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VPLIV IZGRADNJE HIDROENERGETSKIH OBJEKTOV NA VODNI REŽIM
THE IMPACT OF HYDROPOWER PLANTS ON THE WATER REGIME

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Namen prispevka je predstaviti vplive izgradnje pregrad v Mavčičah in Medvodah na vodni režim Kranjsko-Sorškega polja. Obe pregradi sta situirani na reki Savi med Kranjem in Medvodami, na bolj ali manj debeli plasti vodonosnika. S pregraditvijo reke Save se je rečni režim spremenil v jezernega, pri čemer se je povečal vnos savske vode v podtalnico, prekinjena je bila prodonosnost. Za namen ugotavljanja vplivov sprememb smo izdelali bilanco reke Save, model podtalnice Kranjsko-Sorškega polja s programom Modflow ter primerjavo meritev volumnov obeh akumulacijskih jezer v razmiku 12 let. Ugotovili smo pretok in smeri toka podtalnice, večje dotoke vode na pregradi Medvode zaradi dreniranja podtalnice dolvodno od pregrade Mavčiče in zmanjšan volumen akumulacije Mavčiče za razliko od akumulacije Medvode. Zaradi zablatenja se dotok vode iz reke Save v podtalnico polagoma zmanjšuje, kar smo podrobneje prikazali s pomočjo meritev piezometričnih tlakov.
Ključne besede: *vplivi pregrad, Modflow, podtalnica, vodna bilanca, sedimentacija, reka Sava*

The purpose of this paper is to discuss the impacts of hydropower plants of Mavčiče and Medvode on the water regime of the plain Kranjsko-Sorško polje, Slovenia. Both hydropower plants are situated on the Sava River between Kranj and Medvode on an aquifer layer of variable thickness. The hydropower plants have changed the river regime into a lake regime. As a result, the infiltration of the Sava into groundwater increased, while sediment transport was cut off. We prepared the water balance of the Sava River, a groundwater model of Kranjsko-Sorško polje using Modflow and a comparison of volume of both reservoirs. We established the flow rate and directions of groundwater flow, a larger inflow at the Medvode hydropower plant, which is a consequence of groundwater drainage downstream from the hydropower plant Mavčiče, and considerable volume change in the Mavčiče reservoir. Due to sedimentation the infiltration of the Sava is decreasing, which was demonstrated with measurements of piesometric pressures.
Key words: *hydropower plant impacts, Modflow, groundwater, water balance, sedimentation, Sava river*

1. UVOD

Izgradnja pregrad je ukrep, s katerim oblikujemo zbiralnike vode za različne potrebe. Med razloge za gradnjo pregrade spada predvsem pridobivanje energije s pomočjo obnovljivega energetskega vira – vode, ki ima v primerjavi z ostalimi metodami pridobivanja energije, kot so izkoriščanje fosilnih goriv ali jedrske energije, manj negativnih posledic.

Hidroelektrarna Mavčiče in njeno akumulacijsko jezero ležita 7,5 km zračne razdalje dolvodno od mesta Kranj pod

1. INTRODUCTION

The construction of dams is a measure that results in the formation of water reservoirs in support of different purposes. These include the production of energy from a renewable energy source – water, which has fewer negative effects compared to other methods of energy production, such as exploitation of fossil fuels or nuclear power.

The Mavčiče hydropower plant and its reservoir are situated at a distance of 7.5 km downstream from the town of Kranj, below Mavčiče, on the plain Kranjsko-Sorško polje naseljem Mavčiče na Kranjsko – Sorškem polju v soteski Save. Akumulacijsko jezero je zalilo ozko sotesko Save in sega malo višje gorvodno od mostu pri tovarni Planika. To mesto velja tudi za začetek akumulacije Mavčiče.

Hidroelektrarna Medvode leži nad sotočjem reke Save in Sore v občini Medvode 11,8 km zračne razdalje od mesta Kranj in 4,8 km od pregrade Mavčiče. Za pregrado je nastalo Zbiljsko jezero, imenovano po naselju Zbilje nad akumulacijskim jezerom, ki sega malo nad smledniški most (slika 1). Jezero se je pretežno oblikovalo v mejah stare rečne struge in delno s potopitvijo nizkih obrežnih teras.

in the Sava gorge. The reservoir filled the narrow Sava gorge, spreading a bit further upstream of the bridge at the Planika factory. This is also the start of the Mavčiče reservoir.

The Medvode hydropower plant is situated above the confluence of the Sava and Sora rivers in the municipality of Medvode, 11.8 km from Kranj and 4.8 km from the Mavčiče dam. Behind the dam, Lake Zbilje was formed, getting its name after the town of Zbilje located above the reservoir. The lake extends just above the Smlednik bridge (Figure 1). It was mostly formed within the boundaries of the old river channel and partly with the flooding of the low alluvial terraces.

Slika 1. Prikaz lokacije Trbojskega in Zbiljskega jezera na karti v merilu 1:108583.
Figure 1. Location of Lake Trboje and Lake Zbilje, scale 1:108583.

Pri določanju vplivov pregrad Mavčiče in Medvode na tok podtalnice in rečni režim smo uporabili program Modflow, ki simulira tok podtalnice. Najbolj neposreden in neizbežen vpliv obeh pregrad je bil namreč dvig gladine podtalnice, ki obsega širše območje Kranjsko-Sorškega polja. Dvig podtalnice je povzročil precej neprijetnosti pri prebivalcih na območju akumulacije vse do mostu pri tovarni Planika, ki še spada pod vplivno območje. Podtalnica je poplavila okoliške kleti, vključno s kletjo tovarne Planika. V času obilnejših deževij je voda začela zastajati na travnatih površinah in

For evaluating the effects of the Mavčiče and Medvode dams on the groundwater flow and water regime we used the model Modflow. The most direct and imminent effect of both dams was the rise in groundwater levels, which occurs in the wider area of the Kranjsko-Sorško polje. The rise in groundwater levels caused has several problems to the inhabitants in the reservoir area, up to the Planika factory bridge, which is still inside the impact area. The groundwater flooded the basements in the area, including the Planika factory basement. During heavy le počasi odtekala.

Med pomembnejše vplive, ki so nastali s pregraditvijo reke Save, spada tudi zaprojevanje oziroma zamuljevanje jezera. Sava ima v zgornjem toku izrazito hudourniški značaj z značilno prodonosnostjo. Novonastali jezeri sta postali naravni usedalnik za rečne naplavine, ki so lahko zaradi vsebnosti škodljivih snovi pomemben ekološki problem.

2. MATERIAL IN METODE

2.1 MODEL PODTALNICE KRANJSKO – SORŠKEGA POLJA V PROGRAMU MODFLOW

Izdelali smo model podtalnice Kranjsko – Sorškega polja s programom Moflow (proizvajalca U. S. Geological Survey, ZDA; programski paket Processing Modflow (PMWIN53), verzija 5.3.0) s katerim smo ugotavljali vpliv pregrade na gladine in tok podtalnice (Horvat, 2006). Model je izdelan na osnovi matematičnega modela podtalnice Sorškega polja (Brilly et al, 1982). Namen modela je bil določiti nivo podtalnice s pomočjo umerjanja parametrov, tako da se merjene vrednosti čim bolj ujemajo z izračunanimi. Končne razlike med meritvami in izračunom nivojev talne vode so v večini ±50cm, z nekaterimi izjemami. Dve merilni mesti nista upoštevani in sicer Sveti duh in Polje pri Vodicah, ker tam prihaja do prevelikih odstopanj zaradi vplivov, ki segajo izven območja in v območje niso zajeti.

Območje modela zajema Kranjsko – Sorško polje, kot je prikazano na sliki 5. Površina aktivnega območja meri 218 km^2, kjer vsak kvadrat meri 400x400 m.

Celotno območje ima en sloj, ki je vodonosnik s prosto gladino.

2.1.1 Parametri, ki jih je potrebno določiti v obravnavanem območju

<u>*Kote terena in kote neprepustne podlage:*</u>

Uporabili smo kote terena pri piezometrih in vodnjakih iz Hidrološkega letopisa za leto 2001 (ARSO, 2001) ter jih interpolirali za

rainfall, the water was retained on grasslands and the runoff was slow.

The damming of the Sava also caused the reservoirs to silt up. In its upper reach the Sava boasts a predominantly torrential character with significant bed-load transport. The new lakes provide a natural settling basin for alluvial deposits, which can represent a serious ecological problem in case of pollution.

2. MATERIALS AND METHODS

2.1 MODEL OF THE KRANJSKO-SORŠKO POLJE GROUNDWATER IN MODFLOW

The model of the Kranjsko-Sorško polje groundwater was prepared by using Modflow (U. S. Geological Survey; program package Processing Modflow (PMWIN53), version 5.3.0), which enabled us to determine the impact of the dam on the groundwater level and flow (Horvat, 2006). The model was based on the mathematical model of the Sorško polje groundwater (Brilly *et al.*, 1982). The purpose was to determine the groundwater level based on the calibration of paramers, ensuring a best possible fit between the measured and calculated values. The final differences between the measurements and the calculated levels of groundwater are, with a few exceptions, mostly within ±50cm. Two measuring sites were excluded from the calculation, Sveti duh and Polje pri Vodicah, where there were large variations due to the impacts from outside the investigated area, and which are not captured within the area.

The model covers the area of Kranjsko-Sorško polje, as shown in Figure 5. The surface of the active area is 218 km^2, where each grid measures 400 x 400 m.

The entire area consists of one layer, the unconfined aquifer.

2.1.1 Parameters to be determined in the relevant area

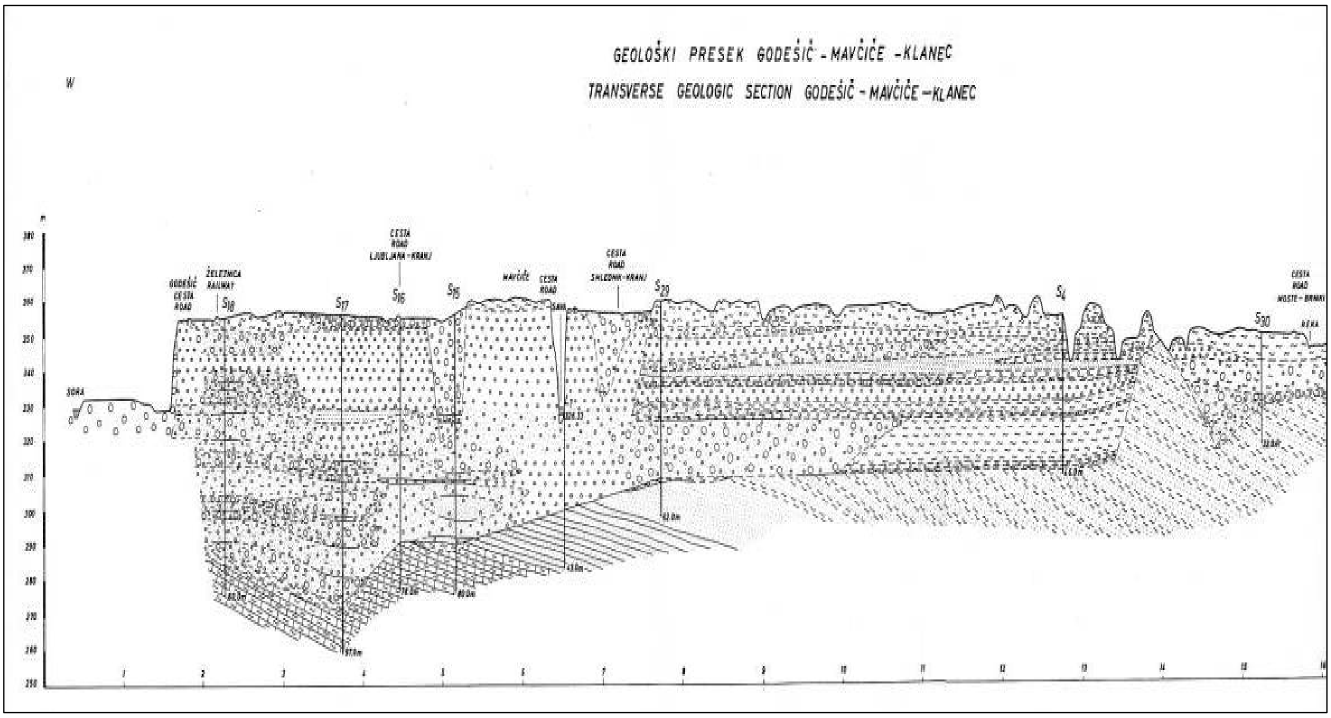
<u>*Levels of terrain and impervious surface:*</u>

We used the terrain levels of piezometers and wells from the 2001 Hydrological Yearbook of Slovenia (ARSO, 2001), which celotno območje.

Kote dna smo določili s pomočjo geološkega prereza Godešič–Mavčiče–Klanec, ki je bil uporabljen že pri matematičnem modelu (Brilly et al, 1982), (Slika 2).

were interpolated for the entire area.

The bottom levels were determined using the geological cross-section Godešič–Mavčiče–Klanec, which was used previously in the mathematical model by Brilly *et al.* (1982), (Figure 2).



Slika 2. Geološki prerez Godešič–Mavčiče–Klanec.
Figure 2. Geological cross-section Geodešič–Mavčiče–Klanec.

Časovni parametri:

Časovno obdobje simulacije je 12 mesecev.

Začetne gladine podtalnice:

Za začetne gladine podtalnice v simulaciji smo vnesli srednje mesečne vrednosti gladin januarja 2001, ki smo jih s pomočjo programa interpolirali za celotno območje (ARSO, 2001).

Vrtine in meritve opazovanj:

V program smo vnesli podatke o lokaciji in meritvah srednjih mesečnih vrednosti v 20-ih piezometrih in vodnjakih (ARSO, 2001).

Horizontalna hidravlična prepustnost, transimisivnost in efektivna poroznost:

Horizontalna hidravlična prepustnost (k) je izračunana kot količnik med transmisivnostjo (T) in debelino sloja (b). S tema dvema

Time parameters:

The time period of the simulation is 12 months.

Initial groundwater levels:

For initial groundwater levels in the simulation we used the mean monthly levels of January 2001, which were interpolated for the entire area (ARSO, 2001).

Wells and measurements:

Data on the location and measurements of mean monthly values in 20 piezometers and wells were entered into the program (ARSO, 2001).

Horizontal hydraulic conductivity, transmissivity and effective porosity:

Horizontal hydraulic conductivity (k) is calculated as the ratio between transmissivity (T) and layer thickness (b). These two parametroma se model umerja in sicer tako, da se prilagaja vrednosti in meje območij različne horizontalne prepustnosti in transmisivnosti.

Efektivna poroznost je 0.25 oziroma 25 %, enako po celotnem območju (Brilly et al, 1982).

Napajanje podtalnice:

Podtalnica območja se napaja iz padavin, ki znašajo približno 1000 mm/leto. Vrednost parametra napajanja podtalnice, ki smo ga vnesli za celotno območje, je 2,74 mm/dan, kar je 3,2 x 10^{-8} m/s.

Dodali smo še napajanje na severovzhodnem robu območja, ki je bilo ocenjeno na podlagi vodotokov, ki niso zajeti v območje in so prisotni severno od območja, to je ponikanje Kokre in drugih potokov. Ta podatek je povzet iz študije Podtalnica Kranjsko – Sorškega polja (Breznik in Pšeničnik, 1987a) ter študije Vpliv akumulacije HE Mavčiče na okolje (Brilly in Steinman, 1988).

2.1.2 Reke, ki vplivajo na podtalnico

V modelu je zajetih pet vodotokov, in sicer: Sava, levi pritok Save Kokra, desni pritok Save Sora, Pšata na vzhodnem delu območja in Dobrava na jugovzhodnem delu območja. Vsem vodotokom smo določili koto dna, koto gladine in prepustnost dna reke. Pri določanje kot reke Save smo si pomagali s podatki iz SEL-a, kot reke Kokre s podatki iz VGP-ja, kot ostalih treh vodotokov Sore, Pšate in Dobrave pa s podatki Interaktivnega naravovarstvenega atlasa Slovenije.

2.2 REČNA BILANCA SAVE

Vodotoki visokogorskega sveta Slovenije in njihovega neposrednega predgorja imajo snežno dežni rečni režim (Julijske Alpe, Karavanke, Kozjansko, Pohorje). Pri dinamiki razporeditve odtoka sta značilna dva viška in dva nižka. Primarni višek nastopi v pozni pomladi, praviloma maja ali celo junija. Primarni nižek je pozimi in traja od decembra do marca s primarnim nižkom januarja ali

parameters are used to calibrate the model by adapting the values and boundaries of areas with different horizontal conductivity and transmissivity.

Effective porosity is 0.25 or 25%, and it is the same in the whole domain (Brilly *et al.*, 1982).

Groundwater recharge:

The groundwater is replenished through precipitation, which is approx. 1000 mm/year. The groundwater recharge parameter value used for the entire area is 2.74 mm/day, which is 3.2 x 10^{-8} m/s.

Furthermore, we added the recharge at the northeastern border, which was estimated on the basis of the streams outside the area of investigation, present to the north of the area, i. e. infiltration of the Kokra river and other streams. These data were adopted from the study The Kranjsko-Sorško polje groundwater (Breznik and Pšeničnik, 1987a) and Environmental implications of the HPP Mavčiče reservoir (Brilly and Steinman, 1988).

2.1.2 Influence of streams on groundwater

The model includes five watercourses: Sava, Kokra (left tributary of the Sava), Sora (right tributary of the Sava), Pšata to the east of the area, and Dobrava to the southeast. For all streams the bottom level, surface level and permeability of the stream bed were determined. In determining the levels of the Sava we used the data provided by the power company SEL, data for the Kokra by VGP, and for the Sora, Pšata and Dobrava we used the data of the Interactive Nature Conservation Atlas of Slovenia.

2.2 THE SAVA WATER BALANCE

The streams of alpine and subalpine Slovenia have a snow–rain regime (Julian Alps, Karavanke, Kozjansko, Pohorje). The runoff dynamics is characterised by two highs and two lows. The primary high occurs in late spring, usually in May or even June. The primary low occurs in winter, from December to March, with a primary low in January or February, which is lower than the summer februarja, ki je nižji od poletne nizke vode.

Rečna bilanca reke Save je izdelana na podlagi podatkov o srednjih mesečnih dotokih na pregradi Mavčiče in Medvode od leta 1988 do leta 2004. Namen izdelave rečne bilanca površinskega toka je bilo ugotoviti razlike med dotokom na pregrado Mavčiče in dotokom na pregrado Medvode.

2.3 TRANSPORT SEDIMENTOV

Sedimentacija ima lahko številne negativne vplive, kot je zadušitev vodnih organizmov, ko sediment zapolni prostore med kamenjem in prodom na rečnem dnu in posledično uničenje habitata insektov in drugih organizmov v prehranjevalni verigi; če se iz sedimentov sproščajo hranila in nekatere toksične snovi, lahko le-te poslabšajo kakovost vode, pospešujejo rast alg in škodujejo življenju v vodi, zmanjša se bistrost vode in atraktivnost vodnega okolja za plavanje in druge rekreativne in turistične namene.

V tem poglavju so na podlagi meritev Inštituta za hidravlične raziskave predstavljene spremembe v volumnu obeh akumulacijskih bazenov, ki so posledica prekinitve transporta sedimentov.

2.3.1 Volumen bazena HE Mavčiče

Za akumulacijski bazen HE Mavčiče je bil leta 1998 narejen izračun volumna za primerjavo z volumnom bazena v letu 1986, ko je HE Mavčiče začela obratovati. Leta 1986 je bil volumen izračunan s pomočjo prečnih profilov in njihovih medsebojnih razdalj, leta 1998 pa so za določitev volumna uporabili še digitalni model reliefa do kote zajezbe.

Volumen leta 1986 izračunan po prečnih profilih: 12.268.006 m^3;

Volumen izračunan leta 1998 po prečnih profilih: 11.738.298 m^3

in s pomočjo digitalnega modela: 10.836.906 m^3

(Inštitut za hidravlične raziskave, 2000b).

Volumen je izračunan za koto zajezbe, 346,0 m n.m.

Razlike v velikosti izračunanega volumna

low.

The water balance of the Sava was made on the basis of the data on mean monthly inflows on the Mavčiče and Medvode dams from 1988 to 2004. The purpose of making the balance of surface runoff was to determine the differences between the inflows to the Mavčiče and Medvode dams.

2.3 SEDIMENT TRANSPORT

Sedimentation can have many adverse effects, such as suffocation of aquatic organisms when the spaces between the rocks and gravel on the river bed are filled, resulting in the destruction of habitats of insects and other organisms in the food chain; if nutrients and toxic substances are released from the sediment, water quality can deteriorate, algae growth is accelerated, acquatic habitats are damaged, water clarity is reduced and the amenity value of the water environment for swimming and other recreational and tourist activities is reduced.

In this chapter, the changes in the volume of both reservoirs are represented, as a consequence of cut-off of sediment transport, based on the measurements of the Hydraulic Research Institute.

2.3.1 Volume of the Mavčiče HPP reservoir

For the Mavčiče HPP reservoir a calculation of the reservoir volume was performed in 1998, which was compared to that of 1986, when the Mavčiče HPP was put in operation. In 1986 the volume was calculated based on cross-sections and the in-between distances, and in 1998 a digital relief model for the area up to the headwater level was used for determination of volume.

Volume in 1986 calculated from cross-sections: 12,268,006 m^3;

Volume in 1998 calculated from cross-sections: 11,738,298 m^3; and

using the digital relief model: 10,836,906 m^3

(Hydraulic Research Institute, 2000b).

The volume is calculated for the altitude 346.0 m a.s.l.

The differences between the volumes are

po dveh različnih metodah so posledica same metode: pri metodi z digitalnim modelom reliefa je volumen izračunan na osnovi več podatkov in zato tudi bolj točen, kot pri metodi po prečnih prerezih, kjer se izračuna delne volumne, ki se jih sešteje – prav tako pa se sešteva tudi napaka metode.

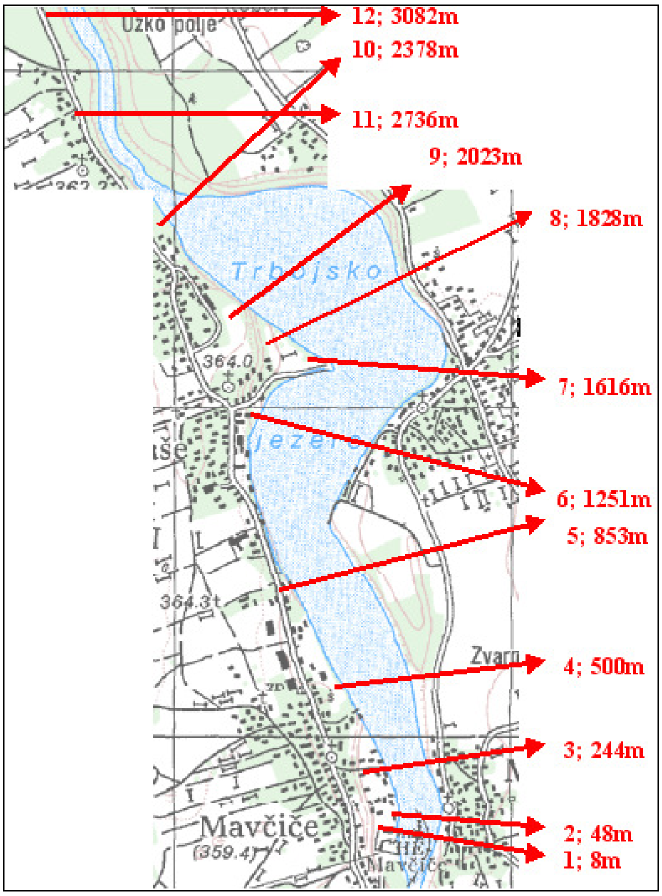
2.3.2 Primerjava površine prečnih profilov bazena Mavčiče

Prečni profili so bili leta 1998 zaradi lažje primerljivosti prav tako izračunani tudi po klasični metodi. Bazen je bil enako kot leta 1986 razdeljen na 26 profilov, ki se pričnejo z 0, ki označuje pregrado (slika 3) (Inštitut za hidravlične raziskave, 2000b). Na sliki 3 je zaradi boljše preglednosti prikazanih le prvih 12 profilov, ostali si sledijo gorvodno do mostu pri tovarni Planika oziroma do konca vplivnega območja pregrade.

the result of different methods of calculation: the digital relief model calculates the volume on the basis of more data and is therefore more accurate, while the cross-section method calculates the volume as a sum of parts of the reservoir by individual measured cross-sections, whereby the uncertainties are also summed.

2.3.2 Comparison of the cross-section surface of the Mavčiče reservoir

To allow better comparison in 1998, cross-sections were also calculated using the standard method. As in 1986, the reservoir was divided into 26 cross-sections, starting with 0, which stands for the dam itself (Figure 3) (Hydraulic Research Institute, 2000b). For reasons of clarity, Figure 3 shows only the first 12 cross-sections, while the rest are located upstream up to the bridge at the Planika factory, to the end of the impact area of the dam.



Slika 3. Prvih 12 merjenih prečnih profilov v akumulaciji Mavčiče, zaporedna številka in stacionaža.

Figure 3. First 12 measured cross-sections in the Mavčiče reservoir, serial number and upstream distance from barrier.

2.3.4 Volumen bazena HE Medvode

Na podlagi večletnih meritev je bilo ugotovljeno, da je Sava v času obratovanja HE Medvode do izgradnje HE Mavčiče odložila v Zbiljskem jezeru do 100.000 m^3 sedimentov na leto. Ocenjeno je, da je zasute približno 40 % celotne akumulacije, kar znaša 2,6 hm^3. Obseg usedanja delcev po izgradnji pregrade v Mavčičah se je zmanjšal (Kryžanowski, 1995).

Za akumulacijski bazen je bil najprej leta 1988 nato pa še leta 2000 izračunan volumen. Leta 1988 so volumen izračunali s pomočjo površine prečnih profilov, leta 2000 pa še s pomočjo digitalnega modela bazena.

Volumen izračunan leta 1988 po prečnih profilih: 3.111.506 m^3;

Volumen izračunan leta 2000 po prečnih profilih: 3.134.552 m^3

in s pomočjo digitalnega modela reliefa: 3.068.430 m^3

(Inštitut za hidravlične raziskave, 2000a).

Volumen je izračunan za koto zajezbe 328,5 m n.m.

2.3.5 Spremembe površine posameznih profilov bazena Medvode od l. 1988 do l. 2000

Leta 1988 je bilo izračunanih 18 profilov od pregrade Medvode gorvodno proti pregradi Mavčiče, leta 2000 pa je bilo izračunanih 21 profilov, s tem da je ničti profil obakrat pregrada Medvode, 21. pa podslapje pregrade Mavčiče (slika 4) (Inštitut za hidravlične raziskave, 2000a). Na sliki 4 je zaradi lažje predstave in boljše preglednosti prikazanih le prvih 12 profilov, ostali si sledijo gorvodno vse do pregrade Mavčiče.

3. REZULTATI IN RAZPRAVA

3.1 TOK PODTALNICE

Rezultat umerjanja modela je bil v obliki toka podtalnice s hidroizohipsami (slika 5), na katerih je napisana tudi kota podtalnice.

2.3.4 The volume of the Medvode HPP reservoir

Based on several years of measurements it was found that during the operation of the Medvode HPP and until the construction of the Mavčiče HPP, the Sava had deposited up to 100,000 m^3 of sediment per year in Lake Zbilje. It was estimated that approx. 40% of the reservoir had been filled, being 2.6 hm^3. After the building of the Mavčiče dam the rate of particle deposition dropped (Kryžanowski, 1995).

The volume of the reservoir was first calculated in 1988 and again in 2000. In 1988 the volume was calculated using the surface of cross-sections, while in 2000 a digital model of the reservoir was also used.

Volume in 1988 based on cross-sections: 3,111,506 m^3;

Volume in 2000 based on cross-sections: 3,134,552 m^3, and

using the digital relief model: 3,068,430 m^3

(Hydraulic Research Institute, 2000a).

Volume is calculated for the altitude 328.5 m a.s.l.

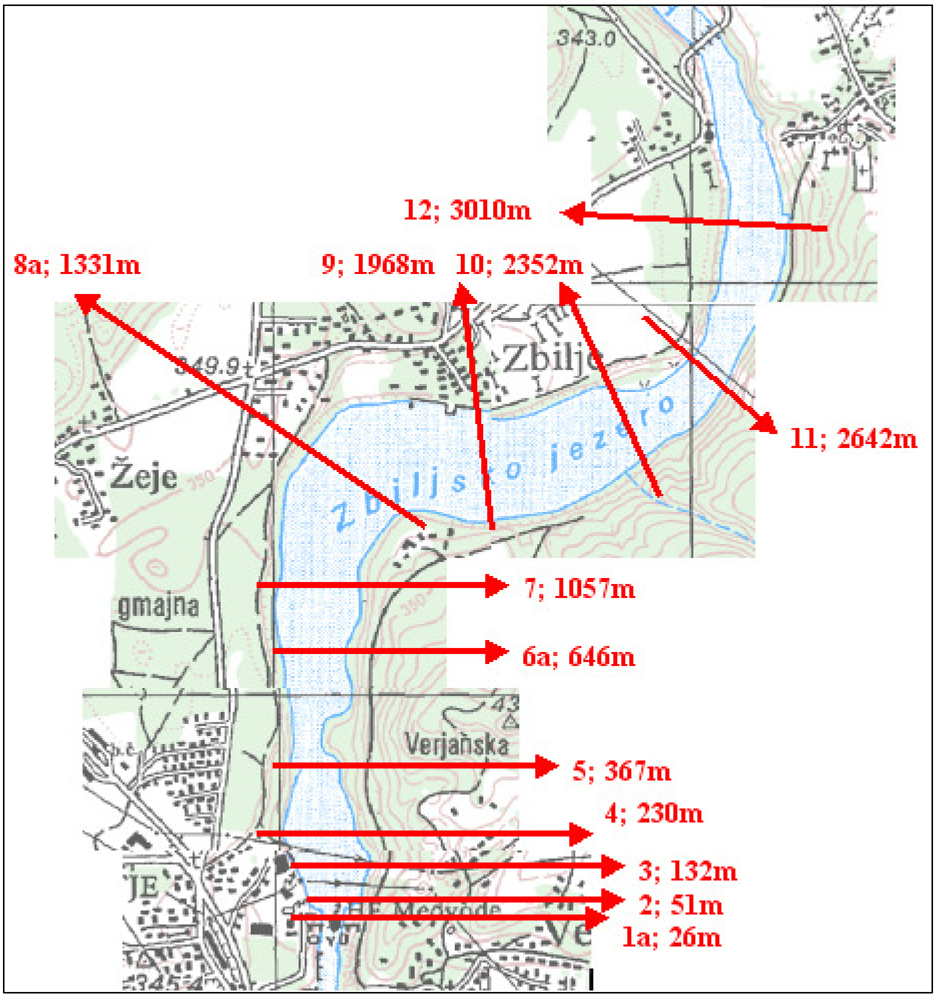
2.3.5 The changes in cross-section surfaces of the Medvode reservoir from 1988 to 2000

In 1988, 18 cross-sections from the Medvode dam upstream to the Mavčiče dam were calculated, while in 2000 21 cross-sections were calculated. In botth cases the 0 cross-section was the Medvode dam, and the 21th cross-section was the stilling basin of the Mavčiče dam (Figure 4) (Hydraulic Research Institute, 2000a). For better illustration and transparency, Figure 4 shows only the first 12 cross-sections, while the rest are situated upstream up to the Mavčiče dam.

3. RESULTS AND DISCUSSION

3.1 GROUNDWATER FLOW

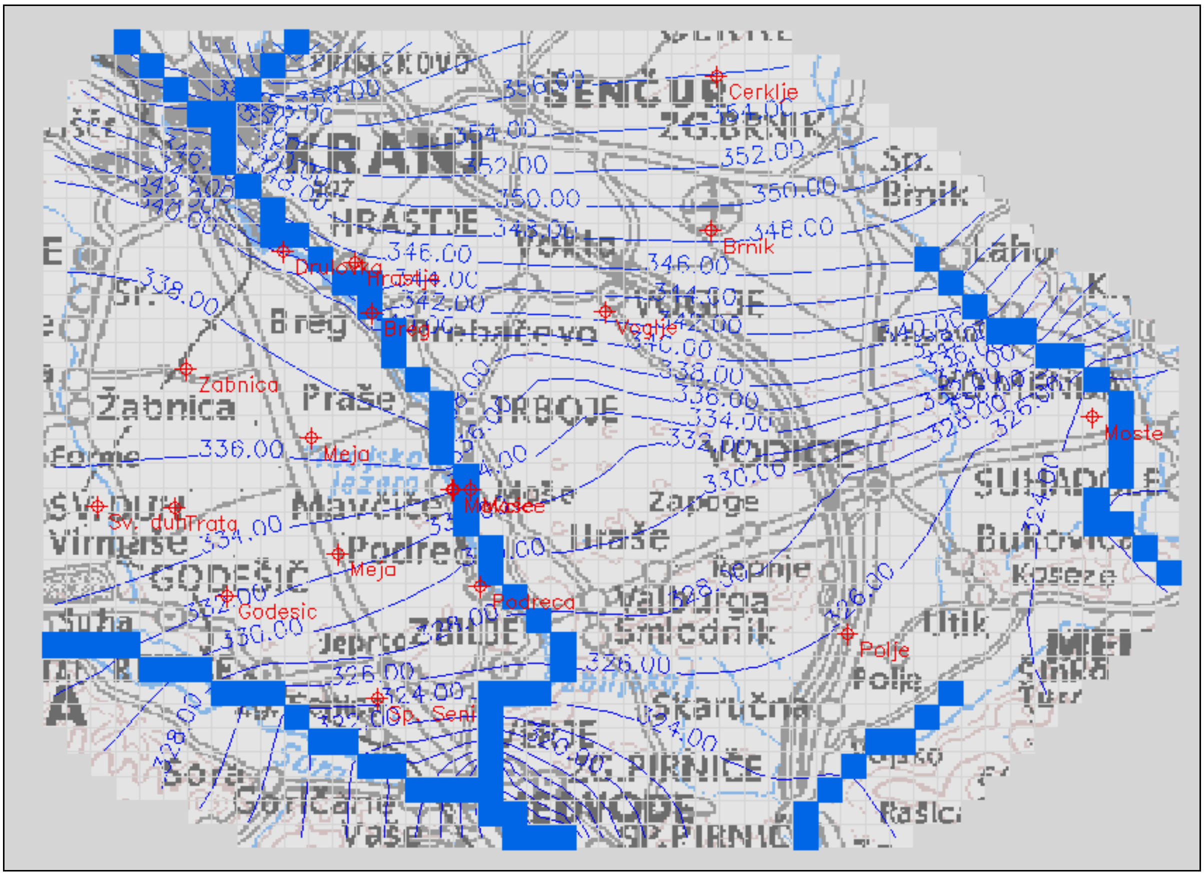
The result of the model calibration was groundwater flow with piezometric head (Figure 5), and indication of groundwater levels.



Slika 4. Prvih 12 merjenih prečnih profilov v akumulaciji Medvode, zaporedna številka in stacionaža.
Figure 4. First 12 measured cross-sections in the Medvode reservoir, serial number and upstream distance from barrier.

Iz izrisanih hidroizohips smo ugotovili, da podtalnica Kranjsko–Sorškega polja teče iz severa-severovzhoda proti jugu, torej iz Kranjskega polja na Sorško. Na Sorškem polju teče podtalnica proti zahodu-jugozahodu. Najvišje kote gladine podtalnice so na severnem robu območja, kjer je največje napajanje podtalnice. Izrazito visoke opazovane kote ima merilno mesto Sveti Duh, na katerega ima velik vpliv podtalnica, ki se preceja skozi slabo prepustne strme sloje na zahodnem obrobju, zato smo to merilno mesto izločili. Z izrazito nizkimi kotami podtalnice pa izstopa merilno mesto Polje pri Vodicah, na katerega vpliva spodnji rob območja, ki ni zajet, zato smo tudi to postajo izločili.

The water table contour lines show that the Kranjsko-Sorško polje groundwater flows in the direction N–NE towards S, that is, from the plain Kranjsko polje towards the plain Sorško polje. In the Sorško polje the groundwater flows towards W–SW. The highest water table levels are in the northern edge, where the recharge is highest. Significantly high groundwater levels were observed at the measuring station Sveti Duh, which is strongly influenced by the groundwater infiltrating through poorly permeable steep layers in the western edge, therefore the station was excluded from the calculation. On the other hand, significantly low groundwater levels were observed at the measuring station Polje pri Vodicah, influenced by the lower edge of the area that is not part of our investigation, therefore this station was also excluded.



Slika 5. Izrisane hidroizohipse Kranjsko–Sorškega polja s koto podtalnice za leto 2001.
Figure 5. Calculated piezometric head of the Kranjsko–Sorško polje with groundwater level for 2001.

Podtalnica se večji del pretaka pod reko Savo iz Kranjskega v Sorško polje, kar sklepamo glede na debelino vodonosnika. Velik del podtalnice, ki teče po vzhodnem robu Kranjskega polja, pa sploh ne pride v stik s Savo.

Dreniranje podtalnice je izrazito pod pregrado Medvode, medtem ko pod pregrado Mavčiče dreniranje ni tako izrazito. Dolvodno od Smledniškega mostu so namreč prisotne neprepustne plasti, ki onemogočajo izcejanje oziroma napajanje podtalnice dolvodno proti pregradi Medvode. Gladina podtalnice, ki teče pod reko Savo, je vedno višja na levem bregu Save, na desnem pa lahko ob visokih vodah pride tudi do delnega dreniranja. Odseki med puščicami na sliki 6 predstavljajo dolžino potovanja podtalnice v enem letu.

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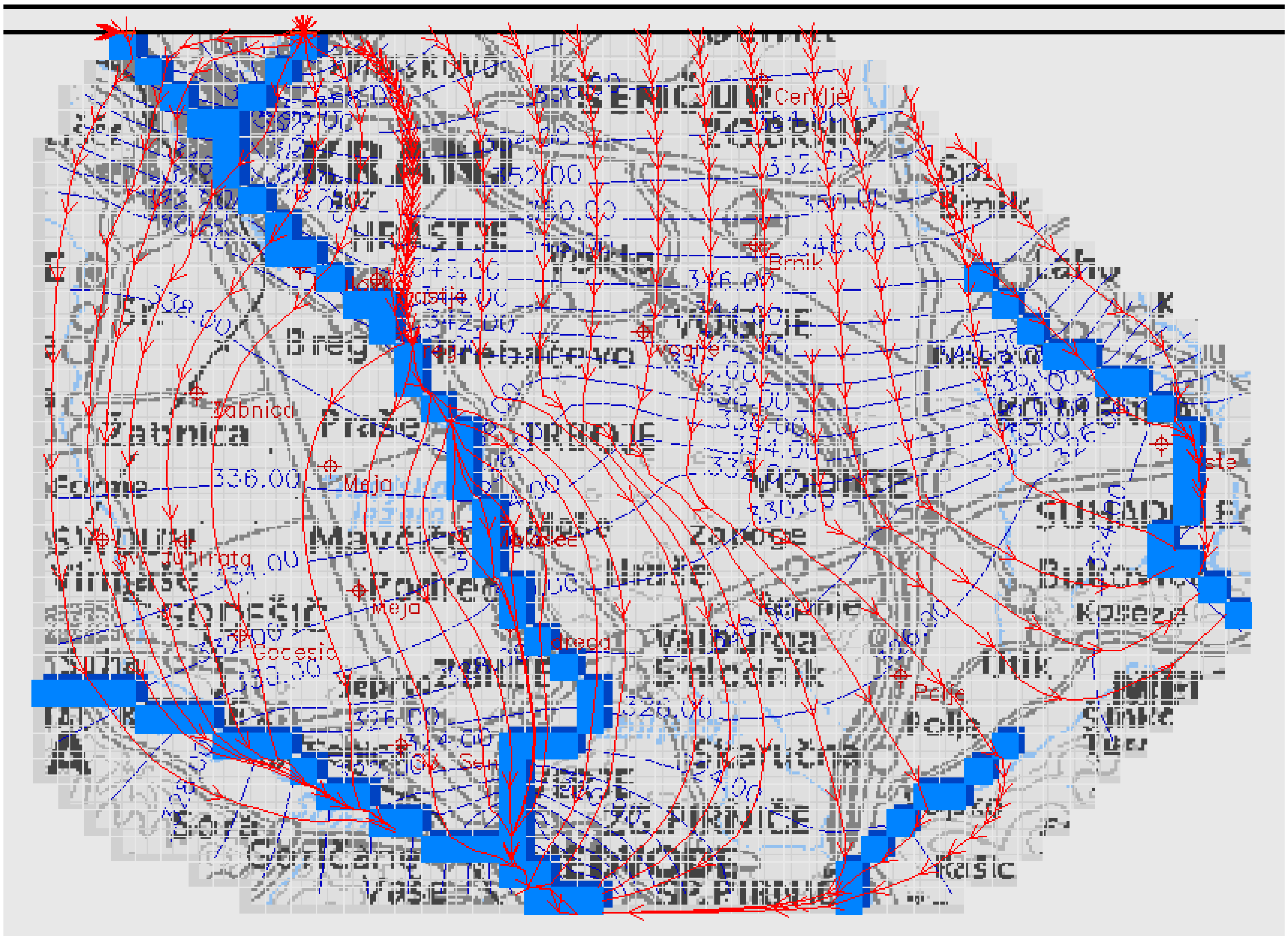
The groundwater mostly flows under the Sava river from the Kranjsko polje to the Sorško polje, which can be inferred from the thickness of the aquifer. However, much of the groundwater flowing on the eastern edge of the Kranjsko polje does not come into contact with the Sava at all.

Groundwater drainage is substantial under the Medvode dam and less pronounced under the Mavčiče dam. Downstream from Smlednik bridge there are namely impermeable layers preventing seepage as well as recharge of groundwater downstream towards the Medvode dam. The water table of the groundwater flowing under the Sava is consistently higher on the left bank of the Sava, while on the right bank partial drainage occurs during high flow. The sections between the arrows on Figure 6 represent the length of the groundwater flow within a year.



Slika 6. Tokovnice podtalnice na Kranjsko – Sorškem polju za leto 2001.
Figure 6. Flow directions of the Kranjsko-Sorško polje groundwater for 2001.

3.2 VODNA BILANCA

Vodna bilanca predstavlja delež vode, ki je izračunan kot razlika med količino vode, ki v območje vstopi in količino, ki iz območja izstopi. Program jo kot tako tudi izračuna za celotno območje skupaj in za manjša območja, ki se jih predhodno določi (največje število območij, ki jih lahko določimo je 50). V ta namen smo določili osem območij vodotokov, za katere je izračunana vodna bilanca (preglednica 1). Program izračuna tudi izmenjavo količin med temi posameznimi območji.

Izračun vodne bilance nam je povedal velikost vpliva Save na podtalnico, torej vpliv pregrad, in koeficient zablatenja v akumulaciji Mavčiče glade na količino vode, ki se izceja pod pregrado Mavčiče. V ta namen smo izdelali tri variante z različnimi koeficienti prepustnosti.

3.2 WATER BALANCE

Water balance represents the storage of water, calculated as a difference between water gain and water loss in a catchment area. The software calculates water balance for the entire area and separately for smaller areas, which are previously determined (the largest number of areas is 50). In our case we determined eight stream areas for which water balance was calculated (Table 1). Furthermore, the exchange of volume between these respective areas is calculated.

The calculation of the water balance gave us an insight into the magnitude of the effect of the Sava on groundwater, that is, the effect of dams, and the clogging coefficient in the Mavčiče reservoir relevant to the volume of water seeping under the Mavčiče dam. For this purpose, we used three variants with different permeability coefficients.

Preglednica 1. Vodna bilanca za celotno območje vodotokov.
Table 1. Water balance for the whole area.

	Pretok v m³/s *Flow in m³/s*						
	Infiltracija padavin in bogatenja na severu *Rainfall infiltration and recharge in the north*	Prepuščanje v podtalnico skozi dno reke *Infiltration through river bottom*			Prepuščanje v reko skozi dno *Drainage through river bottom*		
		k_1	k_2	k_3	k_1	k_2	k_3
Območje izračuna *Calculation area*	l. 2001	$1{,}3*10^{-4}$	$8{,}3*10^{-5}$	$3{,}3*10^{-5}$	$1{,}3*10^{-4}$	$8{,}3*10^{-5}$	$3{,}3*10^{-5}$
1. Sava do sotočja s Kokro *The Sava to the confluence with the Kokra*	0,020	0,493	0,515	0,574	0,342	0,333	0,320
1. Kokra do sotočja s Savo *The Kokra up to the confluence with the Sava*	0,020	3,026	3,047	3,110	0,594	0,612	0,644
3. Sava od sotočja s Kokro do pregrade Mavčiče *The Sava from the confluence with the Kokra up to the Mavčiče barrier*	0,087	23,758	19,941	12,564	0,694	0,536	0,278
4. Sava med obema pregradama *The Sava between both barriers*	0,067	-	-	-	10,594	8,422	4,324
5. Sava od pregrade Medvode do konca območja *The Sava from the Medvode barrier to the end of area*	0,036	-	-	-	11,037	10,757	10,221
6. Sora do sotočja s Savo *The Sora up to the confluence with the Sava*	0,092	1,169	1,376	2,038	10,488	9,681	8,263
7. Vodotok Pšata *The Pšata river*	0,087	0,660	0,660	0,660	3,154	3,025	2,775
8. Vodotok Dobrava *The Dobrava river*	0,041	-	-	-	1,292	1,264	1,209
Vodotoki skupaj *All rivers*	0,451	29,106	25,539	18,946	38,195	34,630	28,034
Območje Kranjsko - Sorškega polja *Area of the Kranjsko-Sorško polje*	9,086	29,105	25,539	18,947	38,194	34,630	28,036

Iz analize vodne bilance smo ugotovili močan vpliv reke Save na tok podtalnice. Količina vode, ki jo reke, v največji meri Sava, drenirajo, je 10 m³/s večja od količine vode, s katero reke napajajo podtalnico. S padavinami po celem območju in z napajanjem severnega

The analysis of the water balance showed a strong impact of the Sava on groundwater flow. The volume of water drained by rivers, mostly the Sava river, is 10 m³/s larger than the volume of water recharging the groundwater. The precipitation in the whole area and the recharge of the northern part bring roba pride v območje 9 m^3/s.

Največji vpliv na tok podtalnice ima vsekakor Sava, ki je osrednja reka Kranjsko – Sorškega polja in ki tekom toka v večji meri napaja podtalnico (odvisno od koeficienta prepustnosti dna v akumulaciji Mavčiče), drenira pa bolj opazno pod pregrado Medvode (10 m^3/s). Na podtalnico imata vpliv tudi vodotoka Sora na jugu Sorškega polja in manjši vpliv Dobrava na jugu Kranjskega polja, ki drenirata podtalnico, ki priteče iz severa (Sora 8 do 10 m^3/s v 6. območju in Dobrava 1,2 m^3/s v 8. območju).

3.3 REČNA BILANCA SAVE

S primerjavo srednjih letnih dotokov na obeh pregradah smo ugotovili razliko v količini dotoka vedno v korist dotoka na pregrado Medvode (slika 7). Glede na lego pregrade Medvode, ki je nizvodno od pregrade Mavčiče, sklepamo na dotoke zalednih vod v akumulacijo.

Razlike med dotoki smo združili z rezultati modela podtalnice Kranjsko – Sorškega polja, s katerim smo ugotovili tok podtalnice.

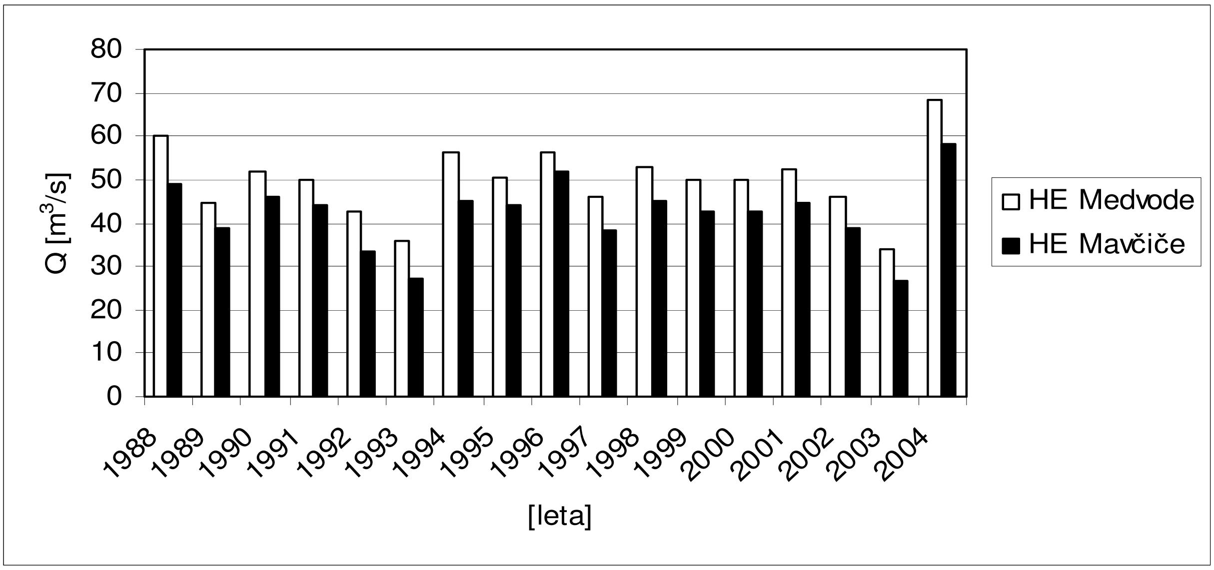
9 m^3/s to the area.

The Sava, being the central river in the Kranjsko-Sorško polje, has the largest impact on the groundwater flow, recharging groundwater along its course (depending on the permeability coefficient in the Mavčiče reservoir), while its drainage is particularly evident below the Medvode dam (10 m^3/s). Also, the Sora stream to the south of the Sorško polje and to a smaller degree the Dobrava to the south of the Kranjsko polje drain the groundwater coming from the north (the Sora 8–10 m^3/s in the 6th area and the Dobrava 1.2 m^3/s in the 8th area).

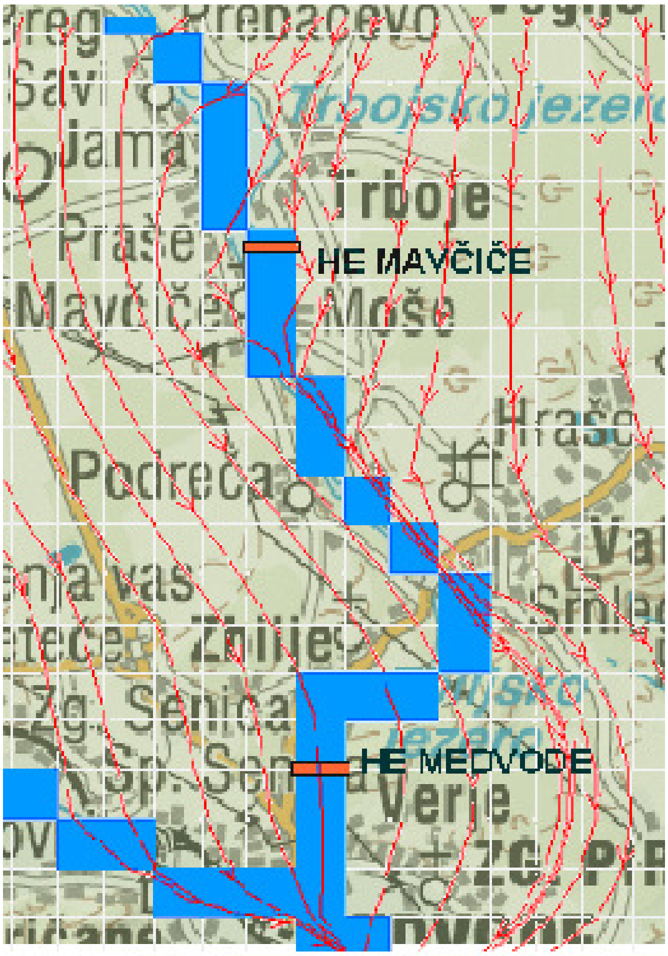
3.3 SAVA RIVER BALANCE

The comparison of mean annual inflows on both dams showed that the inflow to the Medvode dam was consistently greater (Figure 7). The location of the Medvode dam, being downstream of the Mavčiče dam, implies that the reservoir is being filled with inflows of hinterland streams.

With a view of determining groundwater flow, the differences between the inflows were linked with the results of the Kranjsko-Sorško polje groundwater model.



Slika 7. Primerjava povprečnih letnih dotokov na HE Mavčiče in na HE Medvode v obdobju od leta 1988 do leta 2004.
Figure 7. Comparison of mean annual inflow on the Mavčiče HPP and the Medvode HPP from 1988 to 2004.



Slika 8. Prikaz tokovnic na območju pregrad Mavčiče in Medvode leta 2001.
Figure 8. Flow directions in area of dams Mavčiče and Medvode in 2001.

Iz poteka tokovnic na predpostavljenem območju lahko sklepamo, da se del podtalnice, za katero smo ugotovili da teče delno pod reko Savo iz Kranjskega na Sorško polje, izceja pod pregrado Mavčiče do neprepustnih plasti nizvodno od Smledniškega mostu (slika 8). Količina vode, ki se izceja pod pregrado Mavčiče je torej odvisna od količine vode, ki se infiltrira za pregrado Mavčiče in je odvisna od stopnje zablatenja dna.

Flow directions in the investigated area show that part of the groundwater, for which it was found that it partly flows below the Sava river from the Kranjsko polje to the Sorško polje, percolates below the Mavčiče dam to the impermeable layers dostream of the Smlednik bridge (Figure 8). The volume of water percolating under the Mavčiče dam therefore depends on the volume of water infiltrating behind the Mavčiče dam, and it further depends on the rate of clogging.

3.4 ZABLATENJE AKUMULACIJE MAVČIČE

3.4 CLOGGING OF THE MAVČIČE RESERVOIR

Na vsem polju so se gladine podtalnice z izgradnjo akumulacije Mavčiče dvignile in povečala se je infiltracija Save v podtalnico. Ob pregradi Mavčiče so se gladine dvignile za kar 6 m, ob obronkih Kranjsko – Sorškega

After the building of the Mavčiče reservoir, the water table in the whole area rose and the infiltration of the Sava into groundwater increased. Along the Mavčiče dam, the water table rose by as much as 6 m, while on the polja, med drugim tudi ob Planiki, pa za 2 – 3 m (Breznik in Pšeničnik, 1985).

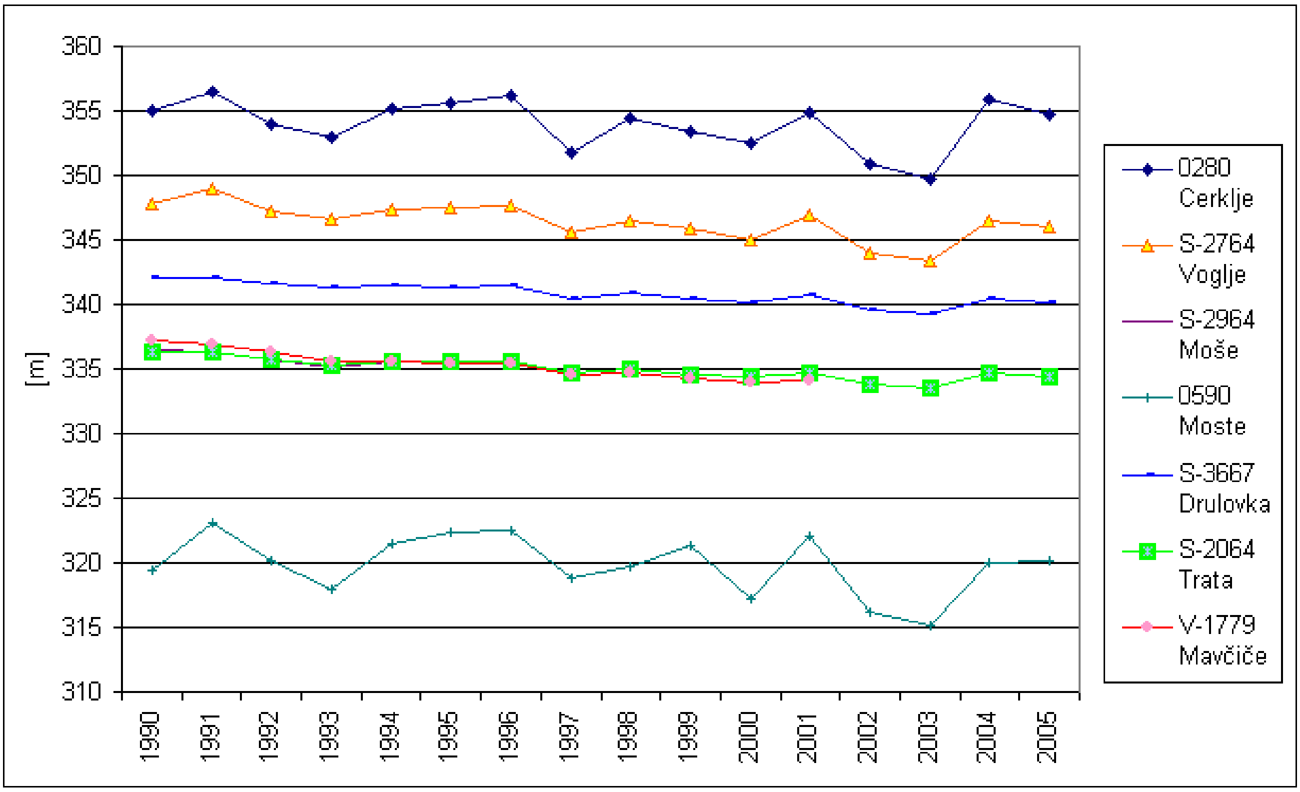
Kmalu se je začelo zablatenje akumulacije, ki vpliva na nivo gladin in količino vode, ki pronica skozi rečno dno. Do delnega znižanja gladin je prišlo že v letih 1989-90, kar so pripisali delnemu zablatenju in sušnemu obdobju. Vpliv zablatenja je možno ugotoviti z zmanjševanjem izvirov nizvodno in nižjim nivojem podtalnice (Breznik in Pšeničnik, 1987b; Breznik in Brilly, 1988; 1991).

Glede na podatke o nivojih podtalnice od leta 1990 do 2005 smo s primerjavo poskušali ugotoviti zablatenje bazena. Primerjali smo meritve gladin podtalnice za sedem piezometrov na Kranjskem in Sorškem polju (slika 9). Lokacije piezometrov so vidne na sliki 5. Piezometri Trata, Mavčiče in Moše imajo podobne linije na sliki 9, ker so tudi razlike med gladinami zelo majhne.

edges of the Kranjsko-Sorško polje, including the Planika factory, the level rose by 2–3 m (Breznik and Pšeničnik, 1985).

The clogging of the reservoir ensued soon, influencing the water table and the volume of water seeping through the river bottom. The levels were partly lowered as soon as in 1989–90, which was probably due to partial clogging and drought. The impact of clogging can be seen in the reduction of springs downstream and lower groundwater level (Breznik and Pšeničnik, 1987b; Breznik and Brilly, 1988; 1991).

Looking at the data on groundwater levels from 1990 to 2005 we tried to establish the clogging rate of the reservoir by way of comparison. We compared the measurements of groundwater levels for seven piezometers in the Kranjsko-Sorško polje (Figure 9). The piezometer locations are shown in Figure 5. Trata, Mavčiče and Moše piezometers have almost the same line, because the differences in groundwater levels are very small.



Slika 9. Prikaz meritev srednjih letnih gladin podzemnih vod na sedmih piezometrih na Kranjsko-Sorškem polju od leta 1990 do 2005.
Figure 9. Measurements of mean annual groundwater level in seven piezometers on the Kranjsko-Sorško polje from 1990 to 2005.

Ugotovili smo trend upadanja gladin podtalnice na vseh piezometrih. Največji trend upadanja ima podtalnica na piezometrih Drulovka, Trata in Godešič, ki so locirani na Sorškem polju. Opaznejše upadanje gladin je še v piezometrih Hrastje in Moše, ki pa sta locirana na Kranjskem polju. Upad gladin je reda velikosti 2 -3 m v vseh piezometrih, razen v Mostah, Zgornjih Bitnjah, Polju pri Vodicah in Cerkljah, ki so očitno izven ožjega vplivnega območja akumulacij.

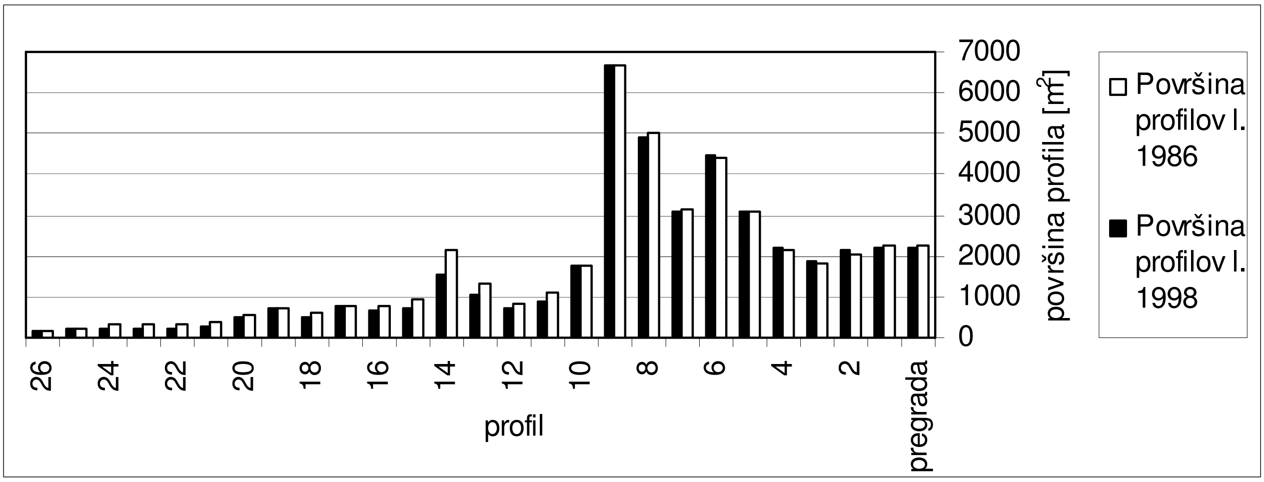
There was a trend of lowering of groundwater levels in all piezometers. The strongest trend of decline was noticed in the piezometers Drulovka, Trata and Godešič, located in the Sorško polje. Significant drop in groundwater levels was also found in piezometers Hrastje and Moše, located on the Kranjsko polje. The drop in levels was within 2–3 m in all piezometers, except in Moste, Zgornje Bitnje, Polje pri Vodicah and Cerklje, which evidently lie outside the immediate impact area of the reservoirs.

3.5 SEDIMENTACIJA V AKUMULACIJI MAVČIČE

Volumen akumulacije Mavčiče se je v 12-ih letih od začetka obratovanja hidroelektrarne zmanjšal za 4% , kar je približno 500.000 m^3. Pri primerjavi delnega volumna posameznih prečnih profilov je opazno celo povečanje začetnih profilov dolvodno od pregradi, kar je posledica izkopavanja materiala zaradi povečanih hitrosti in turbulence. V splošnem se začne manjšati volumen pri osmem profilu na stacionaži 1.828 m, doseže višek pri 15. profilu in se padajoče nadaljuje do zadnjega profila na stacionaži 7.003 m (slika 10).

3.5 SEDIMENTATION IN THE MAVČIČE RESERVOIR

In the 12 years since the start of hydropower plant operation, the volume of the Mavčiče reservoir decreased by 4%, which is approximately 500,000 m^3. However, when comparing the volumes of single cross-sections downstream of the dam, an increase of the initial cross-sections is found, the consequence of erosion of material due to increased velocity and turbulence. In general, the volume starts to drop at cross-section 8 at a distance of 1,828 m, reaching its peak at cross-section 15, gradually reducing to the last cross-section at a distance of 7,003 m (Figure 10).



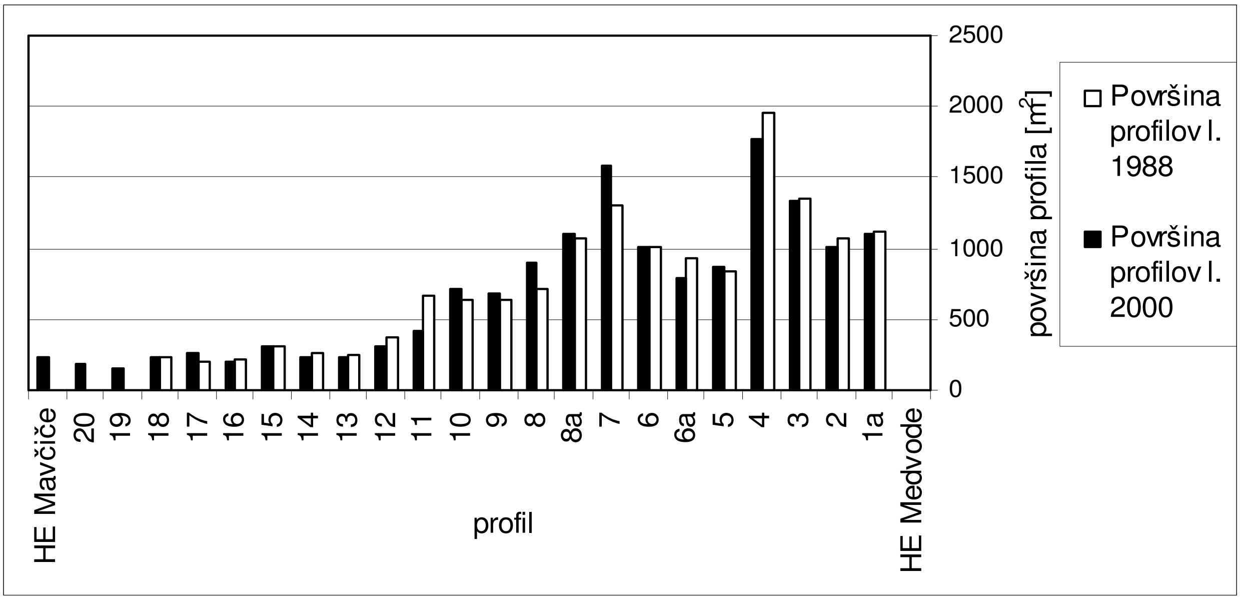
Slika 10. Prikaz primerjave površin prečnih profilov v letih 1986 in 1998.
Figure 10. Comparison of cross-section areas in 1986 and 1998.

3.6 SEDIMENTACIJA V AKUMULACIJI MEDVODE

Volumen akumulacije Medvode je po 12-ih letih, in sicer od leta 1988 (35 let po začetku obratovanja) pa do leta 2000, večji za približno 0,7%, kar je 23.000m^3. S primerjavo delnega volumna posameznih prečnih profilov smo ugotovili precej različne negativne in pozitivne spremembe v volumnih. Takoj za pregrado pa vse do sedmega profila je opazno manjše zmanjšanje volumna. Med sedmim profilom na stacionaži 1.057 m in 11. profilom na stacionaži 2.642 m je prišlo do povečanja volumna, kar lahko pripišemo izvedeni sanaciji v obdobju med obema meritvama (IBE, 1994; Kryžanowski, 1996). Po 11. profilu se volumen zopet zmanjšuje in doseže največje zmanjšanje pri profilu 12 na stacionaži 3.010 m, ki mu sledijo manjša zmanjšanja volumnov profilov do profila 17 na stacionaži 4.596 m. Od profila 17 do pregrade Mavčiče pa pride zopet do manjšega povečanja volumna, kar lahko pripišem posledicam erodiranja Save pod pregrado Mavčiče (slika 11).

3.6 SEDIMENTATION IN THE MEDVODE RESERVOIR

In the 12 years from 1988 (35 years after the start of operation) to 2000, the volume increased by approx. 0.7%, which is 23,000 m^3. By comparing the partial volume of the single cross-sections we found rather diverse negative and positive changes in the volumes. Right behind the barrier up to cross-section 7 a small reduction in volume evident. Between cross-section 7 at 1,057 m and cross-section 11 at a distance of 2,642 m the volume increased, which can be the result of restoration in the period between both measurements (IBE, 1994; Kryžanowski, 1996). From cross-section 11 on the volume starts to reduce, reaching the lowest point at cross-section 12 at a distance of 3,010 m, followed by less pronounced shrinkage of cross-section volumes to cross-section 17 at 4,596 m. From cross-section 17 to the Mavčiče dam there again occurs a small increase in volume, which can be the result of erosive action of the Sava below the Mavčiče dam (Figure 11).



Slika 11. Prikaz primerjave površin prečnih profilov v letih 1986 in 1998.
Figure 11. Comparison of cross-section areas in 1986 and 1998.

4. ZAKLJUČKI

Z izgradnjo pregrade Mavčiče so se dvignile gladine podtalnice po celem Kranjsko – Sorškem polju, na severu do tovarne Planika, zahodu do obronkov hribovja, na jugu do iztokov podtalnice v Soro in Savo ter na vzhodu do vodotoka Pšata.

Dvig gladin podtalnice je bil posledica višjih gladin vode v reki in kasneje v akumulacijskem jezeru. Tekom let sta se jezeri zablatili in gladina podtalnice je pričela upadati.

Podtalnica Kranjsko – Sorškega polja teče od severa proti jugu, večinoma se pretaka iz Kranjskega polja pod reko Savo na Sorško polje. Reki Sava in Kokra v zgornjem toku do pregrade Mavčiče napajata podtalnico. Podtalnica do pregrade Mavčiče teče pod strugo Save, ki jo napaja (13 do 24 m^3/s, odvisno od prepustnosti dna) , dolvodno od pregrade proti Smledniškemu mostu se manj kot polovica te vode izceja v strugo (4 do 11 m^3/s, odvisno od prepustnosti dna za pregrado), preostanek pa teče proti izvirom ob Sori (8 do 10 m^3/s odvisno od prepustnosti dna za pregrado Mavčiče). Večje izcejanje podtalnice je prisotno še pod pregrado Medvode (10 do 11 m^3/s).

Reka Sava ima tipičen snežno-dežni režim z izrazitimi viški spomladi in jeseni ter nižki poleti in pozimi. Značilnosti režima so opazne na dotokih na obe pregradi, za katere smo analizirali podatke 16-letnih dotokov. Pri primerjavi količin dotokov v letu 2001 smo ugotovili manjši dotok na pregradi Mavčiče kot na pregradi Medvode. Povprečna 16-letna razlika je 9,4 m^3/s.

Količina vode, ki predstavlja večji dotok na pregradi Medvode in se izceja pod pregrado Mavčiče, je odvisna od viškov in nižkov pretoka in stopnje zablatenja oziroma koeficienta prepustnosti dna akumulacijskega bazena Mavčiče. Za leto 2001, ko je razlika dotokov 8,2 m^3/s, smo s pomočjo modela dobili koeficient prepustnosti $8{,}3 \cdot 10^{-5}$ m/s, medtem ko je v začetku obratovanja HE

4. CONCLUSIONS

The building of the Mavčiče dam caused a rise in the groundwater level in the entire Kranjsko-Sorško polje, in the north reaching to the Planika factory, in the west to the hill sides, in the south to the outflow of groundwater into the Sora and Sava rivers, and in the east to the Pšata stream.

The dam caused the rise of the groundwater because of the higher level of water in the stream and later in the reservoir, but through the years the reservoirs are being clogged and consequently the groundwater levels are falling.

The groundwater of the Kranjsko-Sorško polje flows in the N–S direction, mostly flowing from the Kranjsko polje under the Sava river to the Sorško polje. In the upper reach the Sava and Kokra rivers recharge the groundwater. Up to the Mavčiče HPP the groundwater flows below the Sava channel, receiving water from it (13 to 24 m^3/s, depending on floor permeability), downstream of the dam towards the Smlednik bridge less than half of the water percolates into the channel (4 to 11 m^3/s, depending on floor permeability behind the dam), while the rest flows towards the springs along the Sora (8 to 10 m^3/s, depending on floor permeability behind the Mavčiče dam). Larger seepage is also present under the Medvode dam (10 to 11 m^3/s).

The Sava river has a typical snow–rain regime with considerable highs in spring and autumn and lows in summer and winter. The regime characteristics are reflected in inflows on both dams, for which 16-year inflow data were analysed. When comparing the volume of inflows in 2001 we found that the inflow on the Mavčiče dam was smaller than that on the Medvode dam. The average 16-year difference is 9.4 m^3/s.

The volume of water representing a bigger inflow on the Medvode dam, and which disappears under the Mavčiče dam, depends on the highs and lows of flow and the rate of clogging, i.e. the permeability coefficient of the bottom of the Mavčiče reservoir. For 2001, with the difference of inflows being 8.2

Mavčiče imel vrednost $1{,}3*10^{-4}$. Zablatenje pa se odraža tudi v gladinah podtalnice v piezometrih po vsem Kranjsko-Sorškem polju, v katerih se gladine nižajo. Ampak tudi, če bi bilo možno popolno zablatenje, bi gladine ostale delno dvignjene zaradi prestavitve drenažnega območja.

Medtem ko je v zgornjem akumulacijskem jezeru prisotno usedanje sedimentov, ki so zadržani za pregrado, je naravni tok sedimentov v dolvodno skumulacijo Medvode prekinjen. Tako se tok sedimentacije prične dolvodno od pregrade Mavčiče, kar je tudi razlog, da vsedanje v akumulaciji Medvode ni več tako intenzivno kot v letih, ko še ni bilo pregrade Mavčiče.

V akumulaciji Medvode je prisotno skoraj popolno zablatenje zaradi dolgoletnega nanosa materialov in tudi manj prepustne podlage kot v akumulaciji Mavčiče. V letih pred izgradnjo pregrade Mavčiče je bilo odloženo za kar 100.000 m^3 sedimentov letno, po izgradnji HE Mavčiče pa se je odlaganje nadaljevalo v manjši meri. Zaradi izgube koristnega volumna je bila leta 1995 izvedena sanacija Zbiljskega jezera, zaradi česar so meritve pokazale 0,7% večji volumna bazena Medvode v 12-ih letih, medtem ko je volumen bazena Mavčiče v 12-ih letih za 4,3% manjši.

m^3/s, we obtained a new permeability coefficient $8.3*10^{-5}$ m/s, while at the start of the Mavčiče HPP operation it had a value of $1.3*10^{-4}$. The clogging is also reflected in the piezometer heads in the entire Kranjsko-Sorško polje where the levels are lowering. However, even if complete clogging were possible, the levels would remain partly raised due to the relocation of the drainage area.

The upstream reservoir (Mavčiče) is being filled with sediments, which are held behind the dam and the natural sediment flow is cut off. Consequently, between both dams the sedimentation flow starts downstream of the Mavčiče dam and the sedimentation in the Medvode reservoir is no longer as intensive.

In the Medvode reservoir almost full clogging is present due to the many years of depositing and less permeable bed than in the Mavčiče reservoir. In the years prior to the construction of the Mavčiče dam as much as 100,000 m^3 of sediment per year were deposited, while after the building of the Mavčiče HPP the process slowed down. Due to the loss of effective volume, in 1995 a rehabilitation of Zbilje Lake was carried out, and as a result the measurements showed 0.7% larger volume of the Medvode reservoir than 12 years before, while the volume of the Mavčiče reservoir in the same period shrank by 4.3%.

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