectively). Thus, alluvial bars became smaller and big alluvial bars were replaced by small alluvial bars. Field observations showed that in many parts of the study site, local residents mined the sands of alluvial bars as a resource for construction. During urbanization, decreasing channel width lead to increasing flow velocities and thus increased sediment transport specifically of fine and small sediment size. O'Driscoll et al. (O'Driscoll et al., 2010) also stated that due to urbanization channel homogeneity is increased.

Also sand mining activities as a consequence of population growth, affects the number of bars. The dimension of bars and braided index decreased from 1.51 in 1955 to 0.46 in 2013. Rinaldi et al. (Rinaldi et al., 2005) in a study in Italy also mentioned that mining sites will change the bar size. However, the SI in the Talar river did not show any significant changes (0.02) in comparison with the RNCI (-3.3 m/year) and braided index (1.06). Morphological indicators are one of the most important characteristics of alluvial river that are affected by urbanization. The RNCI in the study river changed during the past six decades and the average of this index was about -4 m year-1. According to field surveys and subsequent observation of land use maps produced, the study area, particularly in the floodplain, has been interrupted by human activities (Frascati and Lanzoni, 2010; Gordon and Meentemeyer, 2006; Nelson et al., 2013; Spitz et al., 2001; Yousefi et al., 2016). These results may be explained by the fact that SI almost changes in the rivers that flow over slopes no steeper than 0.001 (Ahmed and Fawzi, 2011; Hooke, 2013; Leopold, 1973; Ollero, 2010; Timár, 2003; Yousefi et al., 2016). The morphological pattern of the study reach is braided and the average slope is about 2%. So, the river does not have the required slope in study area to change its pattern.

Bank retreat in the last decades has increased in residential areas (Fig. 9). The main reason of this extensive event is the growth of residential areas, restricting the space available for the river (Fig. 4). We expect that the residential areas close to the channel are more vulnerable to flooding now than in the recent past (Boudou et al., 2016; Hazarika et al., 2016; Maantay and Maroko, 2009). In 1994-2005, the bank retreat in residential areas is more than in the other periods. This can be attributed to a large flood event that occurred in the Talar River on 24/May/2003 with a peak discharge of 492 $m^3.s^{-1}$, which had a return period of more than 20 years (406.2 $m^3.s^{-1}$). Eventhough most of the residential area around the river sides in the study area are protected by armature protection walls, this 20 year return period food that occurred on 24/May/2003 damaged banks and properties.

5. Conclusions

During the last 58 years, the land cover of Talar River floodplain has significantly changed. The area of residential land increased during the period 1955-2013 by about 94 ha (1731%). In addition, in developing countries like Iran, natural resources such as forest lands are rapidly destroyed by human activities; and in alluvial river floodplains because of the high quality of soil, particularly on alluvial banks and in riparian area, previous natural areas are taken into agriculture. The plowing of the land and the destruction of the natural vegetation around the river causes a higher influx of sediment to the river, and more erodible banks. The urbanization causes large scale soil sealing, which increases the water discharge to the river. Sand and gravel mining as a consequence of urbanization further influences the morphology of the river.

In this study we observed the changed channel morphology that comprises of channel narrowing, incision and reduced channel bar size as a result of extensive urbanization. These river changes cause a higher flood risk. Further research on the rate of changes and monitoring and evaluation in the other rivers in northern Iran should be done to better understand effects of human activities in river geomorphology.

Acknowledgments: The authors would like to thank Dr. Jens Martin Turowski (Senior Research Scientist, Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences) for reviewing of manuscript language and its correction before submitting.

Author Contributions: Saleh Yousefi, Oldrich Navratil and Hamid Reza Moradi conceived and designed the experiments; Hamid Reza Pourghasemi. Performed the experiments; Saleh Yousefi. and Saskia Keesstra analyzed the data; Janet Hooke contributed reagents/materials/analysis tools; Saleh Yousefi and Saskia Keesstra wrote the paper.”

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TABLES

Table 1 Aerial photos used in this study

Data	Date	Scale	Flow (m3/s)	Suspended Sediment (g/l)
Aerial Photo	1/Aug/1955	1:40000	3.97	27.33
Aerial Photo	27/Jul/1968	1:20000	4.12	28.25
Aerial Photo	23/ Oct /1994	1:20000	4.31	29.93
Aerial Photo	29/Jul/2005	1:40000	3.86	26.45
Aerial Photo	6/Aug/2013	1:10000	3.92	25.91
Topographic Map	10/March/2008	1:25000	7.42	68.41

Table 2 Average of morphometric parameters at the study sub-reaches

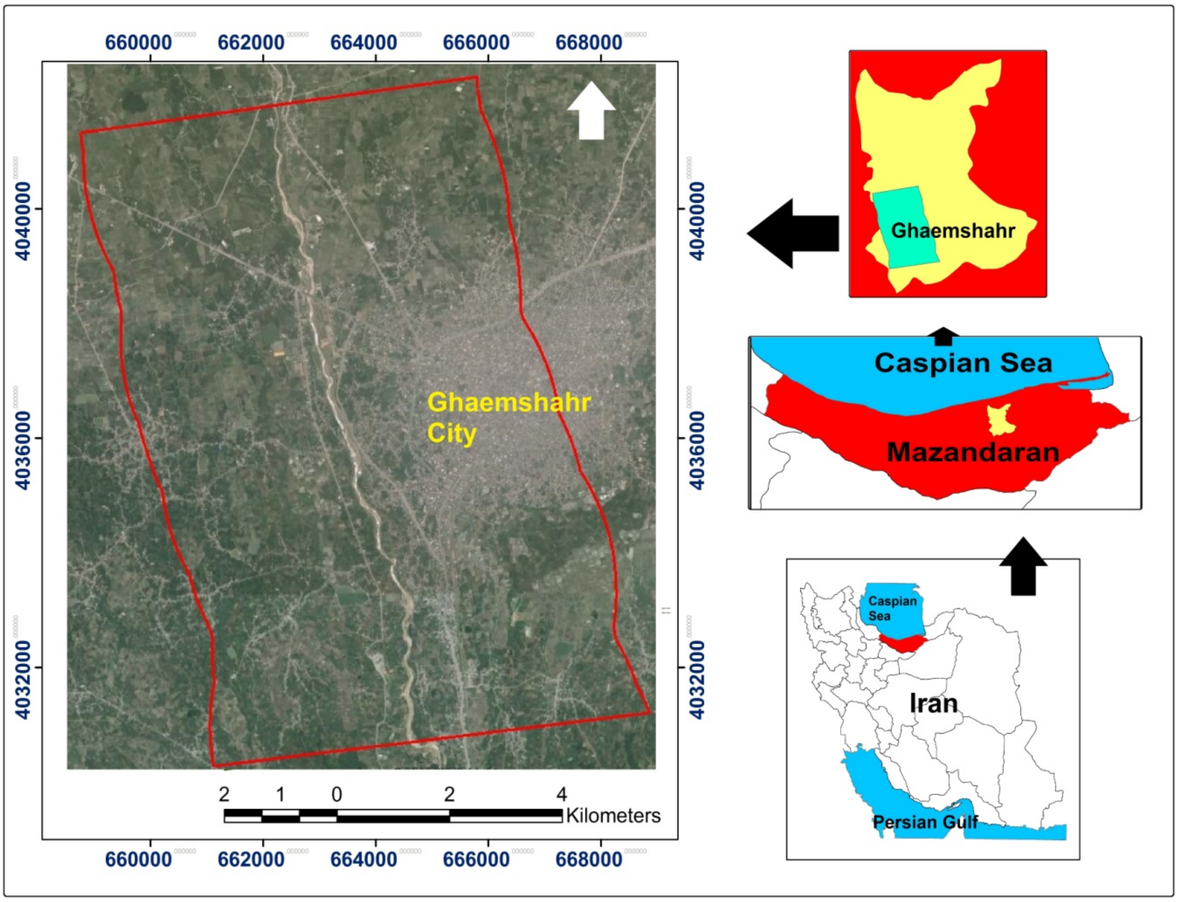
	Alluvial bar length (m)					Flow length (m)					Channel width (m)				
Sub-reach	2013	2005	1994	1968	1955	2013	2005	1994	1968	1955	2013	2005	1994	1968	1955
1	401	357	419	1741	3073	1273	1289	1164	1262	1264	36	75	60	283	355
2	856	1466	1078	4366	1681	1315	1290	1255	1253	1248	92	161	117	472	799
3	310	693	1300	2670	343	1342	1236	1329	1318	1221	62	128	127	328	304
4	353	593	632	3482	2094	1217	1210	1178	1190	1176	53	83	56	439	433
5	732	267	948	2689	2766	1301	1245	1180	1261	1318	59	86	122	331	303
6	739	418	910	1482	2088	1233	1229	1287	1157	1295	77	96	96	232	205
7	342	625	1504	1523	1404	1273	1237	1291	1363	1324	77	121	137	193	168
8	449	514	709	1179	1154	1405	1296	1407	1351	1355	72	115	130	168	154
9	588	616	505	1620	1088	1456	1434	1408	1584	1350	70	109	114	174	165
10	425	512	967	1390	1745	1342	1251	1278	1439	1330	73	117	127	198	210

Table 3 Average of morphological indices at the study sub-reaches

	River network change index (m/year)					Braided index					Sinuosity index				
Sub-reach	55-13	05-13	94-05	68-94	55-68	2013	2005	1994	1968	1955	2013	2005	1994	1968	1955
1	-5.4	-5.4	1.2	-7.9	-6.2	0.3	0.3	0.4	1.5	2.7	1.10	1.12	1.01	1.09	1.09
2	-12.2	-9.8	3.7	-12.7	-30.1	0.7	1.3	0.9	3.8	1.5	1.14	1.12	1.09	1.08	1.08
3	-4.1	-9.2	0.0	-7.0	2.1	0.3	0.6	1.1	2.3	0.3	1.16	1.07	1.15	1.14	1.06
4	-6.4	-4.2	2.2	-13.3	0.4	0.3	0.5	0.5	3.0	1.8	1.05	1.05	1.02	1.03	1.02
5	-4.1	-3.8	-3.0	-7.2	2.5	0.6	0.2	0.8	2.3	2.4	1.13	1.08	1.02	1.09	1.14
6	-2.2	-2.8	0.0	-4.9	2.4	0.6	0.4	0.8	1.3	1.8	1.07	1.06	1.11	1.00	1.12
7	-1.5	-6.1	-1.3	-1.9	2.2	0.3	0.5	1.3	1.3	1.2	1.10	1.07	1.12	1.18	1.15
8	-1.4	-6.5	-1.2	-1.3	1.2	0.4	0.4	0.6	1.0	1.0	1.22	1.12	1.22	1.17	1.17
9	-1.8	-5.6	-0.4	-2.4	0.7	0.5	0.5	0.4	1.4	0.9	1.26	1.24	1.22	1.37	1.17
10	-2.4	-5.9	-0.8	-2.6	-1.1	0.4	0.4	0.8	1.2	1.5	1.17	1.09	1.11	1.25	1.16

Figure captions:

- Figure 1 Geographical location of the study area
- Figure 2 Channel width and alluvial bar length measurements
- Figure 3 Hydrometry data of Kiakola Station
- Figure 4 Land cover maps produced for 1955, 1968, 1994, 2005, and 2013
- Figure 5 Changes in land cover area during study periods
- Figure 6 Land use change trend in study area
- Figure 7 Active channel variations during the study period
- Figure 8 Morphological indices of Talar River during the study period
- Figure 9 Bank retreat in residential area of Talar River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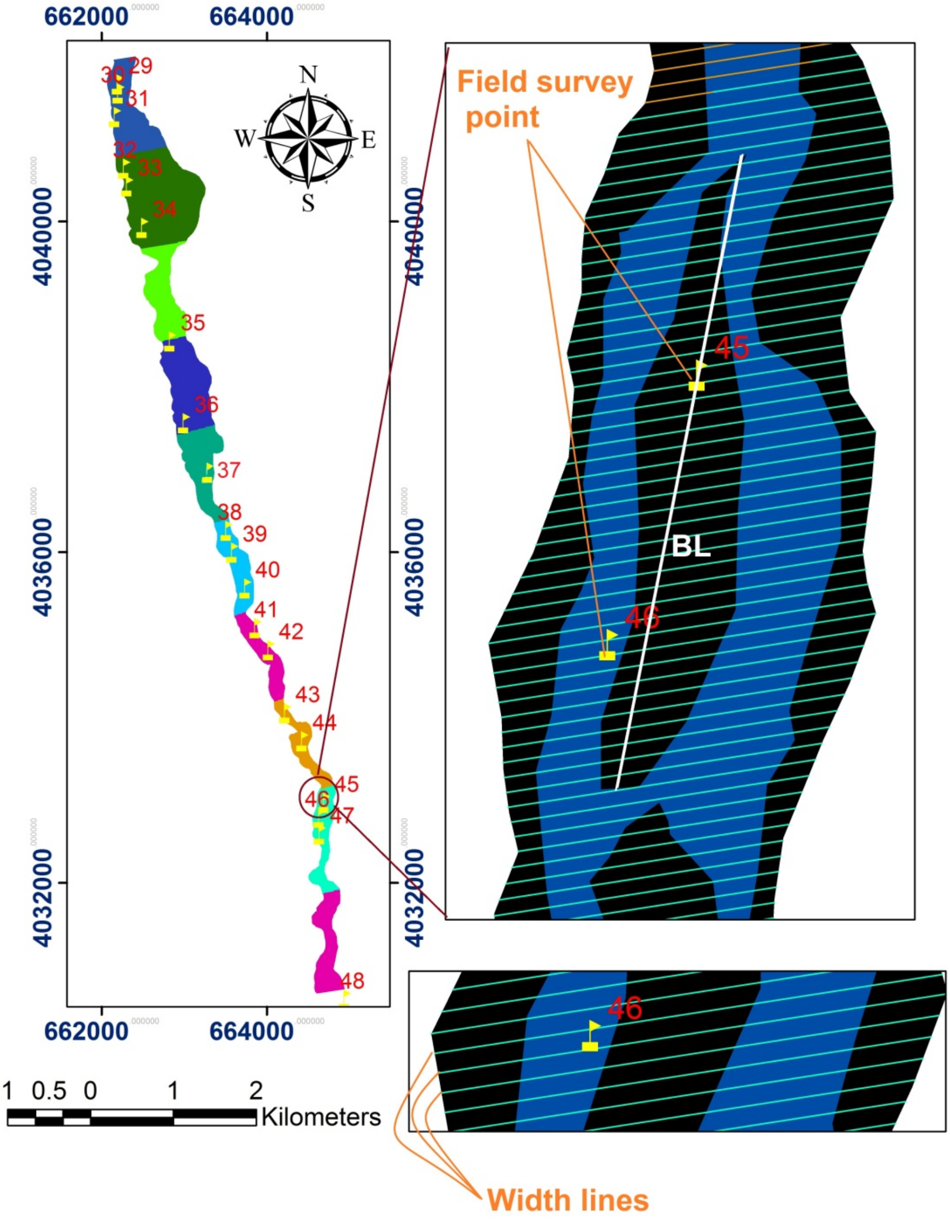
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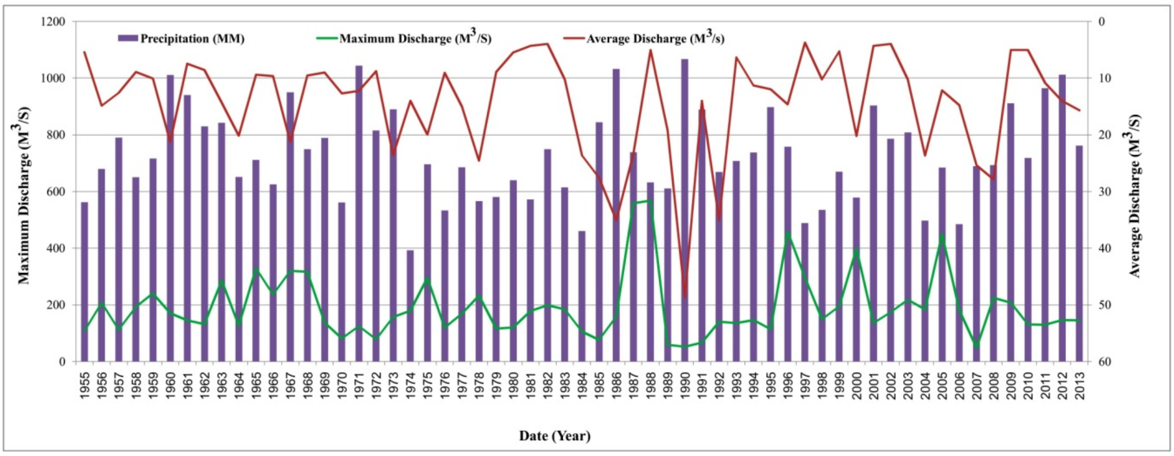
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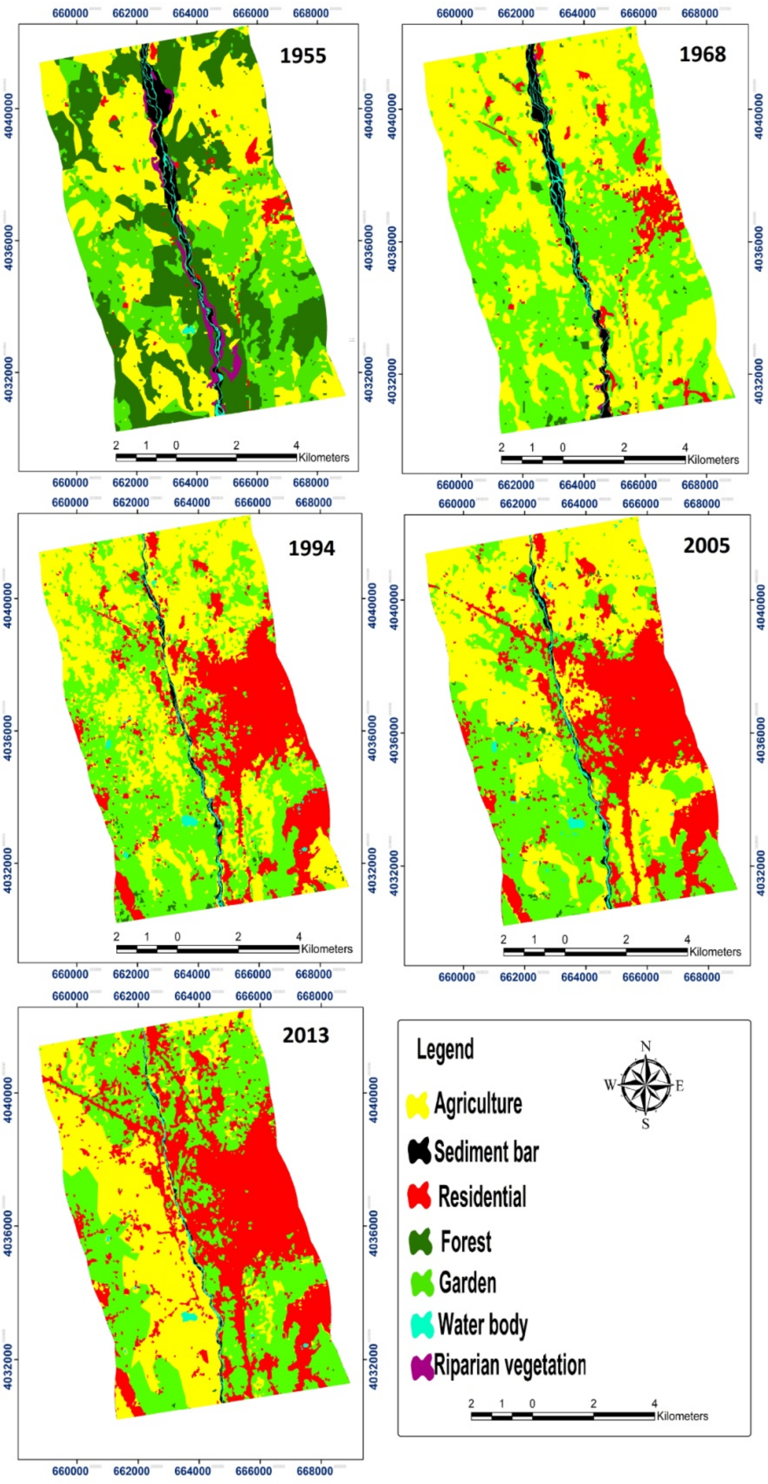
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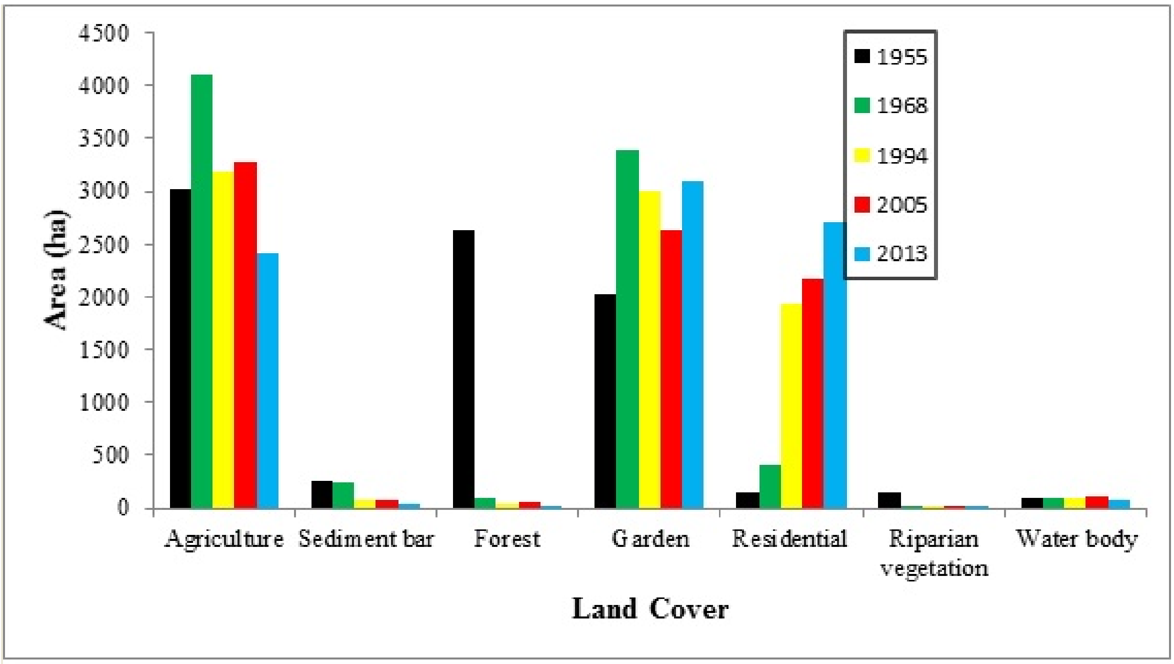
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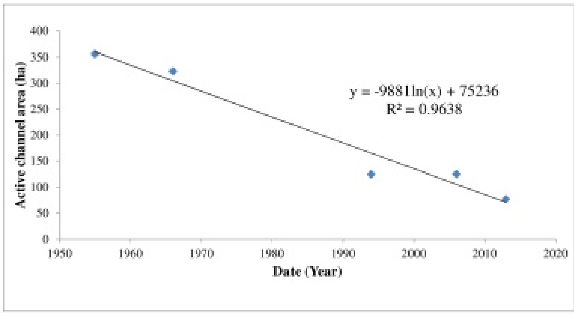
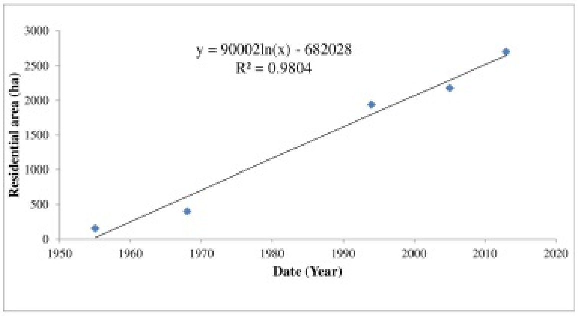
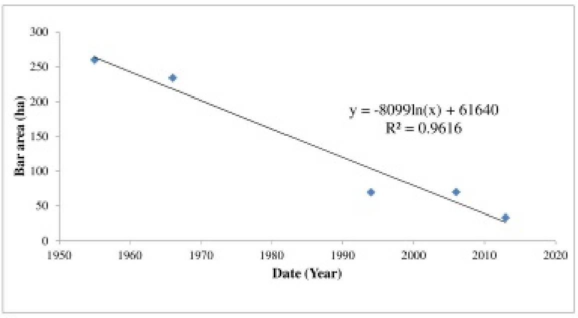
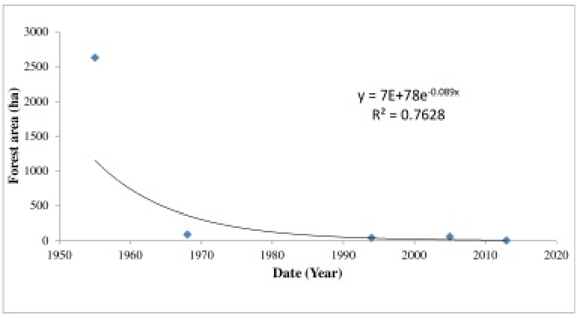
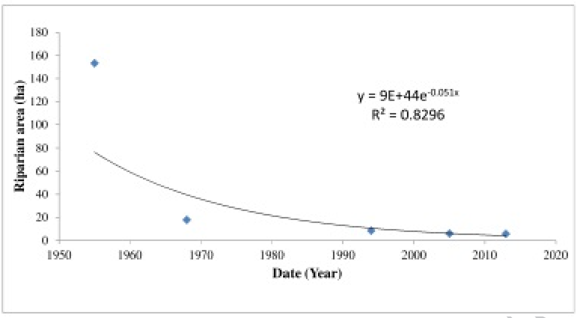
Water body
Land Cover

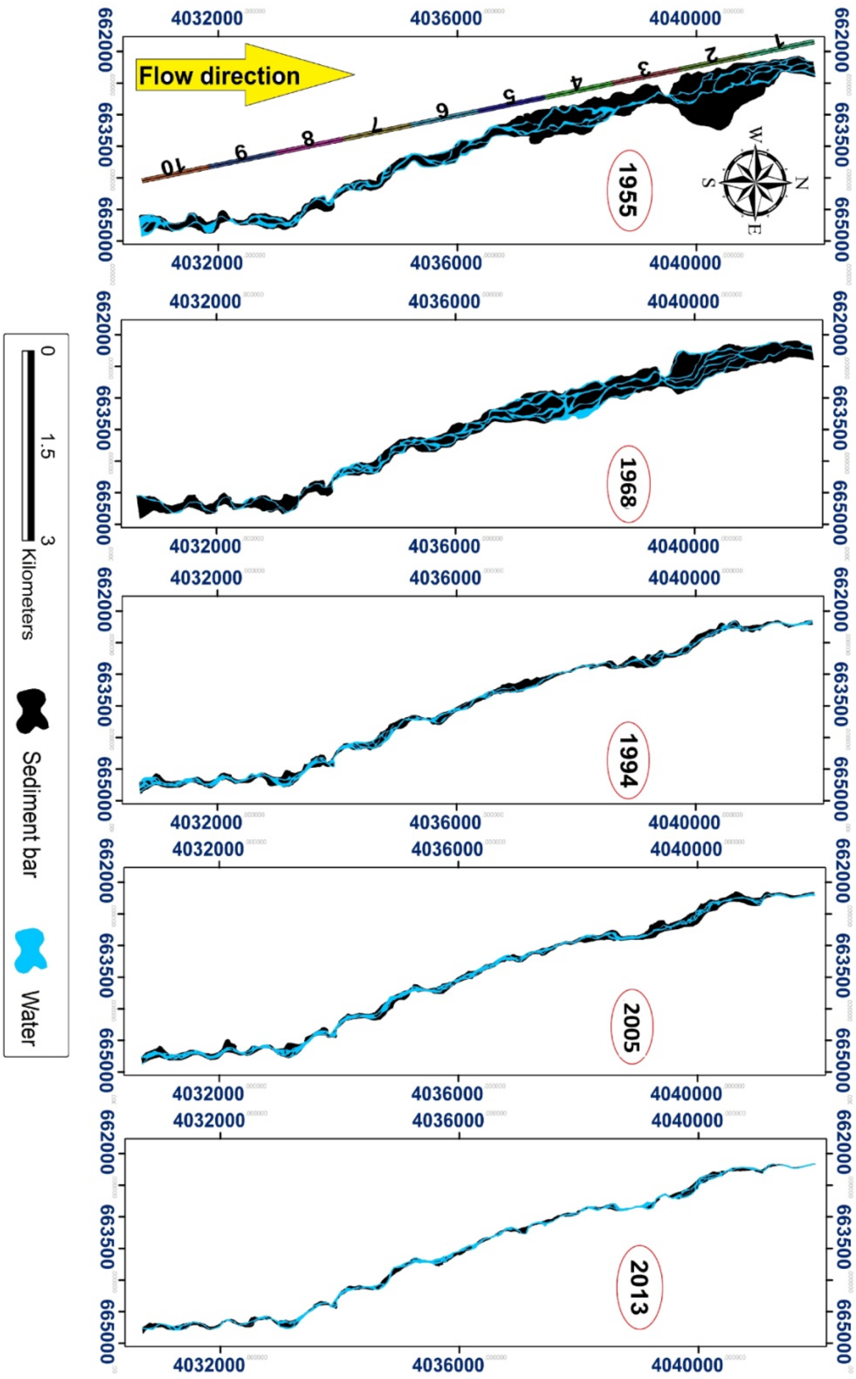

Active channel area (ha)
400
350
300
250
200
150
100
50
0
1950
1960
1970
1980
1990
2000
2010
2020
Date (Year)
$y = -9881\ln(x) + 75236$
$R^2 = 0.9638$

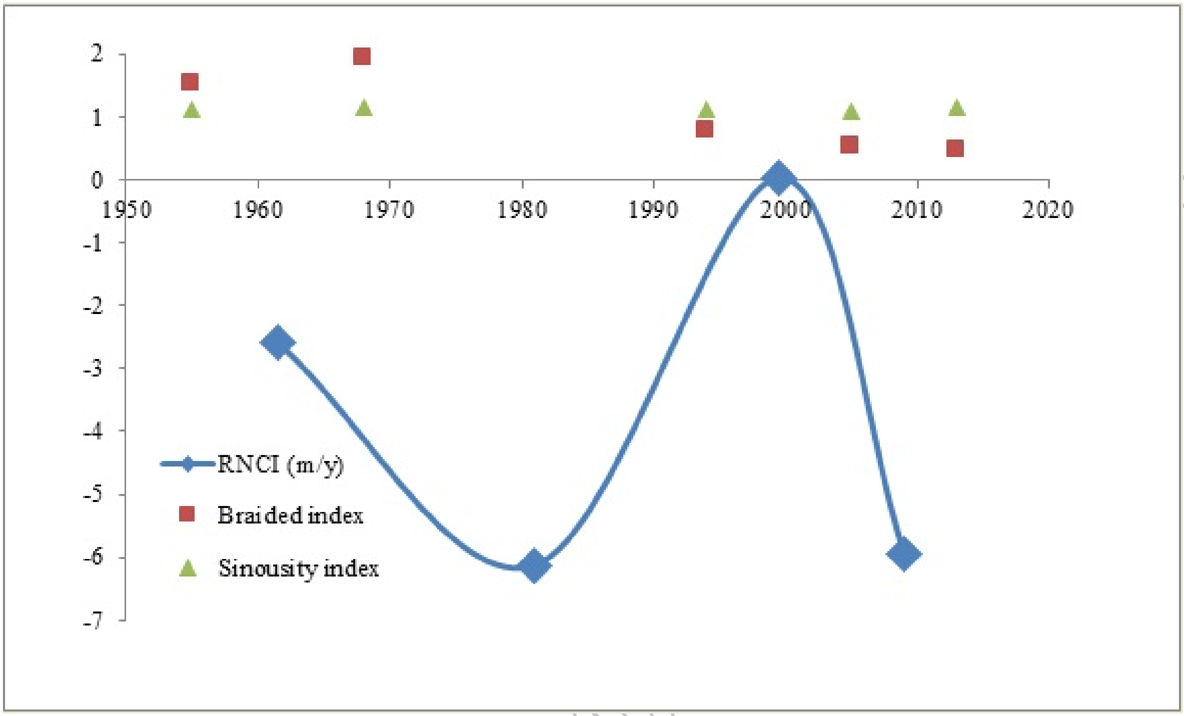

Residential area (ha)
3000
2500
2000
1500
1000
500
0
1950
1960
1970
1980
1990
2000
2010
2020
Date (Year)
$y = 90002\ln(x) - 682028$
$R^2 = 0.9804$

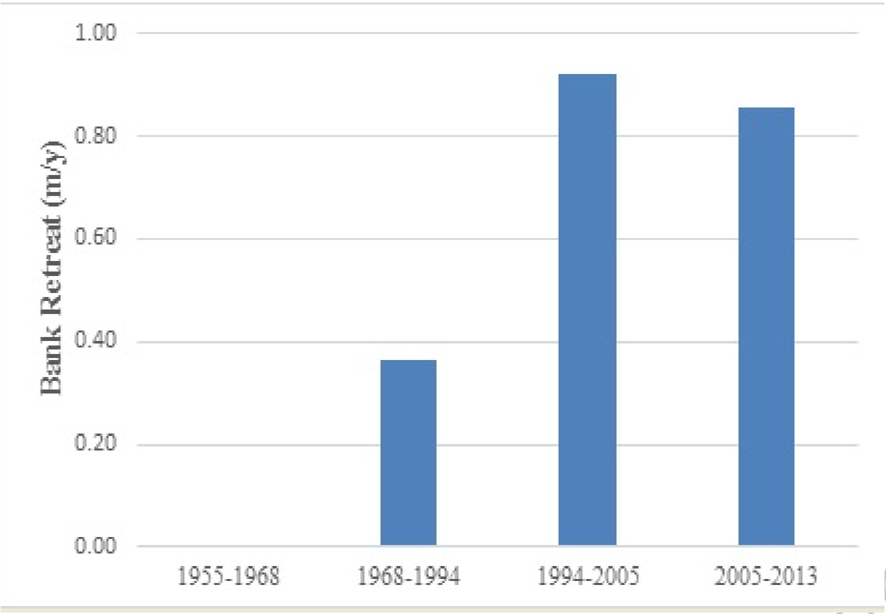

Bar area (ha)
300
250
200
150
100
50
0
1950
1960
1970
1980
1990
2000
2010
2020
Date (Year)
$y = -8099\ln(x) + 61640$
$R^2 = 0.9616$


Forest area (ha)
3000
2500
2000
1500
1000
500
0
1950
1960
1970
1980
1990
2000
2010
2020
Date (Year)
$y = 7E+78e^{-0.089x}$
$R^2 = 0.7628$


Riparian area (ha)
180
160
140
120
100
80
60
40
20
0
1950
1960
1970
1980
1990
2000
2010
2020
Date (Year)
$y = 9E+44e^{-0.051x}$
$R^2 = 0.8296$


Flow direction
1
2
3
4
5
6
7
8
9
10
N
E
S
W
1955
1968
1994
2005
2013
4032000
4036000
4040000
662000
663500
665000
0
1.5
3
Kilometers
Sediment bar
Water


2
1
0
-1
-2
-3
-4
-5
-6
-7
1950
1960
1970
1980
1990
2000
2010
2020
RNCI (m/y)
Braided index
Sinousity index


Bank Retreat (m/y)
1.00
0.80
0.60
0.40
0.20
0.00
1955-1968
1968-1994
1994-2005
2005-2013