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Monitoring of the Surface Water Regime of the Sava River Alluvium in Serbia Using Geographic Information System (GIS) Techniques

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Abstract: In the spacious inundation area on the left bank of the lower course of the Sava River in Serbia, there is an abandoned meander Special Nature Reserve, "Obedska bara", which represents a very important floodplain in this part of Europe. This area is characterized by an exceptional wealth of biodiversity with a significant presence of rare and endangered species of national and international importance. Hydrological conditions in the mentioned area were analyzed from the aspect of surface water movement in nature and conditions altered by human factors (after the construction of the road network, canals, etc.). The movement of surface water, i.e., the filling and emptying of the investigated area, parallel to the water level of the Sava River, is shown using a digital terrain model. Our simulation of the change in surface water level within the studied area included the display of underwater areas, both with the formation of a flood wave (i.e., increasing water level of the Sava) and with the outflow of water from the pond when the water level in the Sava was reduced in both scenarios (natural and conditions altered by human factors). GIS and terrain digitalization were used for geospatial and hydrological analyses and, based on this, maps that display endangered areas could be made. The obtained results show that the largest human impact was recorded at the water level of the Sava River 74 m above sea level. The aforementioned water regime changes were shown to negatively affect dominant vegetation, such as pedunculate oak and ash.

Keywords: water regime; digital terrain model; ArcGIS; nature conditions; human disturbance

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1. Introduction

Water balance in plants plays a very significant role, not just related to their growth and development characteristics, but also to basic physiological processes [1]. It should be noted that a lack of water affects both the radius and height of trees. Two factors are connected with water balance—the water content absorbed by the root system and the water content released during transpiration from the above-ground parts of the plant [2]. Lowland forests, which are mainly located in flooding areas, are closely dependent on the changeable quantity of soil moisture [3]. Many papers have confirmed that climate change is greatly affecting the environment [4–7]. The most significant factor is the increasing average global temperature, which causes large changes related to the aforementioned phenomena [8], i.e., a widening of the tropical belt and the occurrence of a drying environment, which contributes to extreme weather events, such as severe droughts, temperature extremes, and heat waves [9,10]. Many papers [11–14] have analyzed the influence of global climate change on vegetation and water ecosystems.

To understand hydrological processes and to quantify their influence on the surrounding vegetation, we need effective tools to detect and monitor extreme scenarios such as droughts or floods. One of the major shortcomings of conventional models is their inability to deal with the spatial nature of hydrological parameters. In recent years, Geographic Information Systems (GISs) have been widely used in hydrological research [15–18] as sophisticated databases in management systems; they offer efficient storage and retrieval by manipulating, analyzing, and displaying spatially referenced data [19]. The GIS framework is particularly useful for integrating large amounts of historical land use data derived from a variety of sources, with ancillary data pertaining to soil and topography, which may be used for hydrologic models [20]. GISs are widely used for habitat mapping, monitoring the distribution of some species, and analyzing hydrological changes, even using a complex methodology for the restoration and/or revitalization of endangered sites. GISs are also used for different elements, the mapping of processes at wet sites, and three-dimensional model making [21].

The main goal of this paper is to determine, using GIS, the filling and emptying regime of an abandoned meander of the Sava River, i.e., the "Obedska bara" Special Nature Reserve (SNR). In other words, we seek to determine the amount of water present after flooding, as well as the amount of water that is retained in this area due to the impossibility of drainage after the retreat of the flood wave. GIS and various simulations most comprehensively display such extreme hydrological events. The specific goal of this research was to use GIS to very precisely quantify the impact of the flood wave on the protected area in terms of time and space, thus creating a basis for preventive action in terms of adapting management measures in alluvial ecosystems where extreme scenarios are relatively common.

The economic importance of the investigated area is related to the fact that it contains lowland hardwood forests, primarily pedunculate oak and ash, which have a significant market value. The economic importance and production of the pedunculate oak in this location should be noted as it, along with the Slavonian pedunculate oak, which is also located along the banks of the Sava River but only on the Croatian side, has outstanding anatomical, technical, and practical properties [22]. Ash is also a very high-quality species of wood; its growth rings are visible and have a nice texture, and it is widely used in the wood-processing industry. The ecological importance of this area is reflected in its mosaic of bogs, ponds, shafts, swamp vegetation, wet meadows, and forest ecosystems, with a very high diversity of ecosystems and species, especially those that are endangered. Considering it is a protected area, its environmental value is clear. It can be said that the ecology of the protected area of SNR "Obedska bara" is endangered as a result of global climate change and anthropogenic activity. Under the influence of the mutual action of these factors, significant changes have occurred in the water regime that negatively affect associations with plants and animals that are adapted to these site conditions.

GIS has been used as a tool in a wide variety of water research settings. For example, assessments of the location of highly productive groundwater are often problematic due to the lack of a systematic approach and the requirement of expensive laboratory analyses [23]. However, this type of research can be improved by using GIS data to measure the hydraulic characteristics of the source and then using GIS spatial analysis methods to obtain hydrogeological data regarding groundwater [24,25]. GIS and remote sensing technologies have great potential for use in analyses of groundwater potential; many studies have applied these techniques together with those concerned with geomorphology, drainage, lithology, and soils [26–29]. Gašparovič and Klobučar [30] mapped floods using geospatial data and noted that floods can suddenly occur and occupy very large areas. Therefore, it is necessary to immediately define the boundaries of a potential flood area. GIS is also used, together with plant growth simulation models, to perform water quantification, which is an indicator of water use efficiency in a basic sense [31]. In the aforementioned research, the combination of GIS and a simulation model enabled a more efficient analysis, because the temporal and spatial dimensions were studied simultaneously, which facilitated the understanding of the investigated problem.

Alexandridis et al. [32] studied the possibility of restoring Lake Koronia in Greece, which, due to the negative impacts of various factors (surface and groundwater pollution from agricultural, industrial, and municipal sources), was completely devastated and swamped. However, those authors had a problem restoring this ecosystem due to gaps in time and space, and for this reason, GIS was applied by creating and using numerous geographic information layers in the restoration plan, which was presented as a vector and raster data set of appropriate thematic maps in GIS. Mester et al. [33] studied how intensive human activity negatively affects wetland ecosystems. In addition, GIS has widely been used for water quality assessments [34,35], to measure the spatial impact of urbanization on surface water reserves in the world's big cities [36], and in efforts to determine how population growth affects surface water runoff processes in suburban settlements [37]. This modern tool has also found application in the prediction of the volumetric flow rate of rivers and the quality of surface water [20], assessments of the capacity of small reservoirs [38], and in management in conditions of flood risk [39].

Beckline et al. [40] considered the possibility of using GIS and remote sensing in tropical forest management. It was concluded that these tools greatly contribute to the sustainable management and protection of these ecosystems on a global level. One of the reasons is the possibility of identifying areas where deforestation, forest conversion, and degradation are present.

2. Materials and Methods

2.1. Study Area

SNR "Obedska bara" is located in a large inundation area on the left bank of the lower course of the Sava River presenting the center of a specific, unique pond-marsh system (Figure 1). Since it is located in the inundation are of the Sava River, the water regime is directly related to the river, whose large and small waters have shaped this water ecosystem for a long period (Figure 2). SNR "Obedska Bara" is a very important floodplain area in this part of Europe, characterized by a great wealth of biodiversity with the presence of a huge number of rare and endangered species.

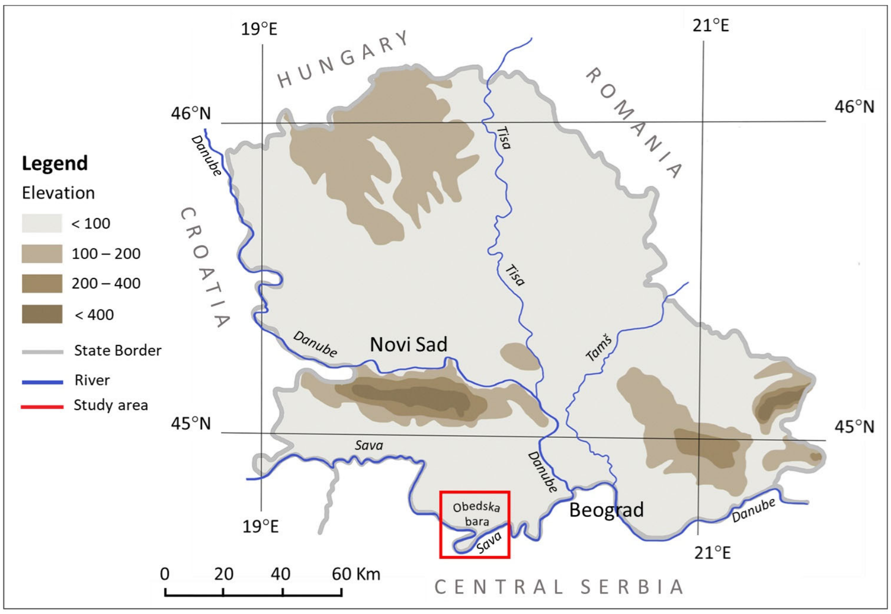


Figure 1. The geographical position of the investigated area—SNR "Obedska Bara" in Northern Serbia.

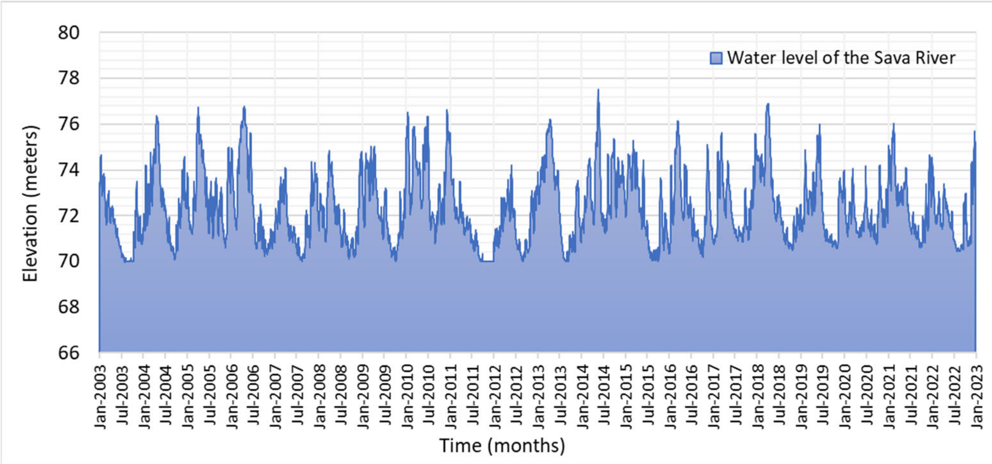


Figure 2. The water regime of the Sava River in studied area for the 2003–2022 period.

About 220 species of birds, over 50 species of mammals, 13 species of amphibians, 12 species of reptiles, 16 species of fish, over 250 species of insects, 180 species of fungi, and over 500 species of vascular plants (many of which are medicinal) were investigated within this reserve [41]. Due to its exceptional natural values, the SNR "Obedska bara" has a verified international status—the first protection dates back to 1874, and in 1968 it was declared a nature reserve within Serbia, while it was included in the Ramsar Convention on Wetlands of World Importance in 1977 [42,43]. It was also nominated as a candidate for the list of biosphere reserves within the UNSECO MAB (Man and Biosphere) program.

2.2. Geostatistical Analysis

Phase I includes the creation of a digital terrain model of the studied area which was done in the ArcGIS program using the ArcMap application (Figure 3). When the terrain model was made, a total of 16 scanned basic state topographic maps were georeferenced, first at a scale of 1:5000; in this way, a unique map of the studied area was formed. After georeferencing, all isohypses were vectorized, as were all height points from these maps (over 2300 points). Based on these data, a digital terrain model was created by first creating a network of irregular triangles, TIN (Triangulated Irregular Network), based on vectorized data, which were then converted into a raster. Two versions of the digital terrain model were created. The first digital terrain model was made based only on the data found in the georeferenced basic state maps, while for the second digital terrain model, in addition to the data used for the first model, data related to terrain changes caused by human activity were used (built roads, canals, etc.). For the second version of the digital terrain model, a map of the present road network in the SNR "Obedska bara" was used, as well as geodetic images of elevation and coordinates of characteristic points on the road network. The characteristic points of the road network refer to the sections of the road where culverts are or where the elevations of the road and the elevations of the lower part of the culverts were recorded.

Phase II includes a spatial analysis and simulation of surface water movement (Figure 3). The simulation of the surface water level changing within the SNR "Obedska bara" was done in the ArcGIS program in the ArcScene application. In the simulation, both digital models of the terrain were used (simulations of the surface water movement and changes in the water level of the Sava River in the area of the SNR "Obedska bara" with and without the influence of the road network on the water regime). Different levels of flood waters are defined as individual layers, and surface water level oscillations are shown by overlaying the layers of water surfaces and the digital terrain model. The surface (flood) water movement depends mostly on the difference in altitude. Since in this case, it was about a specific mosaic of oscillations of height differences, special attention was paid to simulations of the water movement on the surface of the terrain. A logical overlapping of water surface sections and terrain models was carried out by observing the law of water movement in natural conditions.

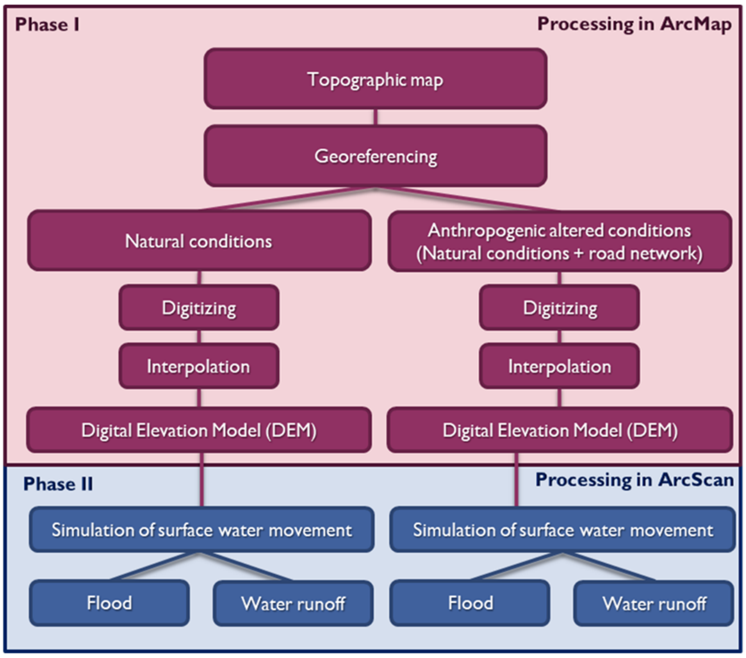
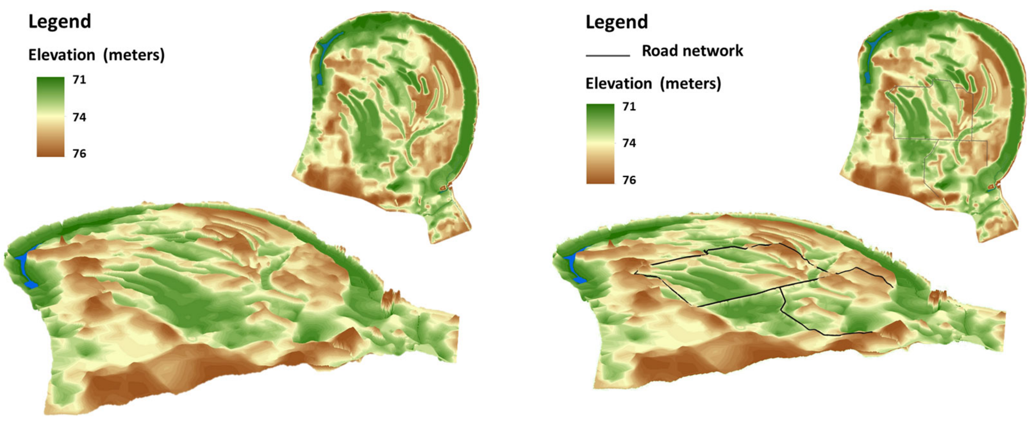


Figure 3. Flow chart of research ideas.

3. Results

Based on 16 pages of topographic maps, a map of the road network in SNR "Obedska bara", and geodetic recordings of the elevation and coordinates of the characteristic points on the road network, a digital model of the terrain was made. Once the data had been processed, two versions of the terrain of the studied area were formed. In the first version, a model of the terrain was displayed in natural conditions (Figure 4a). The second version shows some changes in the relief due to human disturbance (building of roads, canals, etc.); see Figure 4b.

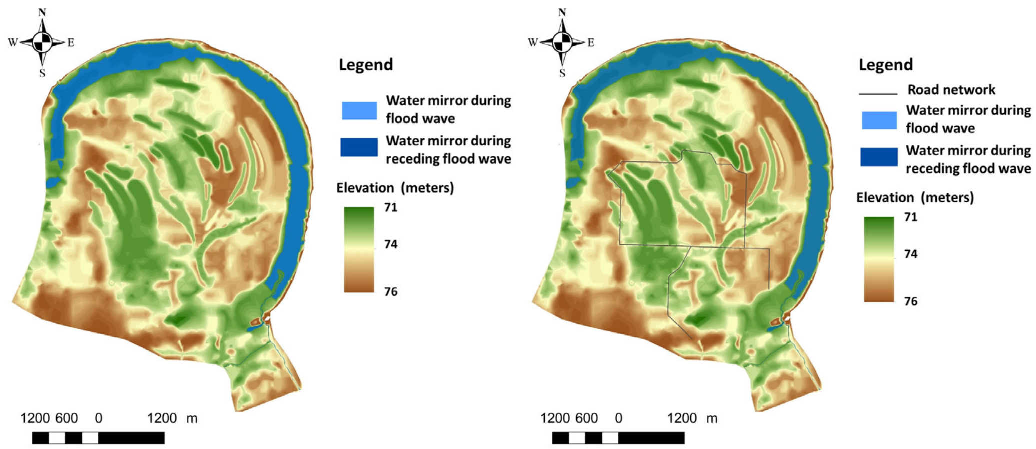


(**a**) (**b**)

Figure 4. Digital terrain model of the researched area: (**a**) Natural conditions; (**b**) Anthropogenically altered conditions.

In our simulation of surface water level oscillations in the area of SNR "Obedska bara", different levels of water mirrors were shown. Surfaces underwater were shown in two ways: the first way, whereby changes refer to underwater surfaces that occur during the formation of a flood wave when the water level is rising (displayed in figures with bright blue); and the second way, in which underwater surfaces form after the water drains from the pond when the water level of the Sava River decreases after a flood (displayed in figures with dark blue). These simulations were performed for two terrain models. The first one represents nature, while the second shows conditions altered by human factors.

Natural conditions: Water movement in SNR "Obedska bara" is shown at the base of the flow simulation for natural conditions, which means that the water levels were not the same in all parts of the studied area because it takes some time to reach certain levels. The inundation zone gradually expanded from the source of water inflow, filling the lowest terrains first. With the rising of the water level, the flood zones concentrically expanded, depending on the terrain configuration. Figures 5a, 6a, 7a and 8a show the water surfaces that formed at different water levels of the Sava River in natural conditions. The rising of the Sava River water level at an elevation of 69.7 m above sea level was responsible for the water supply in the study area. Already at a water level over 72 m above sea level, the water started to fill the eastern arch of the "horseshoe".



(**a**) (**b**)

Figure 5. Water area during a flooding wave in the research area at a water level in the Sava River of 73 m above sea level: (**a**) Natural conditions; (**b**) Anthropogenically altered conditions.

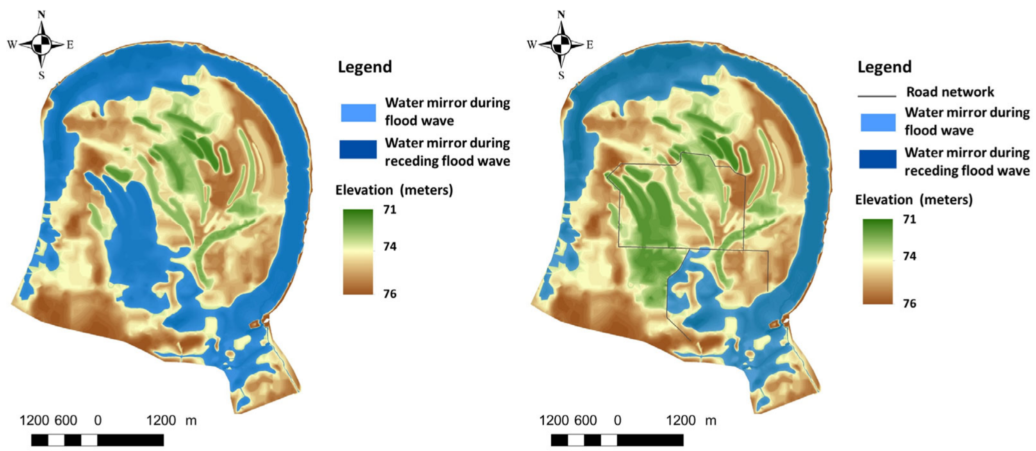


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Figure 6. Water area during a flood wave in the research area at a water level in the Sava River of 74 m above sea level: (**a**) Natural conditions; (**b**) Anthropogenically altered conditions.

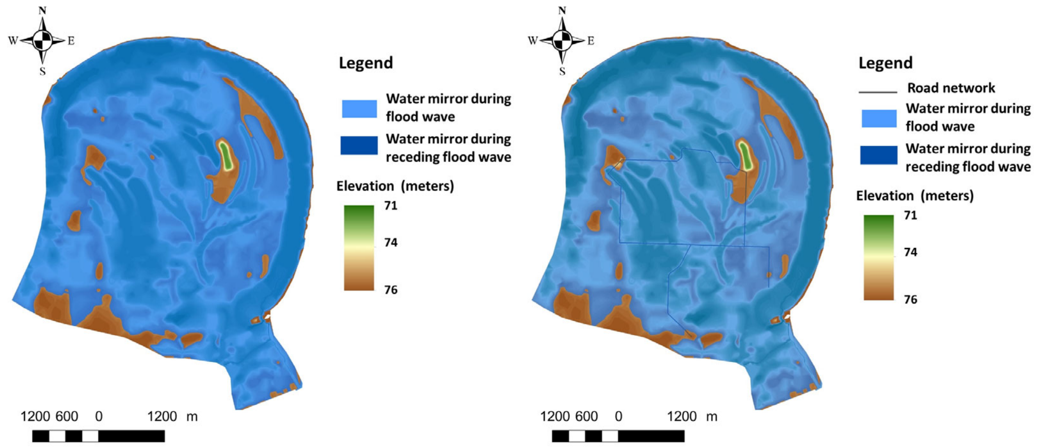

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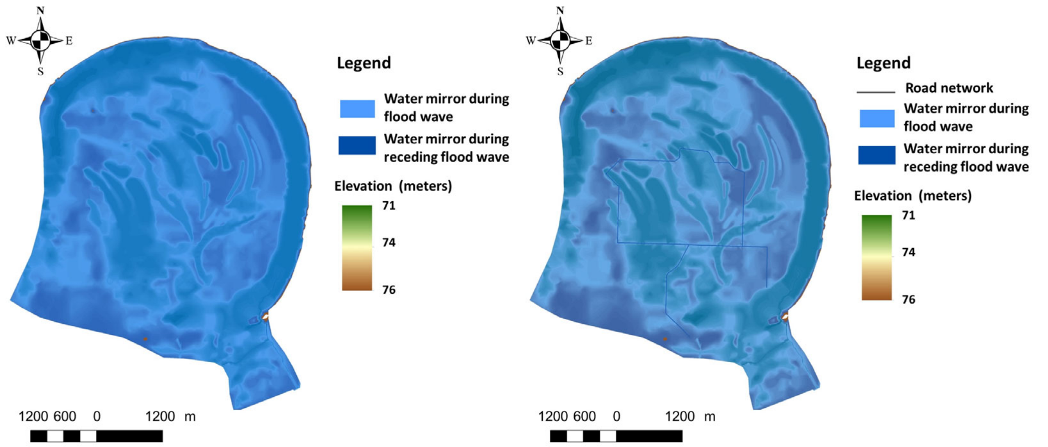
Figure 7. Water area during a flood wave in the research area at a water level in the Sava River of 75 m above sea level: (**a**) Natural conditions; (**b**) Anthropogenically altered conditions.

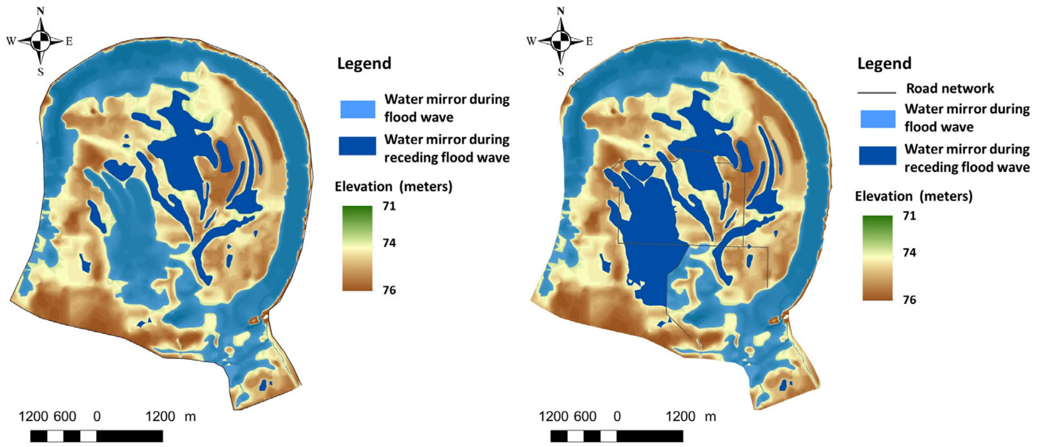


(**a**) (**b**)

Figure 8. Water area during a flood wave in the research area at a water level in the Sava River of 76 m above sea level: (**a**) Natural conditions; (**b**) Anthropogenically altered conditions.

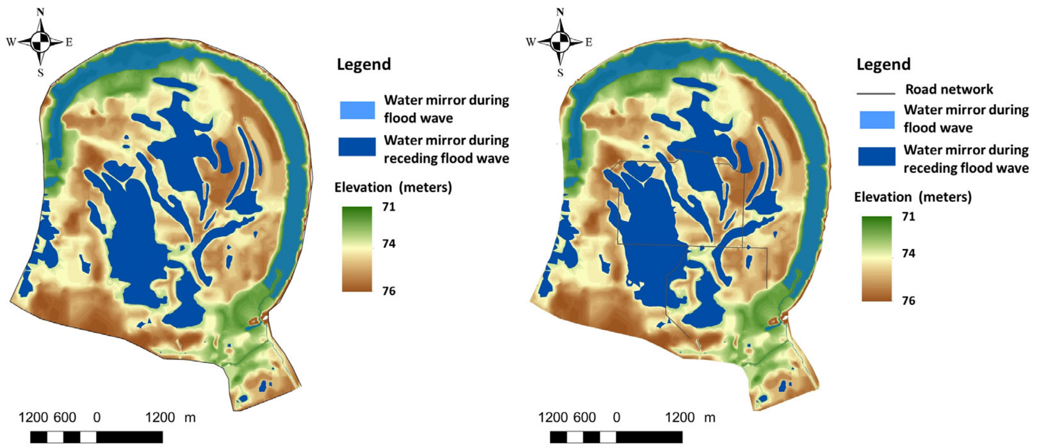
With the rising of the Sava River water level up to 73 m above sea level (Figure 5a), the area under water increased, amounting to about 62.5 ha, and the water volume was about 125,822.07 m^3, while at a water level of 74 m above sea level (Figure 6a), the area was about 418.32 ha and the volume was about 2,184,244.07 m^3. The areas under water at 74.2 m above sea level included about 951.15 ha with a volume of about 4,646,931.27 m^3, while when the water level increased by 20 cm, these areas increased by about 233.94 ha with a volume of about 2,222,958.54 m^3. Sudden flooding in the research area occurs when the water level of the Sava River is high (over 75 m above sea level), i.e., waters spill over the left bank and flood the area (Figure 7a). Larger floods (76 m) also affect the investigated area, i.e., the water from the entire surface of the "horseshoe" joins the water of the Sava River and forms a huge river lake (Figure 8a).

The Sava River is characterized by the occasional occurrence of floods. Floods are of different intensities according to the water level and the duration of the flood waters. As the water level drops after a flood, the water recedes into the river bed and drains the surrounding areas. The water outflow from SNR "Obedska bara" begins when the water level of the Sava River drops below 75 m above sea level. It should be noted that water outflow is very dependent on terrain configuration. In the study area, the microforms of the relief are very pronounced, i.e., they often alternate over short distances of shallow or deeper depressions, and between these structures are smaller or larger elevations. With surface runoff, water is not lost evenly over the surface. It first recedes from higher terrains, but at the same time, it remains in depressions and ponds from which it cannot flow due to the terrain configuration. Surfaces where water is retained after runoff are marked in dark blue (Figures 9 and 10); water is lost from these surfaces through underground runoff and evapotranspiration. The depth of the water in the ponds is changeable and varies over the course of the year, as well as from year to year. There is a tendency of permanent change in the amount of water in depressions and ponds, e.g., small ponds and swamps may dry out. Such conditions affect the existence of different habitats that spatially alternate over short distances and enable the development of many plant associations.



(**a**) (**b**)

Figure 9. Water area that remains after a flood wave in the research area at a water level in the Sava River of 74 m above sea level: (**a**) Natural conditions; (**b**) Anthropogenically altered conditions.



(**a**) (**b**)

Figure 10. Water area that remains after a flood wave in the research area at a water level in the Sava River of 73 m above sea level: (**a**) Natural conditions; (**b**) Anthropogenically altered conditions.

As the water level drops, the linkage with the Sava River in the west is cut off first, and the water from the pond slowly drains away, leaving behind depressions full of water. Surfaces from which water does not run off gradually increase, and at 74.4 m above sea level, these areas occupy about 21.34 ha, with a volume of about 156,978.26 m^3. After the water level drops by 40 cm (Figure 9a), the area increases to about 277.51 ha with a volume of about 1,146,889.91 m^3, while at a water level of 73 m above sea level (Figure 10a), the areas under water occupy about 525.99 ha, with a volume of about 2,401,056.00 m^3.

Conditions altered by human factors: Road network construction in the investigated area affects the site conditions, i.e., the basic relief structure has been changed. The changes caused by human factors (roads and canals) have been shown in the new terrain model. A simulation of the surface water movement which takes into account human factors is displayed in Figures 5b, 6b, 7b and 8b. Surface water flows into the SNR "Obedska bara" through the Vok canal; the water first flows into the eastern part of the "horseshoe" arch up to an elevation of 73 m above sea level, where the water is retained in the surrounding lower grounds. Due to the rising of the water level in the Sava riverbed to an elevation of 73 m above sea level (Figure 5b), there is no difference in the surface water movement in this area compared to natural conditions. The impact of the relief change due to the construction of a road on the movement of flood waters is significant at an altitude of 74 m above sea level (Figure 6b). The water is retained on one side of the road until it reaches above the road level, i.e., 74.2 m above sea level, and does not overflow to the other side to fill the lower terrains (depressions) on that side. This water movement occurs only while the water level is above the elevation of the road level.

When the water level of the Sava River is 74 m above sea level (Figure 6b), the surface water flows into the SNR "Obedska bara" through the lower terrain. Firstly, the water level in the western arch of the "horseshoe" increases, and then the surrounding lower grounds in SNR "Obedska bara" are filled. When surface waters surpass the lowest parts of the road network, the depressions and ponds in the central part of the investigated area start filling. Surfaces underwater at an altitude of 74.2 m above sea level include about 949.09 ha, with a volume of about 4,638,013.69 m^3, while with an increase in water level of 20 cm, these areas cover about 1184.04 ha, with a volume of about 6,863,803.17 m^3. When the water level of the Sava River reaches more than 75 m above sea level, the majority of the research area is flooded (Figure 7b). At a water level of about 76 m above sea level (Figure 8b), the studied area becomes an active bed of the Sava River in both natural and human-altered conditions. As the water level of the Sava River drops, the same happens with the water level in the pond. The water slowly drains away, and due to the specific microrelief, the water is retained only in ponds and depressions. However, the built road network cuts through ponds in this area, which leads to the formation of several smaller ponds. At an altitude of 74.1 m above sea level in natural conditions, runoff stops only on an area of 44.11 ha, while at the same altitude under conditions altered by humans, that area is 251.04 ha. At 74 m above sea level, the areas from which the surface runoff was interrupted (areas marked in dark blue) after the construction of the road network are larger by 196.67 ha compared to the same conditions without the road network (Figure 9a,b). As the water level in the Sava riverbed drops, the withdrawal of water from the SNR "Obedska bara" is more intensive. After the descent of the floodwaters at an elevation of 73 m above sea level, the total area under water is equalized under natural and human disturbance conditions (Figure 10a,b).

It should be noted that road network construction negatively affects hydrological processes such as surface, subsurface, and underground runoff. As a consequence, undesired environmental conditions occur; these have negative effects on the present plant associations in both depression and elevated areas. If we analyze some dominant species such as *Quercus robur* and *Fraxinus angustifolia* that grow in lower positions (depressions), unsuitable site conditions cause a lack of oxygen in the root system zone, which leads to a process of reduction. On the other hand, in elevated positions, dominant species are faced with a lack of water, i.e., water cannot enter the study area at elevations over 74.5 m above sea level.

4. Discussion

A similar approach to that applied for the restoration of Lake Koronia in Greece [32] to assess the ecological condition and the impact of human factors on this ecosystem could be implemented for the SNR "Obedska bara". The key point of this approach was related to achieving a balance between the structural and functional characteristics of the lake to achieve the so-called ideal state [44,45]. Taking into account the primary goal of GIS, which is the revitalization of neglected ecosystems, the main task of these tools is to overcome mistakes in the management of water ecosystems in the past and to define restoration strategies. This scenario would also be applicable in our study area (SNR "Obedska bara") in terms of reducing the impact of human factors and then implementing a detailed sustainable management plan before finally gradually reintroducing species that were among the most dominant, such as *Crataegus nigra*. A few papers [38,46,47] have dealt with the importance of GIS in the mapping of flood scenarios and the management of extreme situations, as well as discussing the comparative advantages of GIS in terms of the timely processing of input data and the visualization and analysis of output data. This coincides with the results obtained in our paper, where the application of GIS indicated the position of endangered zones and quantified the degree to which road network construction has disturbed the water regime and affected existing vegetation. Gašparovič et al. [30] discussed the monitoring and mapping of wetlands and the use of thematic GIS layers. Those authors noted that when assessing the frequency and extent of flooding in lowland forests, it is very important that the GIS layers define the dominant tree species, as well as their economic and ecological importance, age, and stand density. This correlates with our results, considering that the study area it is a very valuable floodplain forest ecosystem in terms of production and the environment but one whose vitality and physiological strength are endangered due to the negative impact of human factors. This means that the application of GIS in this area could greatly contribute to preventive actions and improve the general condition of the endangered area. Abebe et al. [48] found that the main factors in large cities regarding flood scenarios are not climate variations but dense population and intensive human activity in terms of land use. This partly coincides with our results, because negative human activity (road network and canal construction) was shown to contribute to the disruption of the water regime of Obedska bara and the occurrence of extreme scenarios. Nonetheless, global climate change is also having a very significant impact. In terms of understanding hydrological processes and quantifying their impact on the surrounding vegetation, many papers have noted the importance of effective tools that can record data about extreme scenarios, such as flooding or drought, and can cope with the spatial nature of hydrological parameters [15–20]. In this regard, in our paper, a methodological framework with GIS techniques was applied to identify endangered areas, quantify zones where flooding or decline occurs, and determine how the water regime of the investigated location changes with the variability of the Sava River water level under natural and human-altered conditions. Water is a key ecological factor, and the survival of lowlands and floodplain forests depends significantly on soil moisture. Changes in the water regimes of these ecosystems largely determine the growth and development of the main tree species [49]. There are many factors whose interactions lead to extreme floods in coastal ecosystems, and decision-makers, using multi-criteria analysis, should determine the intensity of the impact of each of these factors to create adequate risk maps [50]. Some studies [51,52] have noted a high decline in the numbers of pedunculate oak and ash trees in Croatia, especially regarding trees located in the lowest positions. Several authors have noted that drastic changes in the water regime were significantly responsible for this phenomenon, which correlates with our results. In the area of Srem, pedunculate oak decline is associated with low contents of easily accessible water [53], while Weemstra et al. [54] linked reduced productivity of pedunculate oak populations with extremely dry climatic conditions.

Two very significant factors are most responsible for the endangerment of the SNR "Obedska bara": global climate change and human activities. According to the mutual effect of these factors, the water regime is disrupted, which causes unsuitable site conditions for hygrophilous plant associations. It should be noted that the use of GIS is very beneficial due to its potential to predict extreme scenarios in the future and prevent flooding or the decline of autochtonous species. Therefore, the management of these extremely valuable forest ecosystems may be significantly improved.

5. Conclusions

In this study, the filling and emptying process of the abandoned meander of the Sava River, i.e., SNR "Obedska bara", which is directly related to its water level, was analyzed. The obtained results show that with an increase in the level of the Sava River to an elevation of 72 m above sea level, the "horseshoe" of the SNR "Obedska bara" is filled and several shallow ponds are formed. As a consequence, different hydrological conditions occur until an elevation of 76 m above sea level is reached, at which point the complete surface is submerged and included in the mirror of the Sava.

As the level of the Sava River drops after a flood, the water recedes from the wider area of SNR "Obedska bara", leaving behind many filled ponds and depressions, which lose water through sinking, evaporation, and transpiration. It should be noted that in lowland ecosystems, even minimal differences in the water level of the Sava River (up to 0.5 m) lead to large variations in habitat conditions which affect the size of the areas under water, as well as the volume of water in some micro-relief forms.

Relief modelling has become an integral part of research and planning in the field of nature conservation. GIS and terrain digitalization are used to perform many geospatial and hydrological analyses, including analyses of catchment areas, drainage systems, flood forecasting, and the definition of active protective measures. A digital terrain model provides a three-dimensional visualization of the surface of the analyzed area. On this basis, the modelling of flooding in the investigated area at defined water levels was carried out. As a result, maps were made which show the underwater areas in a simple and informative way; these maps also contain data related to the spatial distribution of flooded areas, as well as the volume of the water.

Human factors, i.e., the road network, was shown to disturb the natural process of the filling and emptying ponds and depressions which prevent surface, subsurface, and underground runoff. As a result, undesirable ecological conditions occur for vegetation, i.e., hygrophilous species such as *Fraxinus angustifolia* and *Quercus robur* do not receive adequate oxygen in their root system zone, leading to reduction processes. This occurs not only in depressions but also in elevated positions where, due to dry conditions in past growing seasons, a lack of water may be observed. As such, water cannot enter the area of SNR "Obedska bara" at elevations greater than 74.5 m above sea level.

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