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Environmental impacts of the Gabcikovo Barrage System to the Szigetköz region

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Abstract In order to commission a large hydroelectric power plant in 1992, the Republic of Slovakia diverted the Danube River with a dam at a common section between Hungary and Slovakia. The dam is located at Gabcikovo in what now is Slovakian territory. The diversion, known as the Gabcikovo Barrage System (GBS), subsequently impacted one of the most ecologically important and unique alluvial floodplains of the Danube Basin. This, in turn, affected the hydrological regime of the Danube downstream and so, potentially, water supplies and water quality for millions of people.

The potential environmental impacts of the diversion to the floodplain and downstream were not thoroughly studied prior to construction of the dam. The project was originally started jointly between Hungary and Slovakia in 1977 and conflicts arose between the two countries resulting in a case before The International Court of Justice (IJC) in 1993. In 1997, the IJC rendered a decision that a compromise solution had to be worked out accommodating the needs of both Hungary and Slovakia. The IJC said, in essence, that the dam would remain in place, but must be modified so as to minimize environmental impact. This paper reviews the history of the project and describes some impacts of the river diversion that may be attributed to changes in the water regime.

In order to assess environmental impacts to the region due to diversion of water from the natural channel of the Danube, this study assessed, using satellite imagery, land cover change between 1988 and 1997. This study also correlated the satellite-derived data with reports from the Hungarian Ministries of Agriculture and the Environment and the North-Transdanubian Environmental Inspectorate. The analysis determined that, although land cover change occurred in the region during this period, not all of the changes could, necessarily, be related to the hydroelectric facility.

The results of the analysis show that: (i) there were land cover changes in the study period within the study area; (ii) more time is needed in order to establish a link between the hydroelectric facility and environmental changes; (iii) satellite imagery could provide useful information in studies of this type, but the imagery must be used in conjunction with ground observations.

This paper represents the views and opinions of the authors and not necessarily those of either the National Science Foundation or the Hungarian Academy of Sciences.

Keywords Gabcikovo Barrage System, Szigetköz, Danube, Landsat

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Introduction

Rivers, together with their adjoining floodplains, form an ecological entity of inundation landscapes that have undergone more human interference than any other type of habitat. Even the near-natural floodplain zones that still remain on earth have not been spared from some human intervention. This is especially the case of European river management schemes, either planned or in progress, due to the high population density and long industrial history of the continent (Wenger et al. 1990).

There are numerous examples of adverse environmental impacts of river impoundment or diversion projects in Europe. One is the Upper Rhine Project, which includes dams, barriers, dikes, barrier elements and an artificial channel. According to Hahn (1994):

- 90% of the original alluvial forests and seasonally submerged fields have been lost in some areas.
- Permanent high water levels and lack of flooding led to a change in the community of the flora and fauna.
- Increase and equalization of groundwater levels has caused the decline of softwood forests.

- Hardwood forests are isolated from seasonal flooding – essential for their long-term survival.

The Moselle River is another example of a European river adversely affected by impoundments. Running through southwest Germany, Luxembourg and northeast France, the Moselle has been transformed from largely free flowing into a sequence of barrages and impoundments primarily to create an international shipping lane. Some of the impoundments serve, effectively, as finishing ponds for sewage-laden water and so are beneficial because water quality is bacteriologically improved before being discharged downstream. The disadvantages, however, from reduced groundwater and aquifer dynamics, as well as the potential enhancement of eutrophication, largely outweigh the positive benefits in the case of the Moselle according to experts (Hahn 1994).

The Danube River is one of the most important rivers in Europe. From its source in the high southern region of the Black Forest, the 2,850-km river reaches nine riparian nations (Germany, Austria, Slovakia, Hungary, Croatia, Yugoslavia, Bulgaria, Romania and Ukraine) before emptying into the Black Sea at Sulina and Vilkovo. Its average discharge of over 2,000m^3 (in the inlet section of Hungary) qualifies it as one of the largest rivers, in terms of volume, in Europe. The Danube is a major transportation route and supplies fresh water for tens of millions of people.

The alluvial zones of the Danube basin constitute a unique heritage that is necessary to the river's life for maintenance of groundwater resources and consequently, to the quality of drinking water. They are some of the richest natural regions in Europe in terms of biodiversity, biomass and productivity. These areas purify the water, assimilating nutrients and other pollutants, reproducing diverse flora and fauna and offering protection against flooding. The Szigetköz and Zitny Ostrov (Csallóköz) regions in Hungary and Slovakia, respectively, are one of the most important alluvial floodplains along the Danube River (Cousteau Society 1993).

A map of the Szigetköz and Zitny Ostrov area is shown in Fig. 1. The region belongs geologically to the Little Lowland Unit, which is 232,700 ha in size. The Little Lowland contains two sub-areas named: (i) the Szigetköz region (52,700 ha on the Hungarian side) and (ii) the Zitny Ostrov region (180,000 ha on the Slovakian side).

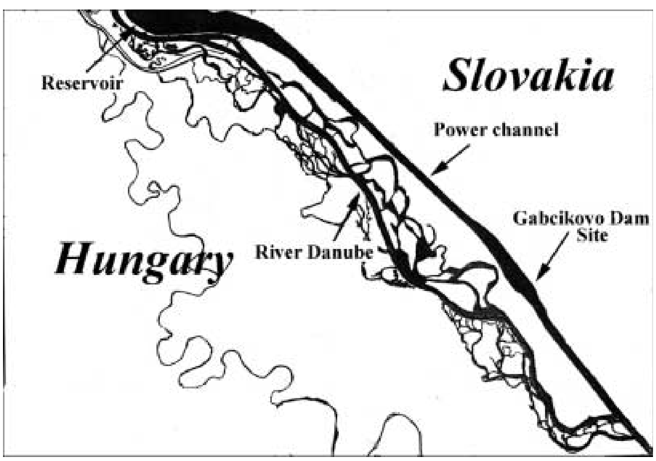

Fig. 1. Map of study area

The study area falls into the common Hungarian and Slovakian Danube River stretch between Rajka/Cunovo (Hungarian and Slovakian place names, respectively) and Szap/Palkovicovo. The total surface of the study area is 10,100 ha, which represents only 4.3% of the Little Lowland Unit. 5,200 ha of the study area are on the Hungarian side (approximately 10% of the Szigetköz) with the remainder on the Slovakian side (approximately 3% of the Zitny Ostrov). The study area includes the floodplain situated between the flood protection dikes in this river section.

The delineation of the study area was based on the following logic: (i) this area was the one most impacted by the dam; (ii) the more important floodplain forests with a high value of natural protection were situated here; (iii) this area was closest to the dam and so environmental effects of the diversion could be expected here.

Due to the fact that the GBS was put into operation only recently, literature describing its environmental impacts in scientific journals is sparse. Newspaper and magazine articles, papers filed in the IJC case and lengthy discussions on both sides of the controversy abound in forums such as the Internet. Most of the scientific work, however, is still in progress and is yet unpublished in peer-reviewed international scientific literature.

History of the Gabcikovo Barrage System

A 50-year history of events led to the construction of the GBS. Highlights can be summarized as follows (Láng 1992; HAS 1993a, 1994; Láng 1994):

- A concept to build a hydroelectric power system on the Danube River between Rajka and Nagymaros emerged in the late 1940s.
- The first official proposal to build a joint hydroelectric power system at that site was made in 1950.
- The decision to construct the system jointly by Hungary and Czechoslovakia was made in 1963.
- A treaty describing the terms of the agreement between Hungary and Czechoslovakia was signed in 1977.
- In the early 1980s, a Commission of the Hungarian Academy of Science warned that the project would damage the ecosystem of the wetland and threaten drinking water supplies.
- In 1983, the initial joint construction effort was started.
- In 1985 funding to start the project was secured through Austria with a loan to be repaid between 1996 and 2010 by supplying electricity to Austria.
- Construction was carried out on both sides of the Danube until 1989.
- In 1989, Hungary suspended construction, while the Czech and Slovak Republics continued. By this time, nearly all the vital components of the system (e.g., dikes, channels, dam and locks at Dunakiliti, Gabcikovo hydroelectric power plant, etc.) were completed. A notable exception was the dam at Nagymaros, which was only partly completed.
- Early in 1992, Hungary terminated the treaty after public outcry over environmental impacts.

- The Czech and Slovak Republics redesigned the system so that they could circumvent Hungary and operate the GBS entirely within Slovakian territory.
- In October 1992, Slovakia diverted the Danube into a concrete-lined power channel.
- Conflicts over the situation between Hungary and Slovakia resulted in a case before the IJC in 1997.
- In 1997 the IJC decided that a compromise solution had to be negotiated between the two countries such that the GBS would remain in place, but be modified so as to minimize environmental impact. In terms of financial compensation, the IJC said, "each party must compensate the other for damage caused". In the original treaty, construction costs were split evenly between Hungary and Czechoslovakia. Hungary failed to complete its part of the project causing Slovakia to end up paying more. Hungary must still repay Austria 1.2 billion kWh/year until 2015 for work done. It also loses out on income from additional electricity and shipping fees that are now being kept by Slovakia.

Hungary claimed losses due to increased cost for treating drinking water, agricultural production decline, shipping revenue loss and legal expenses. The IJC decided that a portion of these claims were valid and had to be paid by Slovakia to Hungary.

Statements made by the two respective governments can characterize the two very different opinions over the impacts of the GBS. The Slovakian government stated, in 1995, that "postponement of putting into operation the completed structure of the GBS resulted in significant economic and environmental damages" (Abaffy et al. 1995). Slovakia disputed, in the IJC case, the extent of most of the detrimental effects of the GBS claimed by Hungary.

The main Hungarian objection to the plan was, and remains, that there have been significant environmental impacts due to the diversion, and the long-term consequences are poorly understood and so require further study. It is also the Hungarian government's position that insufficient engineering studies had been performed before construction of the GBS. Additionally, issues with respect to international law and policy in terms of a riparian nation's impact on the water quality, water quantity and biodiversity of another are at stake (Dobson 1992; WWF 1992a, 1992b; Chelminski 1993).

Original plan for the GBS

The entire complex, as originally envisioned, would have been nearly 200 km long and included a 52-km^2 reservoir, dams, hydroelectric plants and a diversion canal. There were to be dams and locks at Hrusov in Slovakia and Dunakiliti in Hungary and power plants at Nagymaros in Hungary and Gabcikovo in Slovakia.

The GBS project had four major objectives:

- Hydroelectric power production
- Improved navigation in an area of the Danube known for navigation problems
- Improved water supply
- Economic development of the region related to the production of electricity

The plan was to build a dam at Dunakiliti which would route approximately 95% of the Danube flow into a 25-km power canal located entirely within Slovakia running parallel to the original Danube bed. The Gabcikovo power plant was intended to operate only during peak times and so large water level and flow fluctuations were expected. For this reason, a dam at Nagymaros (downstream) was to be built 100 km from the Gabcikovo dam in order to compensate for the anticipated fluctuations and return the Danube to its normal level.

A weir would raise the level of the Danube at Dunakiliti creating a reservoir. A power canal would take water from the reservoir to a power generating station at Gabcikovo returning to the original Danube riverbed at Palkovicovo. The Gabcikovo barrage, diversion canal and part of the reservoir were to be in Czechoslovakia, while the Dunakiliti weir, the Nagymaros barrage and part of the reservoir were to be in Hungary.

In the original project design the Dunakiliti reservoir was to occupy the flood plains between Dunakiliti and Bratislava within existing flood protection levees. The reservoir's total capacity was to be approximately 200 million m^3 with a live storage capacity of 60 million m^3. A weir at Dunakiliti would regulate the water level in the reservoir and release water into the original Danube riverbed.

The 25-km-long diversion canal was to be divided into two parts: a 17-km upstream portion that would lead to the GBS between the dikes and an 8-km downstream portion that would end at the confluence with the old Danube at Palkovicovo. Eight turbines were to be installed at the Gabcikovo power plant giving it a total capacity of 720 MW.

The GBS project would have created a 3.5-m-deep channel. The old Danube riverbed between Dunakiliti and Palkovicovo was to have a continuous 50-m^3/s discharge, which was only about 5% of the normal flow. A barrage at Nagymaros would compensate the discharge released during peak times of operation of the power plant at Gabcikovo and its backwater extending to Gönyü was to ensure the depth required for navigation. The Nagymaros power plant in Hungary was to operate as a hydroelectric generating plant equipped with six turbines with a combined capacity of 160 MW.

Plan for the GBS after Hungary declined continued participation

Joint construction activities of the GBS began in 1983 and continued on the Slovakian side until 1996. Hungarian construction operations ceased in 1989 after the government decided to abandon the project. Dismantling of structures on the Hungarian side took place in 1995 to insure that the original design could never be easily revived.

The Slovakian government decided to complete the Gabcikovo power station without Hungarian participation. The objective was to commission the Gabcikovo power station and navigation lock by the weir and reservoir feeding the power canal built entirely on Slovakian territory.

The new plan had the following features:

- A curved embankment closing the western flood plain of the Danube upstream of the Hungarian border that raises the water level in the impoundment to an elevation of approximately 130 m above sea level.
- A weir and spillway in this embankment that release water to a river branch called Mosoni Danube in Hungary when the spillway passed flood flows between 4,000 and 10,000 m^3/s.
- Closure of the Danube bed at Cunovo by a rock-filled dam. The embankment connecting to the rockfill on the Slovakian side of the Danube bounds the Hrusov reservoir to the opposite embankment of the power canal.
- Navigation through locks was diverted to the power canal on the Slovakian side of the flood plain.
- The power canal of the Slovakian alternative plan is about 8 km longer than in the original plan, the volume of the reservoir is approximately one-third and its surface area is about two-thirds of the original plan.

The permanent flow released to the original Danube bed is between 350 and 400 m^3/s compared with the pre-dam flow at Rajka of 2,000 m^3/s. The power canal is capable of carrying a flow of 4,000 m^3/s and water to laterals (irrigation channels) will be admitted only at natural Danube flows of 2,500 m^3/s or higher.

For the second stage of the new GBS plan, locks, a weir and a power station for 350 m^3/s discharge were completed in Slovakia in 1996. The weir contributes to the passing of flood flows and ice and also to releasing discharges higher than 350 m^3/s to the original Danube bed.

This plan made the Dunakiliti weir in Hungary unnecessary and so eliminated the possibility that control of the Danube in this area could ever be achieved by Hungary. The entire operation of the GBS was placed under Slovakian control when the new plan was implemented.

By 1996, the Gabcikovo hydroelectric power plant produced nearly 4% of Slovakia's electricity with the rest going to Austria for debt repayment. A sports park is under construction adjacent to the dam site in Gabcikovo as part of a larger plan for an entertainment complex planned for the area. Other economic activities are planned in the vicinity of the dam including manufacturing sites.

On the Hungarian side, the land within the inundation zone is a nature park with virtually no economic activities within the dikes. The public is allowed limited access to the area since it is intended for wildlife protection and protection of water supply.

The situation in 1999 can be characterized as follows:

- The new GBS plan is complete with hydroelectric power being produced and ship traffic routed through locks.
- Management of the existing system is entirely within Slovakia because it is the upstream country.
- Slovakia takes the profits of the GBS (i.e. generating electricity and shipping fees) whereas Hungary suffers most of the environmental impacts of the system.
- The decision of the IJC did not resolve the conflict.
- In order to eliminate the conflict, further discussion involving the two governments and the IJC must take place. Also, long-term research must be conducted.
- In order to mitigate the harmful effects of the diversion, a water supply system was put into operation on the Hungarian side in 1995 which supplies the side branches with water. The capacity of this system is 100 m^3/s.

An environmental monitoring system is running in the area in order to follow the environmental changes including the following parameters: water quality and hydrology of surface and groundwater, soil moisture, forestry and ecology. Data from the monitoring system are collected in a Geographical Information System (GIS) for data storage and interpretation although the GIS is not yet capable of performing complex data analysis, modeling or decision-making. Investigations were also made by the Hungarian government to analyze the environmental effect of the diversion with respect to establishment of the water supply system for the side branches. No results from this study or from the GIS have yet been made public.

The potential and immediately realized environmental impacts of the existing GBS are examined in this paper. An objective analysis of the actual and potential environmental impacts is timely due to the fact that much unsubstantiated information currently is being publicized which serves neither Hungary nor Slovakia well. This paper (i) analyzes the potential environmental impacts of the GBS project; (ii) describes some of the realized short and long-term environmental impacts; (iii) shows the usefulness and limits of satellite remote sensing techniques used in the project for assessing the short- and long-term environmental changes in the study area.

Methods

The Hungarian Academy of Sciences and the National Science Foundation of the United States through the Joint Fund program supported this research. It focused on the Hungarian side of the region affected by the GBS, although clearly both sides of the Danube are impacted by the GBS. It was beyond the scope of this study to make a comprehensive assessment of the environmental impacts of the GBS. Rather, the purpose of this research was to report on some observations made with satellite imagery and other sources regarding potential environmental impacts of the GBS.

Pre-processing of satellite data

Image processing was performed at the National Remote Sensing Center in Budapest and the Remote Sensing Applications Laboratory at the University of Florida. A time series of Landsat Thematic Mapper (TM) satellite images was selected. They consisted of scenes taken in August over a period of 9 years (from 1988 to 1997). The similar acquisition date in each year facilitated the analysis and comparison of vegetation cover. The 1988 and 1992 images were taken before the diversion of the Danube. The other three images were acquired after the diversion. Pre-processing consisted of both geometric and radiometric correction of the satellite data.

Geometric correction of satellite data

Subimages 29 km by 24 km of the Landsat quarter scenes were selected that covered both the Hungarian and Slovakian sides of the Danube in the vicinity of Gabcikovo. First, the parameters for registering the subimages to a reference image were determined using an automated technique (Büttner and Parareda 1993). The sub-images were subsequently transformed to the Hungarian National Grid using a composite transformation formed by the image registration parameters and a previously established reference-image to map transformation.

Radiometric correction of satellite data

Satellite images taken at different dates must be normalized to account for different acquisition parameters (e.g., sun angle and sensor response) and environmental parameters (e.g. atmospheric attenuation) in order to compare them with each other. It was also necessary to normalize the images to each other radiometrically so that we could utilize the normalized difference vegetation index (NDVI) derived from the visible red and near-infrared bands of the imagery (Swain and Davis 1978; Mather 1987).

We used the "dark-object subtraction" method to radiometrically normalize the images using a pine forest as the dark target (Cracknell and Hayes 1991). Since images were acquired in the same time of year (August) selected for clear atmospheric conditions; the radiometric differences attributed to the atmosphere were assumed to be minimal. Systems-based radiometric corrections were made using coefficients supplied by the EOSAT Corporation.

Classification of satellite imagery

A separate maximum likelihood classification was performed using the six reflective channels of 1992 and 1993 images for the forest- and water-dominated floodplain. The floodplain area was outlined manually on the TM color composite by following the dikes on both sides of the river. Color infrared aerial photographs taken in 1992 were used for training set selection.

Training sets were selected for water, grassland, forest and exposed surface categories. There were three subcategories for water, which corresponded, respectively to the main river, two lakes and the side branches of the former Danube riverbed. Two subcategories of grassland were related to wet and dry grass cover. The exposed surface class identifies highly reflective targets such as disturbed areas associated to the construction site around the dam or point bars within and adjacent to the riverbed. The selected categories were highly separable in terms of transformed divergence, except some pairs of subclasses of the same category.

Image interpretation

Using the water classes from the 1992 image classification, buffer zones were delineated with widths of 1, 2, 4 and 8 pixels. These represent, respectively, areas 25, 50, 100 and 200 m wide along both sides of any water surface.

The purpose of the analysis was to detect the change of biomass as indicated by the NDVI of forestland adjacent to the Danube. We expected to find changes near the river due to the fact that numerous observations have correlated the loss of willow trees alongside the river with a decline in the river flow and subsequent water level. The question was whether the TM resolution was adequate to document this phenomenon, which was thought to be restricted to within 10 m from the water edge.

Statistics of NDVI values were computed for only those pixels of the buffer zone classified as forest on the 1992 image. This way we could take into account the possible decline of trees between 1992 and 1993. A potential drawback with this analysis approach was that areas of forestry operations such as clear-cutting were not removed from the analysis. For comparison, NDVI for all 1992 forest pixels were also computed. To assess damage related to the diversion of the Danube, NDVI values were computed for forest stands along the Mosoni (small) Danube.

Results

Hydrological regime

A reservoir with a large surface area (37 km^2) occurred as a consequence of the diversion. The potential impact of the diversion is that the it can cause a significant decrease in the water level of the former riverbed downstream of the reservoir due to the fact that 80–95% of the river's discharge is diverted into a concrete-lined power channel. Consequently, water levels in the side branches will decrease and many branches will dry out completely.

Figure 2 shows flow rates of the original channel of the Danube at Rajka between 1991 and 1995. It shows a dramatic decline in discharge in October 1992 due to implementation of the diversion. Pre-diversion levels averaged approximately 1,500–2,000 m^3/s compared with post-diversion rates of about 400–500 m^3/s. The water supply increased measurably after 1995 for two reasons: (i) Slovakia agreed to release 10% more water to the original channel and (ii) natural precipitation levels were higher after 1995 than in 1993 and 1994.

The natural dynamics of diurnal water level fluctuations changed appreciably during this time period. During times of peak hydroelectric demand, nearly all of the Danube's water is diverted to the power channel thus leaving the

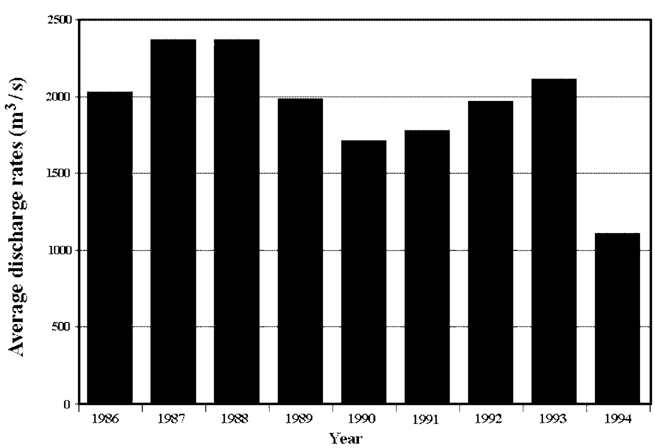

Fig. 2. Discharge of the River Danube at Rajka between 1991 and 1995

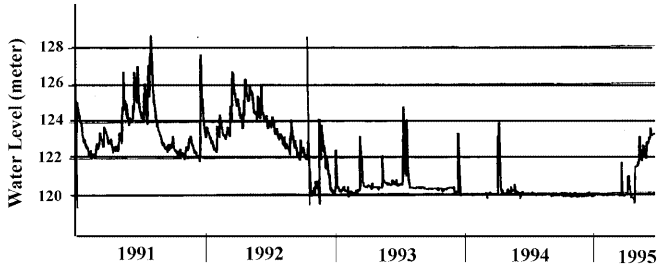

Fig. 3. Water level of the River Danube at Rajka between 1991 and 1995

natural channel dry in a matter of minutes. The situation is completely reversed when demand for electricity slackens and water is rapidly placed back into the original Danube riverbed.

Flow rate is related to water level and the levels at Rajka between 1991 and 1995 are shown in Fig. 3. Water level decreased in 1993 and stayed below average in 1994 and most of 1995. Late in 1995 and through 1998, water levels increased, but were still well below their average levels. The diversion and subsequent drop of water level, followed in 1995 by increased discharge and wetter weather conditions can probably explain these observations.

Water levels vary spatially according to the configuration of the streambed. For example, upstream of the impoundment in the city of Bratislava water levels increased by as much as 2 m between 1992 and 1996. On the other hand, in portions of the downstream part of the original Danube riverbed on the Hungarian side, water levels fell by as much as 4 m compared to pre-dam conditions.

The reduced water level in the old Danube is clearly evident in the satellite imagery by exposed riverbanks throughout the Szigetköz region. Parallel to the power channel between the reservoir and the back-flow area the water surface in the original main riverbed became narrower and several new point bars were visible. This was not the case, however, for the lower third segment due to the effect of the power channel. Many tributaries dried up entirely in the upper Szigetköz area. Images taken before the diversion and afterwards of a typical low-lying area are shown in Figs. 4 and 5, respectively.

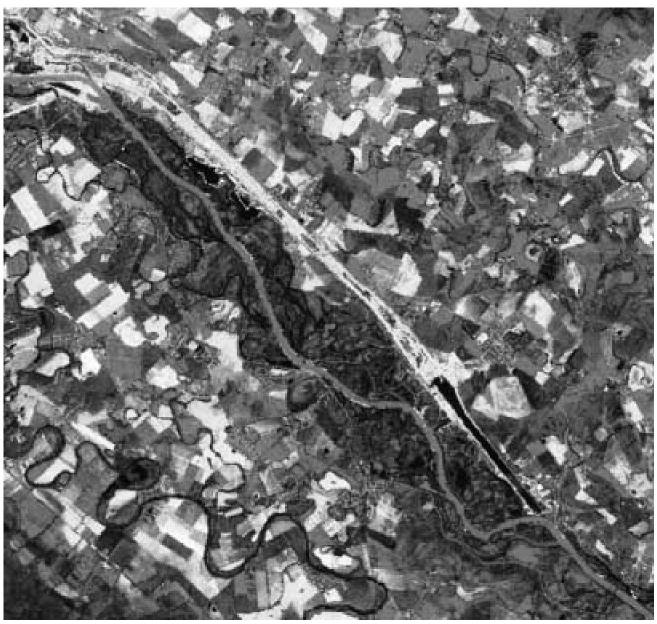

Fig. 4. Satellite image of study area immediately prior to diversion of the Danube

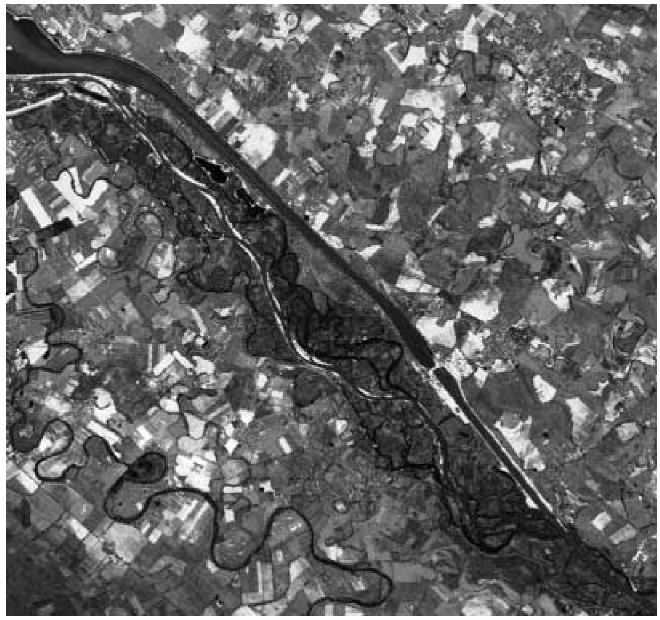

Fig. 5. Satellite image of study area immediately after diversion of the Danube

Groundwater level

It would be expected that groundwater levels in the vicinity of the diversion would decrease except at the end of the system where a backwater effect might cause levels to rise. Since irrigation water is primarily derived from wells in the diversion zone, it could be anticipated that water levels in those would be lower and so pumping costs higher. Also, many of the species of trees in the forests are shallow rooted and so will be adversely effected by a lowered ground water level.

Groundwater levels have dropped appreciably since the diversion took place in most parts of the diversion zone. In the backwater region of the reservoir, groundwater levels have generally risen. It is not known at this time whether these changes are entirely attributable to the diversion or if climate and other factors also played a part. Measurements taken in Zitny Ostrov in 1993 showed that the groundwater levels either increased or were unaffected as compared to pre-dam conditions (HAS 1993b). The increases occurred mainly in the upstream area close to the reservoir, i.e., in the area most negatively affected by a long-term trend of decreasing groundwater levels. In the central part of the Szigetköz region, however, between Dunakiliti and Ásványráró, groundwater levels have decreased in areas close to the Danube.

Hungarian farmers have been quoted in the local newspapers as saying that the water level in some of their wells has dropped appreciably since 1993 and, at times in summer, dried out completely. This observation could not, however, be corroborated with scientific studies.

Sediment storage

Although the sediment loading of the Danube River is reduced by dams located upstream in Germany and Austria, the river still transports nearly 7 million tons of sediment a year to the GBS. Approximately 70% of this load is deposited in the bed of the reservoir. Hydrocarbons and heavy metals can be adsorbed to this sediment and dredging will be necessary eventually in order to maintain draft for shipping lanes. The dredging action will result in a release of the contaminants to the water.

Lack of sediment in water discharged by the dam has caused increased scour of the downstream riverbed (Cousteau Society 1992). This will eventually require shore protection devices since the entire flood plain downstream from the dam is highly developed.

Although the government of Slovakia conducts regular cross-section surveys of the reservoir, no reports have been published to date. Therefore, the rate and location of sedimentation could not be ascertained by this study. It is known from the suspended solids measurements that the sediment loads of the river downstream have decreased appreciably.

The remote sensing technique used in this study was not appropriate to estimate the sedimentation in the reservoir or in the riverbed.

Water quality

Two major impacts of the diversion can be identified with respect to water quality:

- Impairment of drinking water quality
- Eutrophication

Nearly all drinking water in this region comes from the Danube. The river created the largest alluvial reservoir in Europe, representing 14 km^3 of drinking water. The aquifer represents a capacity of approximately 1 million m^3/day in the region. The river is lined with bank filters that lie on top of a near surface aquifer and a deep gravel bed. The 25-km stretch of the old Danube adjacent to the power channel supplies drinking water to hundreds of thousands of people. Downstream, the city of Budapest derives nearly all of its water from the Danube and so potentially millions of people would be affected by a change in water quality of the river at this point. A decrease in water volume supplied to these aquifers will lead to lower water quality simply because there is less water to dilute contaminants.

The water of the Danube contains sufficient nutrients for algal growth. It was anticipated that the combination of reduced currents, increased temperature and higher degree of sunlight in the Hrusov reservoir would lead to accelerated eutrophication of the water that might cause surface water quality problems. This was especially the case in shallower areas since they have a longer retention time. An increase in trophic level was expected in the Hrusov reservoir (VITUKI 1989). A higher trophic state can lead to increased organic matter content of the water and, subsequently, to groundwater contamination.

The North-Transdanubian Environmental Inspectorate collects water samples in the study area and downstream of the study area. Samples are taken at prescribed locations throughout the river several times a year. The water is analyzed for a variety of water quality parameters including biological and physical constituents. The following conclusions can be drawn from the results of water samples taken in the study area by the Inspectorate on the former Danube and on the side branches both before and after the diversion:

- The salinity of the river water was unaffected by the diversion.
- Water temperature has increased due to the Hrusov reservoir.

Changes in the concentrations of other chemical water quality components were, in general, small, but some trends could be noted. For example, measurement of COD over time demonstrates the following: (i) COD concentrations before the diversion were significantly higher; (ii) there were both increasing and decreasing COD concentration trends in the 10 years prior to the diversion; (iii) changes in COD concentrations after the diversion were generally lower.

The PO_4-P concentration trend decreased from the middle of the 1980s until 1993 at a rate of approximately 5%/year. Since 1993, an increasing trend toward increasing concentration has occurred.

The dissolved oxygen concentration of the river did not change significantly due to the diversion.

There is a decreasing trend in suspended solids concentration of approximately 5%/year., total phosphorus of more than 20%/year. and ammonia of 40%/year. after the diversion.

There was a decrease in iron concentration of more than 10%/year. due to the diversion.

The concentration of chlorophyll-a decreased by 10% since the diversion in the outlet of the Hrusov reservoir in comparison with the pre-diversion conditions. This increase contradicts what would have been anticipated, but may be explained by the significantly cooler weather in the region over the past 6 years.

Summarizing the water quality situation, it can be stated that: (i) the changes due to the diversion were not dramatic and the variations are comparable with fluctuations prior to the diversion; (ii) trends have developed and most indicate an improved water quality; (iii) water quality changes due to other factors (such as sewage purification, or other measures) are of the same order of magnitude or even higher than that of the changes caused by the diversion.

The water quality changes in the test area were not investigated by remote sensing techniques in this project due to the fact that it was outside its scope. Methods are, however, known for this purpose and any long-term study of the impact of the GBS on water quality should include satellite-based remote sensing.

Ecological impacts

The large and active alluvial floodplains (including the Szigetköz and the Zitny Ostrov regions) along the Danube River are unique ecosystems in Europe due to the fact they were never regulated completely by water retaining structures. Centuries ago, these types of forests ran along all the major European rivers (Cousteau Society 1992), but all have been altered in time.

The ecosystem of the study area was practically in a natural condition before the diversion. The ecosystem was in equilibrium with respect to the century-long dynamics of the river. In the continuously changing side branch system of the Szigetköz, the ecosystem could slowly follow the processes taking place. Relatively rapid changes caused by the river diversion caused damages in this ecosystem resulting in loss of biodiversity (Láng 1994). Hahn (1994) also confirmed the prediction of ecological damage to the floodplain as a result of the diversion adding that most of the change will occur on a long-term basis. Plant and animal communities are unable to establish themselves under these conditions resulting in a reduction in the biodiversity of the region (Pineda 1992; Láng 1994).

Information concerning ecological changes following the diversion is sparse. According to results of a program to monitor vegetation health conducted by the Hungarian government, significant damage occurred after the diversion until 1995 in the indicator populations of *Nuphar lutea*, *Plantago altissima, Quercus robur*, *Alnus incana*, *Fraxinus exelsior* and *Salix alba*. The leaf area of the trees reduced and so showed the negative effects of the diversion (Szabó et al. 1996). An increased population of terrestrial weeds indicated the negative effect of groundwater level reduction. The drought-tolerant species of plants, which were primarily weeds, became more frequent after the diversion (Czimber 1996). Findings by Gergely et al. (1996), who analyzed the structure of terrestrial macrophytes, showed that the surface of the exposed bank areas became increasingly covered by terrestrial macrophytes after the diversion.

The overall results of the ecological investigations indicate that the flora and fauna in the Szigetköz are undergoing structural changes, but it is too early to predict the direction of the changes. Some of the ecological changes can be measured by remote sensing (for example macrophyte cover, habitat types, etc.), but analysis of land cover changes was the objective of our project. An increased cover of macrophytes in the exposed bank areas can be confirmed from the analysis of the satellite imagery.

Forestry

The Szigetköz region is a mixture of natural wooded lands and tree plantations that were established at the end of the last century. Private companies in the region, making assessment of the impact of the GBS difficult, conduct limited commercial forestry operations. There are no reliable data of the areas where the cutting has taken place and so it must be assumed that changes in the forested area detectable with the satellite imagery are a mixture of commercial forestry operations, natural changes, those resulting from the dam and other factors such as pest damage. The logging operations are limited in scope and do not constitute a significant percentage of the study area and there is not a major pest problem in this region (S. Smith, personal communication, 1998).

Natural and plantation forests adjacent to the original Danube rely on a steady high water table level for survival. The types of trees, both planted and natural, do not have deep rooting systems. Tree stands have, for decades, provided for both a profitable lumber operation and wildlife habitat in the undisturbed stands. The concern is that monogamous drought-tolerant trees will take the place of more diverse stands and so render the region a less robust ecosystem. From the approximately 15 different species found in the Szigetköz area (we had no data from the Zitny Ostrov area), improved poplar covers about two thirds; the so-called "local" poplar covers 8% and willow covers a quarter of the area. All three species of trees require a great deal of water. Although these species can survive with less water, rapid growth and so therefore a profitable timber business can be expected only on natural flood plains. The growth of these species – as opposed to the approximately 7 m^3 per hectare annually as a national average – is about 20 m^3 per hectare in some places and reaches up to 60 m^3 per hectare in the maximum growth period. Although the growth period can be influenced and limited by other factors such as temperature, light and humidity, what significantly retards the growth is lack of water at the root level (Somogyi 1996).

Modification of the composition of tree species and general health of forests brought on by the diversion will take several more years to ascertain. Other indices, such as leaf area index (LAI), are more suitable for detecting short-term changes. LAI data taken on both the Hungarian and the Slovakian side of the Danube show a marked increase of near the reservoir and a corresponding decrease of loss of leaves in the same areas during the same time period (Somogyi 1996). This indicates that groundwater levels have risen adjacent to the reservoir – a fact substantiated by field data – and this fosters high levels of foliage. There is limited published LAI data and leaf loss data for areas remote from the reservoir, although a series of monitoring stations have been established throughout the Szigetköz, which will provide this information eventually.

Changes in forest cover can be triggered by a number of phenomena, including pest infestation and damage by wildlife. Some of these changes only manifest themselves after a period of time while other reactions are immediate. The ability to perceive changes is largely influenced by the length of time the observation takes. During the 9-year period of study (1988–1997), only major environmental effects (natural or man-made) were perceptible. This fact remains valid even though the trees of the floodplain of the Szigetköz were highly water dependent, had a relatively short lifetime or quick reaction time compared with other trees (Somogyi 1996).

In general, clear-cutting and reforestation are easily detectable events that cause major changes. On the other hand, smaller scale operations such as thinning and nurseries have no visually perceptible effect on the satellite imagery. The reason for this is probably that, even after a major disruption of the canopy, there was enough foliage and undergrowth remaining to make its spectral reflectance indiscernible from that of its original state. This means also that pest or wildlife damage was also unverifiable. Some specific examples of problems for forested areas do exist. Since 1992, conditions have deteriorated in the forest sections near the village of Dunasziget. What was not discernible on the satellite images was destruction that affected smaller patches consisting of groups of trees or single trees – mostly willows – since the size was smaller than the pixel size of the images. According to field observations, the number and groups of trees that have died due to drought have been approximately 5% of the total tree population since 1992. Tree perimeter growth data taken in the vicinity of the village of Dunasziget and near Dunakiliti indicate a measurable decrease in growth between 1991 and 1993 (Somogyi 1996).

Analysis of the satellite images along the former riverbank shows that there was a decrease in NDVI values in this region after the river diversion as indicated in Table 1. This suggests that the forests by the riverside were appreciably damaged due to loss of water.

Precipitation is a critical factor in the health of forests, and 1992 and 1993 were unusually dry years Furthermore, days in which the maximum daily temperature exceeded 30 °C and days where the daily maximum temperature exceeded 35 °C were very numerous in those two years. This situation increased the loss of water by trees, which "exhausted" themselves and then spent 1993 "resting" and accumulating reserves instead of growing. Highly favorable precipitation from 1994 to 1998 explains why the growing stands are back to normal (Palkovits and Schummel 1996).

Agricultural land changes

Intensive agricultural production is carried out in this region. Crop yields of major plants (wheat, maize, sugar beet, spring barley, fodder maize) were about 15–20% higher here than the national average before the GBS was implemented. Cultivation is primarily based on the utilization of natural precipitation, which is supplemented by groundwater. Irrigation is usually not economical due to high cost and thus only applied to highly valued crops. However, the percentage of irrigated areas is higher (10%) than the national average (5%). Obviously, Hungarian farmers have reason to be concerned about any potential threat to water supply in the diversion zone.

The primary economic activity in the Szigetköz region is agriculture with approximately 70% of the region composed of cultivated land. The region is a floodplain and so the soil is rich in nutrients. The business of agriculture changed in Hungary and Slovakia radically starting in 1990 as a result of the major political and economic reforms in Eastern Europe due to the collapse of the Soviet Union. Large collective operations were broken down into smaller private farms. Field sizes became smaller as the process of transferring land title from the state to private individuals took place (Smith et al. 1998).

In addition to field size, the type and pattern of crops also changed after the collapse of the Soviet Union. For example, the percentage of cereals increased compared with the percentage of maize, alfalfa and vegetables which have declined. The percentage of crops such as wheat sown in the autumn has increased in the Szigetköz region since 1990 compared to spring crops such as maize. This is due to the fact that spring crops require irrigation and more fertilizers than autumn crops. Both irrigation and fertilizers add to production costs and year-round water availability is now in question (HAS 1994).

Satellite imagery was not useful in determining whether or not the diversion has had an impact on agricultural activities in the Szigetköz region. The reasons for this are that the satellite data are not useful in assessing crop production nor can they indicate a lack of irrigation water. A long time series of images might indicate whether or not the amount of land devoted to agriculture in the region has changed, but even those figures could not answer the central question of whether that change was caused by the diversion.

Table 1. Precipitation for study area between 1989 and 1997

Period	Sum of precipitation (mm)	Number of standard deviations	Description
1989–1990	488	–0.821	Droughty
1990–1991	532	–0.458	Droughty
1991–1992	480	–0.887	Droughty
1992–1993	508	–0.656	Droughty
1993–1994	637	–0.410	Wet
1994–1995	721	–1.104	Wet
1995–1996	806	–1.806	Extremely Wet
1996–1997	527	–0.499	Droughty

Policy implications of findings

There are three primary lessons learned from the GBS experience with respect to policy:

The decision to go to the International Court of Justice was a mistake. The Court rendered a decision that was unsatisfactory to either party and did nothing to correct the situation. The case took away resources that could have otherwise been used to perform important environmental monitoring and also been used for simple, yet effective, means of ameliorating the problem such as the lateral irrigation ditches which were eventually constructed.

More environmental impact studies ought to have been performed prior to the construction and commission of the GBS. The effort should have focused more on the ecology and water quality aspects of the situation rather than only the water quantity and other purely hydrological aspects.

More discussion should have taken place between Hungarian and Slovakian engineers and ecologists after the GBS was commissioned. This might have resulted in the water laterals in the Szigetköz being constructed much earlier than 1995 and so mitigating the drought conditions in both the forest and agricultural areas.

It is not the intention of this paper to decide whether or not the GBS should have been built. Society must make these decisions and then it is the responsibility of the engineers to minimize the impact to the environment. Hydroelectric generation, generally, results in the least environmentally damage of all the sources of electric power. If it is decided that electricity is needed, this is the best way to go in most cases.

In the case of the GBS, it is clear that the environmental impacts could be mitigated through simple, yet effective, measures such as the laterals built by Hungary in 1995. There are a number of ongoing monitoring efforts being conducted by Hungarian, Slovakian and international groups. It should be the clear policy of the governments of Hungary and Slovakia to share data from these studies so that long-term changes to the environment can be evaluated.

Conclusions

The following conclusions can be drawn from the results of the research summarized in this paper:

Large hydroelectric power systems such as the GBS can have numerous disadvantageous environmental impacts that should be taken into account during their planning and construction. The most significant damage can occur in groundwater level, sedimentology, ecology, forestry and agriculture. Some of the impacts can be mitigated by adequate water management methods.

- Satellite remote sensing is a suitable means for detecting obvious changes in river morphometry downstream from the diversion and other manifestations of the water loss such as stress to and actual loss of forestland cover. The satellite imagery was also able to detect changes in NDVI, which is a reliable indicator of vegetation vigor.
- Land cover change occurred in the study area between 1988 and 1997, although there appears to be no obvious trend towards increased or decreased vegetation cover. This means that there were no obvious significant changes caused by the river diversion during the last 5 years that could be ascertained using our techniques. This fact is partly attributable to the installation in 1995 of lateral water supply channels, weirs and other flow augmentation devices that supply the river branches on the Hungarian side of the system with water.
- Apart from the obvious manifestation of the diversion (e.g. exposed river banks), the difference between the 1992 image and the 1993 image with respect to vegetation cover was not significant, even though NDVI values in the zone immediately adjacent to the river were significantly lower in 1993 as compared to 1992. This would indicate that the trees, primarily willow, that line the shoreline will likely be adversely affected in time because of the diversion and subsequent loss of water. Field data support this finding.
- The environmental changes can be a direct result of the diversion or a combined result of atypical climate, diversion and other man-made activities. It is possible that the changes caused by the diversion are comparable to those changes having other origins.
- It is not known if these changes are short or long term in nature. Several additional years of monitoring are needed in order to produce sufficient scientific evidence to reach any definitive conclusions regarding the long-term impacts of the GBS.
- While insufficient time has elapsed since the GBS was put into operation to make definitive conclusions regarding its long-term environmental impacts, some indications are emerging that merit further study.
- Scientists should continue to monitor the area for evidence of long-term sustained environmental change. The procedures outlined in this paper would be suitable for long-term monitoring of land cover changes resulting from the diversion.

Recommendations

The following recommendations can be proposed from the results of the research summarized in this paper:

- In general, a significant improvement in the existing simplified Geographical Information System (GIS) should be performed in order to store, handle and analyze data from different fields of research and monitoring. This improved system would contain the following levels: (i) data storage and handling; (ii) data interpretation; (iii) data evaluation including simple or more complicated statistical analyses; (iv) transport and water quality models describing the mass flow processes in surface waters and in groundwater; (v) models for decision making including cost elements and other management points of view.
- The GBS will be in operation for many decades. An improvement of the existing monitoring system should be achieved in order to analyze the mid-term and long-term impacts of the operation. One of the key elements of this monitoring system would be the use of satellite remote sensing which can be useful in the following: (i) determination of land cover changes; (ii) determination of the main water quality components (chlorophyll-a, dissolved organic matter and suspended solids); (iii) detection of changes in different habitats.
- More data collection is necessary in the field of ecology to demonstrate the changes in habitat structure and species composition, elimination or colonization of species, etc., in order to investigate the changes in the structure of the ecosystem. This monitoring work would provide data for assessment of adverse or reverse environmental impacts of the diversion.
- Presently, the data collected are evaluated in the specific fields separately. An integrated and overall analysis and evaluation of the existing database is necessary in order to estimate and weight the different environmental impacts detected in the impacted area during the past several years.

Hydrological data are essential for a complete study and understanding of the impacts of this diversion. Hydrological data exist for the Hungarian side at the National Water Research Center (VITUKI) and should be utilized for future analysis of the situation.

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