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Review / Pregledni znanstveni članak

Moving Borders: Mapping and Monitoring Amu Darya River Dynamics Using Remote Sensing Data and Techniques

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ABSTRACT. Assessment of water-related disaster risk is essential for risk mitigation and management for sustainable development. This problem arises with transboundary waters, adding geopolitical problems to the existing ones. For moving borders, such as the border between Afghanistan and Tajikistan and Uzbekistan, mapping and monitoring of the river dynamics is essential for resolving potential problems that may occur due to shifts in the river bank. In order to achieve the objectives of this study, mapping and analyzing land conversion, river channel dynamics, quantify lateral erosion and accretion in the period between 1990 – 2020, four Landsat images were used. The results of the investigation showed significant shift of the river bank, especially from north to south, causing damages over agricultural areas of the local people in Afghanistan. Also the results showed the total area of the river shift on both sides of the border. The most critical parts of the river were also detected, and it was concluded that some parts of the border moved up to 3 km inside Afghanistan. Such information can help both local and international administration in resolving problems due to unresolved water sharing policies, and can help in making geopolitical decisions beneficial for both parties.

Keywords: remote sensing, Amu Darya, river channel dynamics, Landsat, classification.

1. Introduction

As the essence of life, water is one of the most important substances on Earth. It plays crucial environmental and societal role in all ecosystem services. People`s

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dependence on water is clear as 82% of the world`s population live on previously flooded land, whereas 87% are settled along a river (Tomsett and Leyland 2019). Also, rivers have been used to divide lands, leading to waterways as political borders. According to Popelka and Smith (2020), rivers make up 23 percent of international borders, 17 percent of worlds state and provincial borders, and 12 percent of all county-local borders. The number of international borders as river is the highest in South America, and lowest in Asia. The division of states, cities, and countries with water bodies, often causes political controversies. Also, river dynamics can often cause considerable hazard to those in the surrounding area (Hirabayashi et al. 2013). River dynamics are often described as natural autogenic occurrences for fluvial rivers generally caused from human modifications such as dam constructions, irrigation infrastructure construction, and land use changes, and climatic factors (Langat et al. 2019a). Understanding, monitoring and mapping of the rivers are essential in order to prevent and lower the hazards caused by the river channel dynamics. If the river is transboundary, along with the natural hazards, it can also cause geopolitical problems (Glantz 2005, Yousefi et al. 2017). Transboundary waters have been a reason for conflict in many parts of the world (Ovezova 2015), and it is believed that the struggle for clean and safe water can cause even bigger geopolitical conflicts (Alexandrova and Dhaliwal 2010).

One of the transboundary rivers prone to conflicts is the Amu Darya river. The Amu Darya river is a major river in Central Asia and Afghanistan, and beside being internationally shared water between Tajikistan, Afghanistan, Uzbekistan, and Turkmenistan, it also represents border between Afghanistan, and Tajikistan and Uzbekistan. Since its watercourse is constantly changing, it is very challenging for the local people who depend mostly on agriculture, to claim their rights (Glantz 2005). Afghanistan as an extremely poor country, is highly dependable on farming. Due to war in the past few decades, economic considerations have been secondary to political and military problems (Glantz 2005).

Researchers have been searching for solutions for managing transboundary water resources in the Aral Sea Basin (Haleemzai and Sediqi 2018), as the lack of effective management in the use and development of water caused severe consequences for the natural environment, the human population, and the economies of the sharing countries (Vinogradov and Langford 2001). Situated in the hearth of the Eurasian continent, the Aral Sea Basin is extending over parts of five Central Asian Republics. One of the two major rivers of the Basin, Amu Darya, originates in the mountains of Afghanistan and Tajikistan, and flows through Uzbekistan and Turkmenistan to the Aral Sea. Amu Darya is one of the major transboundary rivers, also representing an international border between Afghanistan, and Uzbekistan and Tajikistan. Although some attempts have been made for agreements for water resources in the Amu Darya basin, trying to deal with the use and quality of the water resources, no significant progress has been achieved. If no progress is made on this topic, this would result in further economic hardship, environmental damage, and create a potential for conflict (Vinogradov and Langford 2001). It has been clearly stated that action is required in order to stop the increase of the crisis in the Aras Sea Basin that affects more than 21 million people, with increased mortality rates, disease and health disorders (Dinar et al. 2007, Bekchanov et al. 2018).

For large areas like the Amu Darya river basin, and poor countries like Afghanistan, efficient and cost effective scientific tools are of great importance. Geospatial data and tools have become valuable tool for mapping and monitoring land use and river dynamic changes all over the world. However, remote sensing as an efficient tool for modern geospatial mapping, has not being widely used in for waterways as political borders. Using Landsat data, Popelka and Smith (2020), recently released a new geospatial database of the world's river borders for large rivers. Langat et al. (2019a) used aerial imagery combined with Landsat for monitoring the river channel dynamics over the river Tana, Kenya and were able to analyze the temporal and spatial channel changes of the river from 1975 – 2017. Billah (2018) used Landsat imagery from 1975 – 2015 for mapping and monitoring the erosion and accretion in the Padma river, Bangladesh, and Dabojani et al. (2014) made similar investigation over the Manu river in Bangladesh. Remote sensing has been successfully used in many studies for river channel dynamics (Langat et al. 2019a, Tadese et al. 2020, Cai et al. 2016, Langat et al. 2019b, Legleiter et al. 2020, Tomsett and Leyland 2019, Sichangi et al. 2016). Together with geoformation systems, remote sensing data can provide excellent tools for river channel dynamics, processing, visualization, and analysis. Beside the river channel dynamics, land cover maps can be produced from the remote sensing data. With spatial analysis, the land cover changes caused by the river dynamics can be also determined. Also, not many studies can be find in the literature on monitoring shared international waters using remote sensing data, except for few study cases over transboundary lakes (Kaplan et al. 2020). This leaves space in the literature for monitoring transboundary rivers and river dynamics with the use of remote sensing and geo-information systems. While most studies in the literature focus only on river dynamics (Langat et al. 2019a, Billah 2018) or land cover changes in the river basin (Langat et al. 2019b, Cai et al. 2016), this study evaluated both land cover changes and river dynamics of Amu Darya river.

The purpose of the presented study is the apply remote sensing data and geoinformation techniques in order to understand the temporal and spatial channel changings and dynamics of Amu Darya river. As a study area in this paper, the Afghanistan border with Tajikistan and Uzbekistan from the beginning of the Amu Darya river, the place where Pyandzh and Vakhsh rivers join, until the Afghanistan border with Turkmenistan (Fig. 1) was selected. The surrounding of the river from the both sides are occupied with croplands. Several provinces are vulnerable in this study are from the floods that usually starts from March till May. The floods happen due to the heavy rains in the mountainous regions where afterwards fills the river basin causing serious river dynamics responsible for hazards, which can be very challenging for the local people who depend mostly on agriculture, to claim their rights (Glantz 2005, Kostianoy et al. 2013).

The first objective is to map and analyze the land cover changes of four classes over the study area and to determine lad conversion from 1990 – 2020 between the investigated classes. The second objective is to map river channel dynamics and to quantify lateral river channel erosion and accretion, and to detect the most changed areas between 1990 – 2020. To achieve the goals in this study, four Landsat images (1990, 2000, 2011, 2020) were used from the same period

(May – July) in order to avoid seasonal changes. The results can be useful in practical applications where regular monitoring of river behavior is needed for decision making. Such information can help both local and international administration in resolving problems due to unresolved water sharing policies, and can help in making geopolitical decisions beneficial for both parties. Also, the results can be crucial in flood risk management strategies, irrigation plans, monitoring systems, etc.

Fig. 1. *Location of the study area.*

2. Materials and Methods

2.1. Satellite imagery

In order to estimate the land cover changes and the river dynamics in the study are, three Landsat TM and one Landsat OLI satellite images from four different years (1990, 2000, 2011, and 2020), in the period between end of May till middle of July, have been used. These periods were cloud free, enabling us to perform the needed analyses. Also, the date selection was made according to the meteorological data, where May to July is the driest period after a wet period in March when flood is most likely to occur. In 2010, there was no cloud-free imagery, and 2011 has been selected instead. Details about the used satellite images can be found in Table 1. All of the scenes were level-1 open-access data sets downloaded from the USGS webpage. The satellite images were then pre-processed applying atmospheric and geometric correction.

Table 1. *Landsat satellite images used in this study.*

No	Sensor	Senor Type	Date of Acquisition	Spatial Resolution (m)
1	Landsat	TM	22/05/1990	30
2	Landsat	TM	17/05/2000	30
3	Landsat	TM	19/07/2011	30
4	Landsat	OLI	07/06/2020	30

2.2. Methodology

One of the most common methods to obtain land-cover information from satellite images is remote sensing image classification. Image classification converts the data into meaningful information. Depending on the supervision, classifications can be supervised and unsupervised, while depending on the data type, two different classification types can be distinguished: pixel and object-based classification. The pixel-based classification has been widely used since the revolution of remote sensing in the 1980s. Pixel-based classification uses multi-spectral classification techniques that assign similar pixel in the same class (Yan et al. 2006).

In comparison with pixel-based classification, object-based classification classifies the image based on objects instead of pixels. Although this technique has been introduced in the 1970s, its application in the remote sensing field started a decade ago (Makinde et al. 2016). Even though this technique has been generally used for high and very high-resolution imagery, it has also been successfully applied in middle-resolution imagery. In comparison with the traditional pixel-based classification technique, several studies have reported the superiority of object-based image classification (Kaplan and Avdan 2017, Esetlili et al. 2018). In order to classify the land cover in the study area, in this paper, OBIA were used. The OBIA was performed in eCognition software. The first and most meaningful step of object based classification is the segmentation, in which the pixels are grouped as objects, or segments. The multiresolution segmentation has been successfully used in segmenting middle-resolution satellite images, like Landsat (Benz et al. 2004). The objects are then formed based on the given criteria (Yan et al. 2006). The criteria in this study were selected as in Kaplan and Avdan (2017). Furthermore, the land cover was classified into four different classes using, Water, Cropland, Bare Land, and Wetland. Using the land cover maps, a land conversion analysis of the study area have been made, calculating the changes and shifts from one class to another. In the second part, using only the water class, river channel analysis have been made, thus calculating the erosion and accretion amount, and also, determining the shift of the river bank on both left and right side of the river (Fig. 2). For the accuracy assessment of the classification, 400 random points have been used, and thus the overall accuracy and the kappa statistics have been calculated.

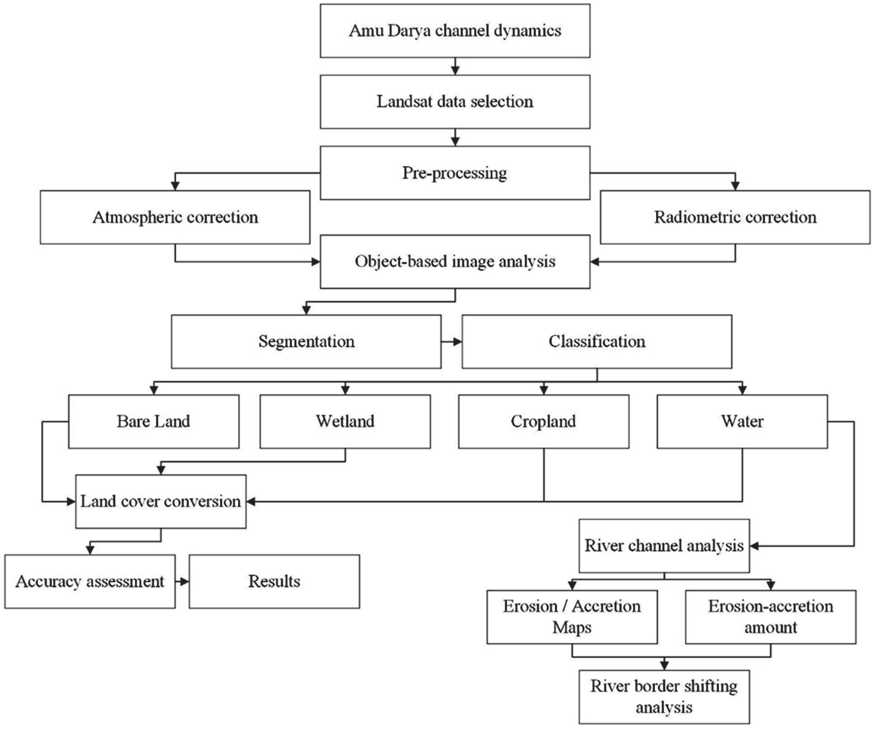

Fig. 2. *Methodology used in this study.*

3. Results

3.1. Land cover classification results

The land cover classification results were mapped and analyzed. The overall accuracy of the classification is 85%. For the accuracy assessment, 400 random points have been used. As a reference data, the Landsat images were used, complied with high-resolution imagery from Google Earth from the same season and year as the classified images. The acceptable critical accuracy value in classification with middle-resolution satellite imagery is 75%, which means that the results of the classification in this paper are acceptable (Barakat et al. 2019). The total area of the study area is approximately 8,720 km^2. The results reviled that, of the total area, in 1990, 76.8% (6,700 km^2) was occupied by bare land, 16.8% (1,470 km^2) was occupied by croplands, 2.2% by water, and 4% by wetland areas. In the year of 2000, the land cover has changed as follows, 76% bare land, 17% cropland, 2.6% water, and 4.3% wetland areas. In 2011, there was significant changes in the land cover, where the bare land area dropped to 71.7%, the cropland area increased to 22.6%, 2.4% was covered by water, and 3% by wetlands. The area cover with water was lowest in 2020 with 1.9%. The land conversion between the classes can be seen in Fig. 3. From Fig. 4 it can be clearly seen that there is a constant transition between the classes water, wetland, and cropland, where the areas covered with bare land are usually stable. The biggest transition between land cover classes can be noticed between water and wetland classes. Also, it should be noticed that more than 30% of the water areas changed in the investigated periods. In the period between 1990 – 2020, more than 50% of the wetland areas transited to cropland (approximately 30%), and water and bare land (10%).

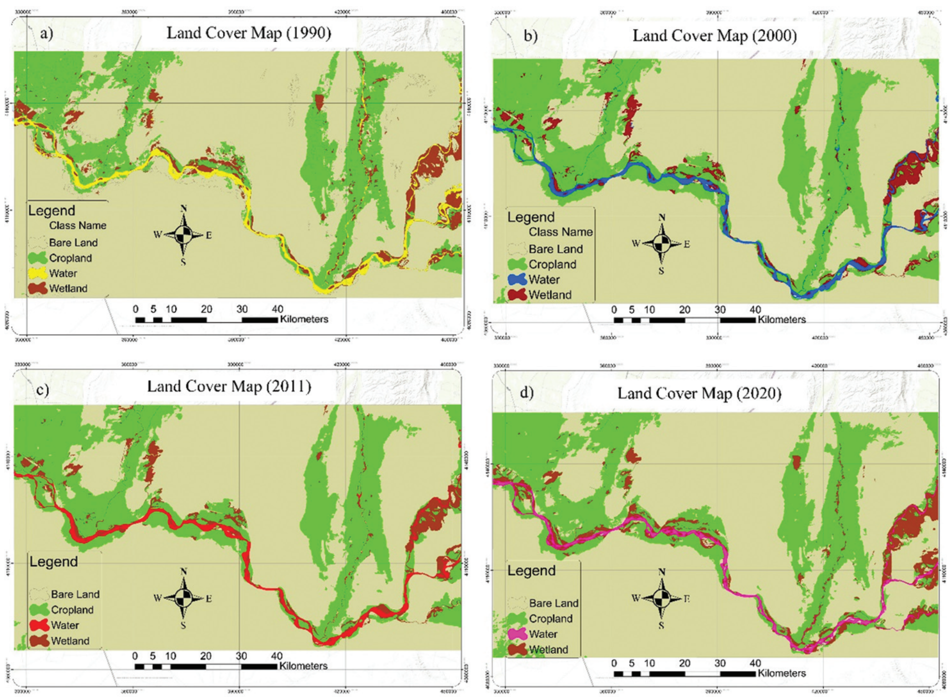

Fig. 3. *Land cover classification results for: a) 1990, b) 2000, c) 2011, d) 2020.*

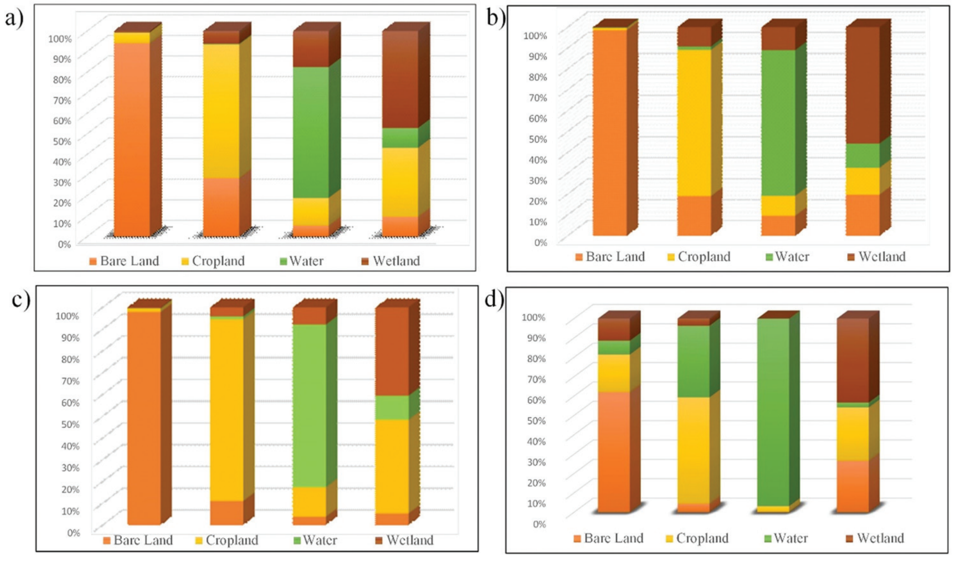

Fig. 4. *Land conversion between: a) 1990 – 2000, b) 2000 – 2011, c) 2011 – 2020, d) 1990 – 2020.*

Table 2. *Confusion matrix for the land cover classification.*

Class	Bare Land	Cropland	Wetland	Water	Total
Bare Land	**247**	33	2	1	283
Cropland	13	**59**	4	0	76
Wetland	1	3	**19**	0	23
Water	1	1	2	**14**	18
Total	262	96	27	15	**400**
AA	OA = 85%; kappa = 0.75				

3.2. Spatial and temporal river channel changes and dynamics

The historical river channel changes are shown in Fig. 5 (a–c) in three different periods from 1990 – 2020. The blue color represents the active river channel in both years, with yellow color are represented the eroded areas, while with red color are illustrated the accretions. From the results, it can be noticed that very small part of the channel remained unchanged in the last thirty years. Comparing each period individually, and thirty years' changes, during the first period, 1990 – 2000, the overall erosion and accretion areas are 4,878.1 ha and 8,377.4 ha, respectively. The second period, 2000 – 2011, showed different results, where the accretion area was bigger than the eroded area. The overall accretion and erosion areas in this period are 8,257.9 ha and 6,415.8 ha, respectively. Similar were the results from the second period where the overall erosion and accretion were 7,692.4 ha and 5,069.5 ha, respectively. The comparison between the first (1990) and last investigated year (2020), with duration of thirty years, showed overall erosion and accretion of 9,775.6 ha and 8,810.0 ha, respectively. The details are presented in Table 3.

Table 3. *Erosion-accretion amount from 1990 – 2020 in the study area.*

Duration	Erosion		Accretion	
	Total (ha)	(%)	Total (ha)	(%)
1990 – 2000 (10 years)	4,878.1	24.9	8,377.4	42.8
2000 – 2011 (11 years)	8,257.9	35.8	6,415.8	27.8
2011 – 2020 (9 years)	7,692.4	36.2	5,069.5	23.9
1990 – 2020 (30 years)	9,775.6	52.5	8,810.0	47.3

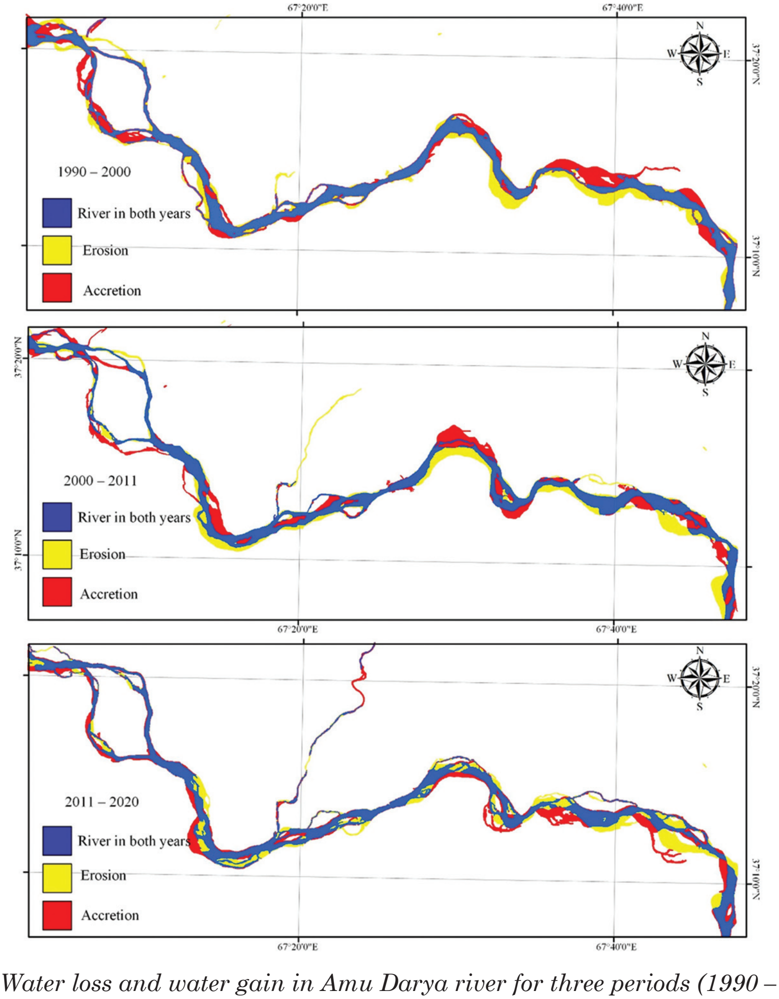

Fig. 5. *Water loss and water gain in Amu Darya river for three periods (1990 – 2020).*

The shifting of the channel line from 1990 to 2020 on both sides of the river was measured through 7 cross-sections at an interval of 10 km along the river and the results are presented in Fig. 6 and Table 4. The analysis showed that the highest amount of erosion of land observed on the both sides of the bank occurred in section F (right bank, 1.4 km) in the period of 1990 – 2000. The maximum amount of accretion of land was noticed in the left bank along section G (1.3 km) in the period of 1990 – 2000. If the first and the last period of the investigation over the study area is analyzed the maximum amount of erosion of land observed on the both sides of the river occurred in section A and E (over 1 km), and the maximum accretion occurred in sections E and F (over 1.3 km).

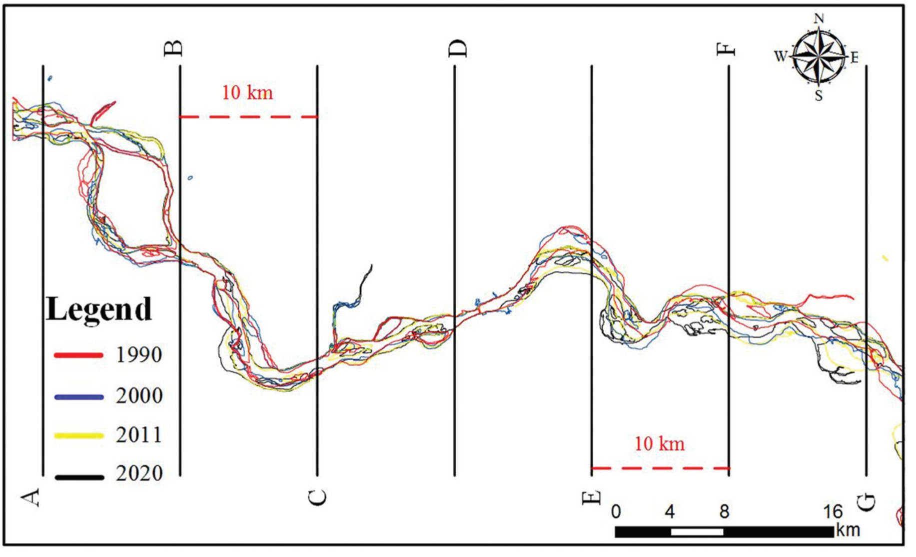

Fig. 6. *River border shifting from 1990 – 2020.*

Table 4. *River border shifting 1990 – 2020 in m. Minus sign (–) indicates narrowing (from north to south) and plus sign (+) indicates expanding (from south to north).*

Section	1990 – 2000		2000 – 2011		2011 – 2020		1990 – 2020	
	Left bank	Right bank	Left bank	Right bank	Left bank	Right bank	Left bank	Right bank
A	+120	+300	+100	+90	+240	+55	+420	–1023
B	+61	0	–391	–170	0	+240	+360	0
C	–210	0	180	0	–510	0	–520	0
D	+95	0	–63	+60	0	– 30	–60	0
E	+420	–450	+730	–660	+150	–390	+1320	–1170
F	+780	–1410	+300	+60	+330	0	+1440	0
G	+1320	–1050	+90	+130	+360	–1140	+420	–930

4. Discussion

The main goals of the presented paper were to determine the Amu Darya river channel dynamics and the changes that occurred in its surroundings between Afghanistan, and Uzbekistan and Tajikistan. River dynamics can often cause considerable hazards to those in the surrounding area, it is more complicated for the locals who depend mostly on agriculture to claim their rights as Amu Darya also represents the international border between several countries. In order to help decision-maker and also to lower geo-political tensions between the sharing countries, timely mapping and monitoring of the shared areas as well as its surroundings are crucial.

Landsat as the only satellite that provides historically imagery since 1980, with 30 m spatial resolution offers valuable data that can be used for accurately monitoring of the Amu Darya river dynamics and land cover changes of its surroundings. Thus, in this paper, four Landsat images in the period of 1990 – 2020 were used. However, in future studies, Sentinel-2 that offers better spatial and spectral resolution can be used for more accurate and more detailed results.

While most studies in the literature focus only on river dynamics (Langat et al. 2019a, Billah 2018) or land cover changes in the river basin (Langat et al. 2019b, Cai et al. 2016), this study evaluated both land cover changes and river dynamics of Amu Darya river. For that purpose, an object-based classification has been made over the study area with four classes (Bare land, Cropland, Water, Wetland) and the land conversion has been estimated for the analyzed thirty-year period. The results showed that large areas of wetland (possible highly watered cropland) and cropland are being flooded by the new course of the river, meaning that the river causes damages to local peoples' lands. Also, it should be noticed that more than 30% of the water areas changed in the investigated periods. In the period between 1990 – 2020, more than 50% of the wetland areas transited to cropland (approximately 30%), and water and bare land (10%). These results are supported with high accuracy of 85% overall accuracy, and accuracy higher than 90% for the water class. After the first part of the study, analyses of the river dynamic have been made. For that purpose, only water class, or the river line in the same period was analyzed. It should be mentioned that the right part of the river represents Tajikistan, while the left, Afghanistan, and with every shift of the river, left or right, the international border between these two countries is being changed. The erosions and accretions of the river have been addressed thus also presenting the active part of the river in both assessed periods (Fig. 5). Results showed that in the studied part of the river (approximately 70 km length), very small part of the channel remained unchanged. The comparison between the first and last classification showed overall erosion and accretion of 9,775.6 ha and 8,810.0 ha, respectively. However, although the areas differ for approximately 900 ha, the damage is rather higher. From the river shifting results, it can be noticed that most of the time, the river shifts from North to South, causing floods and detriment on the croplands on the local people on the Afghanistan side, and benefits to the local people on the Tajikistan side of the border. The results can be useful in practical applications where regular monitoring of river behavior is needed for decision making. Such information can help both local and international administration in resolving problems due to unresolved water sharing policies, and can help in making geopolitical decisions beneficial for both parties. Also, the results can be crucial in flood risk management strategies, irrigation plans, monitoring systems, etc. The most drastically shifts between 1990 and 2020 are shown on Fig. 7.

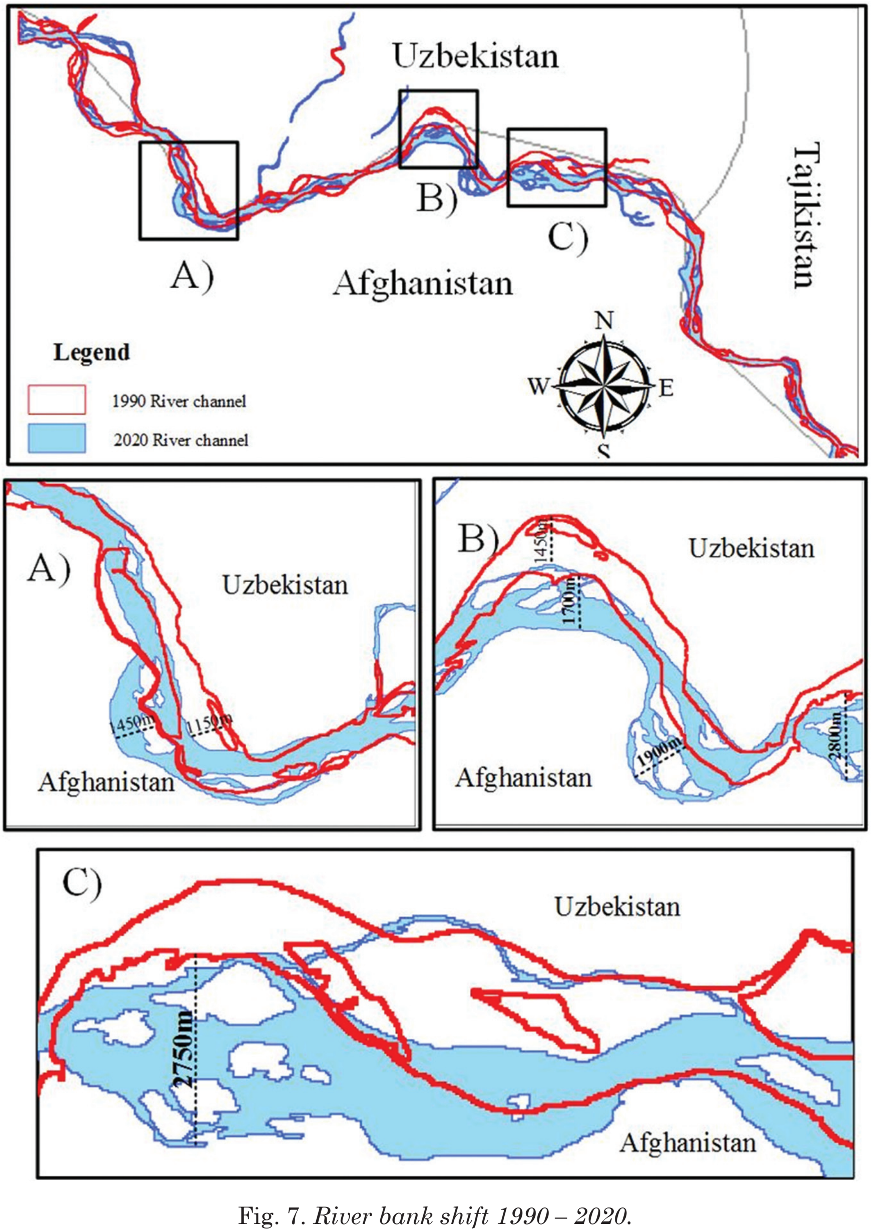

Fig. 7. *River bank shift 1990 – 2020.*

5. Conclusion

In the presented study, the land cover changes and river dynamics of international borders and its surroundings were investigated using remote sensing satellite imagery. The most significant contribution of this paper it that is points out a very important problem many local people are facing, mostly in the developing countries, but in fact, it should also be stated that this is also an international problem. The case study of the Amu Darya river is just an example of what many local people who mainly depend on agricultural are facing with. Having said that, it should not be forgotten, that with the results in the study the international borders are also being monitored though satellite imagery. As not many studies can be found on the topic monitoring river that also represent international borders, we believe that the conducted study can be of great use and open many research opportunities for many interdisciplinary projects. For future studies, we recommend investigating the same topic on different study area, and for more accurate results, the use of imagery with higher resolution, such as Sentinel-2.

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Pomicanje granica: kartiranje i praćenje dinamike rijeke Amu Darya koristeći podatke i tehnike daljinskih istraživanja

SAŽETAK. Procjena opasnosti od katastrofa vezanih uz vodu važna je za smanjenje rizika i upravljanje rizicima u svrhu održivog razvoja. Taj se problem pojavljuje kod prekograničnih voda, dodajući geopolitičke probleme već postojećima. Za pomicanje granica, kao što je granica između Afganistana i Tadžikistana i Uzbekistana, kartiranje i praćenje dinamike rijeke važno je za rješavanje potencijalnih problema koji se mogu pojaviti zbog pomaka obale rijeke. Kako bi se ostvarili ciljevi ove studije, kartiranje i analiziranje prenamjene zemljišta, dinamika riječnih kanala, mjerenje lateralne erozije i nagomilavanja u razdoblju između 1990. i 2020., korištene su četiri snimke Landsat. Rezultati istraživanja pokazali su značajan pomak obale rijeke, posebno od sjevera prema jugu, što je uzrokovalo domaćem stanovništvu u Afganistanu štete u poljoprivrednim područjima. Također, rezultati su pokazali ukupno područje pomaka rijeke na obje strane granice. Najkritičniji dijelovi rijeke također su otkriveni te se zaključilo da se neki dijelovi granice pomaknu do 3 km unutar teritorija Afganistana. Takve informacije mogu pomoći lokalnoj i međunarodnoj administraciji u rješavanju problema nastalih zbog neriješenih politika međusobnog korištenja voda te mogu pomoći u donošenju geopolitičkih odluka korisnih za boje strane.

Ključne riječi: *daljinska istraživanja, Amu Darya, dinamika riječnih kanala, Landsat, klasifikacija.*

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