# ANALYSIS, PROGNOSIS AND DESIGN OF CONTROL MEASURES OF GROUND WATER LEVEL REGIME USING NUMERICAL MODELLING

## ANALÝZA, PROGNÓZA A NÁVRH REGULAČNÝCH OPATRENÍ HLADINOVÉHO REŽIMU PODZEMNÝCH VÔD POUŽITÍM NUMERICKÉHO MODELOVANIA

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## ABSTRACT

The goal of the contribution is on base of analysis and prognosis of groundwater level regime by means of numerical modelling to show the possibility of introducing technical measures which have to decrease the unfavourable groundwater level regime in the vicinity of the Žilina hydraulic structure. For numerical simulation purposes a mathematical model by means of finite element method has been provided in right-side alluvium of the Váh River with detailed concentration on the Mojš village. After putting Žilina hydraulic structure into operation in periods of excessive precipitation activity as well as after sudden snowmelt in the spring time cellars of the majority of houses in the village have been flooded. When setting up the mathematical model lots of hydro-geological data from previous survey have been used which created the base for calibration and verification process of the model in several hydrological situations.

#### **KEY WORDS**

interaction of surface- and groundwater, hydraulic structure, numerical modelling, finite element method,

## KĽÚČOVÉ SLOVÁ

interakcia povrchovej a podzemnej vody, vodná stavba, numerické modelovanie, metóda konečných prvkov

#### INTRODUCTION

The Žilina hydraulic structure was the first structure in Slovakia whose influence on the environment has been assessed comprehensively by means of the EIA method (Environmental Impact Assessment). The passing of the amendment by the NC SR 127/1994 on the assessment of the environmental issues has been confirmed by the hydraulic structure Žilina. The proposals to abate the impact of the structure on the environment have been included into object composition of the structure (1994–1998) and the cooperation with the environment experts was also maintained at the realisation and operation of the

structure. A part of building process of the Žilina hydraulic structure (HS) was setting up the village of Nová Mojšová Lúčka and a part of the village of Rosinky on the left bank of the Váh River.

On the right bank of the Váh River, in the very surroundings of the last-built HS reservoir there was a village of the Mojš that remained untouched. One of the measures taken when building the hydraulic structure was setting up a sealing wall in order to prevent the reservoir water from flowing into the aquifer.

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Although the wall fulfilled its purpose, at the same time it eliminated the draining effect of the Váh River. This accounted for an increase of the ground water level in the Mojš (in extreme hydrological situations– precipitation periods, snowmelt periods), accompanied by flooding the cellars of houses in the Mojš village.

The investigated area is located in the alluvium on the right side of the Váh River, in the very surroundings of the hydraulic structure. It is marked in the east by its tributary-Varínka and in the north by the foot of the Kysuce mountain line. This area is marked by another peculiarity, there is an alternate bio-corridor transporting water and serving as a fish ladder alongside the dam on the right side of the hydraulic structure (filled from the reservoir at the confluence of Váh and Varínka rivers. The alternate bio-corridor due to its level and discharge regime actively affects the water level regime of the ground water in the given area (Kadlec et al., 2001, 2002). Due to the construction of geological the Žilina HS. a complex and hydrogeological research was carried out in this area. The research was done at various times and by various companies. We focused on the geological boreholes drilled, assessed and monitored on the right side of the Váh River with detailed focus on the village of the Mojš.

The objective of the research was to prove the causes of damping the cellars in the Mojš and, based on mathematical modelling of the ground water flow, to design certain technical measures eliminating the negative situation in the real conditions of the region. contribution The presented evaluates the hydrogeological conditions of the area, which were the basis for constructing a mathematical model of the ground water flow using the finite element method. This model was calibrated for dry seasons (November 2001, May 2002) as well as extreme seasons of precipitation (July 2001) and used for the groundwater level forecast by taking particular technical measures. The missing data, such as the discharge and water level regime in the bio-corridor were measured directly in situ by the researchers in June, July 2002 (Šoltész, et al., 2002, 2004).

# GEOLOGICAL AND HYDROGEOLOGICAL CONDITIONS

For the solution of the ground water level mode it was necessary to possess sufficient knowledge about the geological status of the examined area. The assessment of the geological status suggests that the cover layers of soil in the whole area are made up by fine-grained soil of alluvial facies, whose thickness ranges from 0.5 - 2.0 m in the flat areas (Mojš village), and 2.0 - 4.5 m in the sub-mountain areas with alternating sandy clay, clay soil, and sand containing a mixture of fine soil.

Žilina basin is characterised by the absence of

neogenic sediments. The quaternary sediments are mostly represented by fluvial sediments. These include predominantly gravel, creating in the sub-base of finegrained cover layers a continuous, but unequally thick layer. The sediments are characterised as gravel with admixture of fine-grained soil, or unequally gritty gravel. The crucial importance in the assessment of Zilina HS is held by fluvial sediments. They form the aquifer in all objects and to a great degree they form the groundwater. The unequal potency mentioned above grows from 6,5m up to 18 m from the Váh River northward to the sub-mountain areas. Another outstanding feature the attention has been devoted to, was determining the permeability of the aquifer layers (Burger, Gomboš, 2001). Here again, our research work was based on geological research carried out in this area in past years. Fig. 1 shows the samplers and bore-holes, where the hydraulic conductivities were determined. Determination of the hydraulic conductivity in over 50 samplers was done at various times, using various methods and having different calculated and measured values. In accordance with these data an assembly of a map of hydraulic conductivity isolines in m.s<sup>-1</sup> (Fig. 2a) has been obtained with a detailed focus on the Mojš village (Fig. 2b).

The data from 53 bore-holes as well as literary resources (Štofko, 1992 in Šoltész, 2002, Šalaga, 1995) have been used for hydro-geological analysis. The latter suggest that the aquifers are represented by gravel-sand sediments of alluvial plain and stream terraces. These determine the ground water level, which is, in case of settled gravel, slightly pressured. Groundwater level coherent horizon with the depth of creates approximately 2.5 - 16.5 m beneath the terrain. The hydraulic conductivity oscillates (with certain exceptions) between  $1.10^{-3} - 1.10^{-4}$  m.s<sup>-1</sup>. Lowest figures were found in the mountainside (Teplička, Varín). According to these figures it is possible to assess the aquifer of the right side alluvium of Váh River as a porous medium with high permeability, suitable as a source for water supply (Štofko, 1992).

Another factor influencing the groundwater flow is the sealing wall built south of the water source Teplička. In the eastern part of the given area this wall partially splits the stream of groundwater which infiltrates from the northern mountains and Varínka stream. One portion of the groundwater flows down over the wall toward the Teplička water source and another portion flows towards the Mojš village. While the Váh River showed the drainage function, this flow did not necessarily have to cause difficulties in form of high groundwater level in the village. In case of building the sealing wall in the dam on the right side of the water reservoir this becomes a substantial problem, requiring an immediate treatment.



Fig. 1:Map of observation bore-holes where the hydraulic conductivity was determinedObr. 1:Mapa pozorovacích vrtov a sond, v ktorých bol stanovený koeficient filtrácie



Fig. 2a: Map of isolines of hydraulic conductivity (m.s<sup>-1</sup>) Obr. 2a: Mapa izolínií koeficientu filtrácie (m.s<sup>-1</sup>)



Fig. 2b: Map of isolines of hydraulic conductivity (m.s<sup>-1</sup>) – detail in the Mojš village
Obr. 2b: Mapa izolínií koeficientu filtrácie (m.s<sup>-1</sup>) s detailom na obec Mojš



Fig. 3a: Map of the thickness of cover layers (m) Obr. 3a: Mapa hrúbky pokryvných vrstiev (m)

As the Fig. 3a and Fig. 3b suggest, the thickness of the cover layers in the whole area (especially in the Mojš village) is relatively low. The minimum value measured 0.5 m beneath the terrain proves that the cover layers cannot fulfil the function of an isolator of the

aquifer, not only quantitatively but also qualitatively. It means that Mojš village tends to acquire a high amount of water at intensive precipitation events thus causing in a short time period excessive increase in the ground water level.



Fig. 3b: Map of the thickness of cover layers (m) - detail in theMojš village Obr. 3b: Mapa hrúbky pokryvných vrstiev (m) s detailom na obec Mojš

#### DETERMINATION OF THE BOUNDARIES OF THE FILTRATION AREA AND CALIBRATION PERIODS

Firstly, it becomes necessary from hydrological point of view to mark correctly the investigated area. Fig. 4 clearly shows the selected boundaries of the investigated area. The area is marked in the south by the alternate bio-corridor, where the boundary conditions were represented by the water level in bio-corridor. The water level is monitored alongside the entire biocorridor in three points - B1, B2, and B3. The eastern part offered an opportunity to mark the area by the Varínka River. Lacking information about the water level regime of this river and having studied the groundwater level measurements, a decision for narrowing the investigated area and as the boundary conditions the water levels in the bore-holes of Slovak hydro-meteorological institute (SHMI) network (L-320, L-322, L-328), alternatively the regular monitoring bore-holes have been taken into consideration. The most difficult task was to determine the boundary of the region from the north. Fig. 4 shows the samplers, which

could be used by the calibration of the mathematical model. There were not many of these calibration points, however, they helped to set the model for selected hydrological conditions.

Based on the results of the complex monitoring of groundwater level measurements in the years 1999, 2000, 2001 and 2002 (Kadlec et al., 2001), the table of the extreme figures of groundwater level measurements in the years 1999 and 2000 (Kadlec et al., 2001), groundwater level regime measurements in the boreholes of the monitoring network of SHMI and precipitation rate, extreme operation periods have been selected for being the calibration ones. At the same time the attention has been paid to the fact that the selected periods must be from recent years and thus well–documented. The final selection is shown in the Fig. 5.

Primarily, the selected calibration period showing the most intensive amount of precipitation. It is the period of the last decade in July 2001, producing 123 mm of rainfall in 7 days. The groundwater level in the bore-holes reached its maximum, predominantly in the Mojš village (Fig. 5).



Fig. 4: Investigated region - illustration of observation bore-holes and sonds used for determination of boundary conditions Obr. 4: Záujmová oblasť - znázornenie kalibračných sond a vrtov použitých na stanovenie okrajových podmienok



Fig. 5: Course of groundwater level in bore-holes and precipitation in the Mojš village - illustration of the calibration periods Obr. 5: Priebeh hladiny podzemnej vody v sondách a priebeh zrážok v Mojši, znázornenie kalibračných období

The second calibration period is represented by a stable period with relatively low groundwater level-

the other extreme, intended to mark the potential order of magnitude of the groundwater level regime in the

right alluvium of Žilina HS (May 2002). Boundary conditions of two-dimensional groundwater flow in the calibration periods as the conditions of the 1-st order, i.e. the water level in the bore-holes, or possibly in the river-bed of the alternate bio-corridor have been chosen. These were determined as a mean value in the calibration period. The results of the model calibration are elaborated more detailed in the study (Šoltész et al., 2002).

# PROPOSAL OF TECHNICAL MEASURES FOR GROUNDWATER LEVEL CONTROL

Based on given geological, hydrogeological, and morphological properties of the investigated area, and hydrological conditions for extreme cases the proposal of technical measures for decreasing the groundwater level regime in the Mojš have been considered. Various alternatives of measures have been introduced, verifying their efficiency until the final proposal has been reached. The greatest awareness was the fact that the groundwater flow into the area of the Mojš from the north-east, and at the same time into the area is exposed to massive rainfall and snowmelt. Due to thin cover layers in the alluvium of the Váh River, groundwater is constantly infiltrated by the rainwater. This fact greatly influenced possible technical measures proposed in the numerical model.

The technical measures considered in investigation can be divided as follows (Fig. 6):

- Pumping from wells built in the Mojš,
- Construction of drains in various modifications (draining in existing or planned communications)
- Deepening the river-bed of Kotrčina and Gbely streams (numbered 103 and 104)
- The water level control in the alternate bio-corridor (numbered 109).

The first issue which has been dealt with was varied pumping quantities from the private-owned wells used to monitor the groundwater level regime. This procedure has been used in case of most unfavourable hydrological conditions. The outcome of this scenario pointed out to the local efficiency of drainage using the pumping from wells. Apart from this fact, the realisation of this measure requires the utilisation of electricity and the drainage may cause the filtration instability of soil in porous medium with consequent static failure of the houses.

Another possibility to treat the unfavourable water level range was the proposal of draining the water in various modifications. This option was treated as the most economical solution, sufficiently ensuring the drainage of redundant water from the area of the Mojš village. The proposed solutions were always designed for the extreme hydrological conditions. With respect to the fact that the drainage sluices the redundant water due to gravity, the fundamental premise of this procedure is that the infiltrating water is safely drained away. A suitable recipient for the drained water proved to be the alternate bio-corridor. This option was verified and came to a positive conclusion and hence modelling of these variants was proceeded.

Fig. 7 shows only four of all scenarios of drains locations. The first one requires building the drainage system No. 4 and, in a lower-placed street the drainage system No.2. (Fig. 7a) The other variant shown in the Fig. 7 requires building of the drainage system No. 5 located above the inhabited part of the Mojš in the direction of the planned road (Fig. 7b). Scenario shown in Fig. 7c consists of the main downward drainage, which is interconnected with the bio-corridor in the direction of the planned road communication. It requires the construction of another secondary collecting drain built on both sides of the main collecting drain. The final variant, shown in the Fig. 7d, only differs from the previous one in the fact that the collecting drain below the village is headed directly into the lower-placed reach of the bio-corridor stream channel.

The results of the modelling showed that integrating these drainage elements into the filtration area caused the improvement of the situation, especially in the northern part, where the effect of the measures was clearly observable. The weakest solution is certainly the scenario of drainage system No. 5, which is placed too much up to the north and its effect is subtle. The results of the first model (Fig. 7a) show that this variant might meet the requirements of an efficient draining of the redundant water, however, there is a problem with the construction of the draining system itself (excessively narrow street, engineering system). The results of the modelling shown in the Fig. 7d point out to the fact that this variant would reliably solve the situation in the northern part of the village even in the case of extreme hydrological conditions. However, it would fail to resolve the negative situation in the houses near the biocorridor.

As later implied by the model calculation of proposed solutions, the individual technical measures on their own can hardly function in dewatering of the redundant groundwater. However, when meeting the owner requirements have to be proceeded for resolving another scenarios, which came to existence as a combination of particular technical measures.



Fig. 6: Proposal of all technical measures realised in the Mojš village Obr. 6: Návrh všetkých technických opatrení v oblasti obce Mojš

The first scenario examined was pumping from three wells in the village of the Mojš at current water level decrease in the bio-corridor to the minimum level. The results of fitting to the most unfavourable hydrological status proves that this variant is likely to suit the majority of houses in the village, predominantly the areas where the effect of the pumping well is detected. We have previously discussed the inconvenience of the pumping in municipal areas and this variant confirmed our theory again (Šoltész et al., 2002).

Another combined scenario was the possibility of deepening the river-beds of Kotrčina and Gbely stream (in the Fig. 6 theses are numbered as 103 and 104) with simultaneous lowering the water level in the biocorridor to the minimum operational level. This variant would cause all of the houses to be at dry places. We only have to take into account that this model calculation merely applied to the maximum operational time periods. To see the whole situation at the model calculation applied to the most extreme condition, we also did this calculation the results of which are elaborated in the research report (Šoltész et al., 2002). The calculation suggests that this variant at extreme rainfall activity in the area of the Mojš village would be inefficient predominantly in the northern and western part of the village. Beside that, it is worth emphasising that deepening of the river bed would require enormous groundwork (deepening by three meters), which makes the procedure financially restricted.

In the next step the combination of the main drainage system design (No. 4, Fig. 7c, 7d) with lowering the water level in the bio-corridor to the minimum level has been dealt. This variant would meet the objectives even at extreme hydrological condition. A similar situation also arises when considering that the last part of the drain (No. 11) is not active, i.e., it fails to collect the redundant water and serves merely as a transport pipeline. This variant also enables the house cellars to be dry.



Fig. 7a, b , c, d: Proposal of location scenarios of dewatering drains Obr. 7a, b , c, d: Návrh scenárov umiestnenia odvodňovacích drénov



Fig. 8a: Modelling of the most unfavourable hydrological situation without any technical measures Obr. 8a: Modelovanie najnepriaznivejšieho hydrologického stavu bez akýchkoľvek technických opatrení



Fig. 8b: Modelling of the most unfavourable hydrological situation for scenario: drainage element 11, 4, 19 and 40 cm decrease of water level in bio-corridor in the reach from "B2" to "B3"

Obr. 8b: Modelovanie najnepriaznivejšieho hydrologického stavu pre scenár: drenážne prvky č 11, 4, 19 a zníženie hladiny v biokoridore od "B2" po "B3" o 40 cm

#### CONCLUSIONS

In accordance with the results of the modelling calculations during the solution a most realistic conclusion has been considered. It was based on the possibility to control the water level regime in the biocorridor in the river section from B2 (below the footbridge) down to the profile B3 (the bridge below the village) (Fig. 4).

To the lowered water level in the section of the biocorridor from B2 to B3 (which has been proposed by ourselves) the scenario of the main drainage system with two additional collecting drains was applied. The results of modelling this type of solution in the extremely negative hydrological conditions prove that this variant with simultaneous decrease of the water level in the bio-corridor by 20 cm is sufficient and by decreasing the water level by 40 cm absolutely convenient. The house cellars in the whole village are in this case in the dry. If a secondary collecting drainage system No. 20 is excluded from the simulation process, similar results will be obtain, which are only a little less unfavourable than in the previous scenario, but still suitable. The modelling results are shown in the Fig. 8a, Fig. 8b.

The research was performed on behalf of the projection and investment companies responsible for the water management of the Žilina hydraulic structure. Presented results are not complete and do not show the complexity of the research work which has been done in looking and investigating for convenient solution. The numerical modelling was supported by measurements in the field, mostly for determination of surface water levels as boundary conditions in the alternate biocorridor of the Žilina hydraulic structure.

### REFERENCES

Baroková, D. 2004: Determination of Impact of hydraulic structure on groundwater level regime and possibilities of its control. PhD. Thesis (In Slovak). 151 p.

Burger, F., Gomboš, M., 2001. Determination of the aquifer filtration parameters for the purpose of groundwater modelling. Acta Hydrologica Slovaca, 2. pp. 272-283.

Frankovský, P., 1997. Žilina hydraulic structure-project of the measurement of groundwater table and seepage. Hydroconsult Bratislava (In Slovak). 12 p.

Kadlec, J., Kvál, J. Bukvová, J., 2001. Complex monitoring of the environment with respect to construction and operation of the Žilina hydraulic structure. Annual Report 1999, 2000, 2001, 2002, 2003. VV Bratislava (In Slovak). 68 p. Kovařík, K.: Numerical Models in Groundwater Pollution, Berlin Heidelberg, Springer - Verlag, 2000. 221 p. Royal Haskoning, 2002: TRIWACO a Simulation Package for Groundwater, Version 3.0, Rotterdam, Netherlands, B.V. Smolka, J. et al., 1992: Žilina hydraulic structure – geological survey, I. and II. stage, Ingeo Žilina (In Slovak). Šalaga, I. et al., 1995. Paleogene of the Žilina region - hydrogeology. Final report, INGEO Žilina (In Slovak). Šoltész, A. et al., 2002. Elaboration of the mathematical model and proposal of technical measures for the solution of unfavourable groundwater regime in the village of the Mojš. Final Research Report, FCE STU Bratislava (In Slovak). 127. p Šoltész, A., 1993. Modern methods of solution in hydrodynamics of porous media (In Slovak). 46 p. http://www.triwaco.com

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# SÚHRN

Vodná stavba (VS) Žilina je prvou stavbou na Slovensku, ktorej vplyvy na životné prostredie boli posudzované komplexne metódou EIA (Environmental Impact Assessment). Návrhy na zmiernenie dopadov stavby na životné prostredie boli zakomponované do objektovej skladby stavby (1994 – 1998) a spolupráca s odborníkmi na životné prostredie pokračovala aj pri realizácii a prevádzke stavby. Jedným zo sprievodných opatrení výstavby vodného diela bolo vybudovanie pozdĺžnej tesniacej steny, ktorá mala za úlohu zabrániť priesaku vôd z nádrže do priľahlého územia. Pozdĺžna tesniaca stena svoju úlohu splnila, zároveň však zamedzila v takmer celej svojej dĺžke drenážnemu účinku toku Váh. Dôsledkom toho vzniklo pri extrémnych hydrologických situáciách (silné zrážky, náhle topenie snehu) zvýšenie hladiny podzemnej vody aj v obci Mojš, ktoré bolo sprevádzané zatápaním pivníc rodinných domov v obci. Cieľom výskumu bolo dokázať príčiny zamokrenia pivníc domov v obci Mojš a navrhnúť také technické opatrenia, ktoré by nepriaznivý stav odstránili. Problém bol riešený pomocou matematického modelovania prúdenia podzemných vôd. Záujmové územie (obr. 4) sa nachádza v pravostrannom alúviu rieky Váh, v bezprostrednej blízkosti vodnej nádrže VS Žilina. Pozdĺž pravostrannej hrádze VS sa navyše vinie náhradný biokoridor, ktorý prechádza aj južným a juhozápadným okrajom Mojša (obr. 1). Biokoridor (rybovod), ktorý je napájaný cez nápustný objekt pri sútoku Váhu s tokom Varínka, svojím hladinovým a prietokovým režimom zasahuje do hladinového režimu podzemných vôd v danej lokalite.

Z archívnych údajov geologického a hydrogeologického prieskumu, ktorý bol v minulosti vykonaný kvôli výstavbe VS Žilina vyplýva, že záujmové územie je súčasťou Žilinskej kotliny, ktorá je budovaná najmä horninami vnútrokarpatského paleogénu. V severnej časti oblasti sa na stavbe územia podieľajú aj kriedové horniny bradlového pásma. Z kvartérnych sedimentov sú najviac zastúpené fluviálne sedimenty, ktoré rozhodujúcou mierou formujú podzemné vody. Nerovnomerná mocnosť vodonosných vrstiev narastá z hodnoty 6,5 m až po 18 m v smere od Váhu na sever k podhorským oblastiam (Teplička, Gbeľany). Hrúbka pokryvných vrstiev hlín sa pohybuje v intervale od 0.5 do 2m v nížinnej časti (v oblasti Mojša) až po 2,0–4,5 m v podhorských oblastiach. (obr. 2a, 2b, 3a, 3b)

Primárne bolo nutné navrhnúť kalibračné obdobie s maximálnym úhrnom zrážok, za ktoré sme zvolili poslednú dekádu júla 2001 (123 mm zrážok za 7 dní). V tomto období hladiny podzemnej vody v obci Mojš dosiahli svoje maximum (obr. 5).

Na základe geologických, hydrogeologických a morfologických vlastností záujmovej oblasti, ako aj na základe hydrologických podmienok pre extrémne stavy sme navrhli variantné riešenie technických opatrení na zníženie hladiny podzemnej vody v Mojši (obr. 6 a obr. 7a, 7b, 7c, 7d). Tieto je možné rozčleniť nasledovne: čerpanie z už vybudovaných studní v obci Mojš, výstavba odvodňovacích drénov v rôznych variantoch, prehĺbenie časti koryta Kotrčiny a Gbelianskeho potoka, manipulácia s hladinou v náhradnom biokoridore a ďalšou z možností bola kombinácia jednotlivých opatrení.

V súlade s modelovým výsledkom riešenia sme sa dopracovali k návrhu, ktorý považujeme za najreálnejší: znížené hladiny v úseku biokoridoru od profilu B2 po profil B3 spolu s návrhom (obr. 7d) hlavného odvodňovacieho drénu č. 4 s dvoma vedľajšími zbernými drénmi č. 9 a č. 19 (prípadne možnosť predĺženia o drén č. 20). Výsledky modelovania takéhoto riešenia pre najnepriaznivejší hydrologický stav dokazujú, že takýto variant so súčasným znížením hladiny v biokoridore o 20 cm je dostatočný a pri znížení hladiny v danom úseku o 40 cm úplne vyhovujúci. Pivnice všetkých domov v obci sú pri takomto variante úplne "v suchu".