# Stream-aquifer interaction in mining conditions using a groundwater flow model

Jacek Szczepinski

*Poltegor-projekt Sp z o.o. Wyścigowa 56f, 53–012 Wrocław, Poland, j.szczepinski@poltegor.pl*

**Abstract** In some areas, particularly those under mine dewatering, streams become dry due to lowering of the groundwater table. On the other hand, mine water pumped out from the mine dewatering system additionally discharges into rivers and streams, increasing their streamflow. This phenomenon can be represented in MODFLOW by the Stream Package, which simulates interaction between streams and aquifers. In this paper the Stream Package has been used in the modeling studies for future open pit dewatering. The numerical model has been developed for pre-mining conditions and for mining conditions.

**Keywords** Modflow, mine dewatering, mathematical model, surface water, groundwater

## Introduction

In some areas, particularly those under mine dewatering, streams become dry due to lowering of the groundwater table. On the other hand, mine water pumped out from the mine additionally discharges into rivers or streams, increasing their streamflow. To simulate the stream-aquifer relation in a three-dimensional groundwater flow computer program MODFLOW (McDonald and Harbaugh 1988), the River Package (RIV) and the Drain Package (DRN) are most often used. The main drawback of the River Package is that it only accounts for leakage to or from the rivers. It does not permit rivers to go dry during a given period of simulation. On the other hand, the Drain Package simulates the effects of features such as small courses, which remove water from the aquifer so long as the head in the aquifer is above the streambed elevation. But it has no effect if the head falls below that level. Neither package tracks the amount of flow in the rivers, nor do they permit simulating mine water discharge into streams. This can be done by using the Stream Package (STR; Prudic 1989), that tracks the flow in one or more streams which interacts with groundwater. It represents the mixed boundary condition. The package can be particularly useful in areas under the influence of mine drainage, where some parts of streams dry up but others increase their streamflow due to mine water discharge. The purpose of this paper is to present the ability of the Stream Package to simulate the impact of the proposed open pit dewatering on stream as well as the influence of mine water discharge on groundwater.

## Site description

The proposed open pit mine is located in the north part of the Pleistocene upland area, which is a ground moraine of glacial sediments. Glaciofluvial and glacial till deposits range in thickness from 40 to 60 m. The underlying bedrock consists of fractured cretaceous marls, sometimes with mudstone. It is a predominantly flat area with the ground level between 85 to 100 m a.s.l., lowered to the north towards the River X flowing through the ice – marginal valley with a flow of about 60 $m^3/s$ and being on the level of 75–80 m a.s.l. The average annual precipitation amounts to 550 mm and the land evaporation is 471 mm. The baseflow for this area is 1.0 – 1.5 $L/s/km^2$.

Within the area of the deposit, the hydrological system is poorly developed and its principal elements are the left-bank tributaries filled with Holocene deposits about 5 m thick.

The Streams A, B, C and D flow in a north direction towards the River X. The ephemeral course, namely Stream B, with flow up to 1 $m^3$/s, is regarded as a body of water where the discharge from the dewatering system will be released (Fig. 1).

There are three aquifers within the area: the unconfined quaternary water table aquifer, the neogen-paleogen aquifer and the Mesozoic aquifer – both confined. The water table aquifer consists of the quaternary sandy formations with an average thickness of 5 m and hydraulic conductivity from $3 \times 10^{-5}$ to $1.2 \times 10^{-5}$ m/s, the average being $7 \times 10^{-5}$ m/s, while the specific yield is from 0.1 to 0.13. The groundwater flow direction is towards the north and is determined by the River X. The glacial till, clays, silts and argil under this aquifer have a thickness of about 20–40 m and act as a confining unit (Fig. 2).

Directly under the glacial aquitard neogen-paleogen, fine and medium-sized sands occur lying on the silts and mudstones, or directly on the cretaceous formations. The sands are up to 20 m thick, the average being 12 m, while the hydraulic conductivity is on average $8 \times 10^{-5}$ m/s. The storativity is from $4.91 \times 10^{-4}$ to $2 \times 10^{-3}$ , while the specific yield is 0.14. The lowest fractured cretaceous aquifer is represented by marls, sometimes with mudstone layers with a thickness of 80 m and the average hydraulic conductivity of $4.4 \times 10^{-5}$ m/s, while the storativity is $3.68 \times 10^{-3}$. Slight isolation enables hydraulic contacts between the cretaceous and neogen-paleogen aquifer, which is provided by the similar water table level. The upper unconfined aquifer is recharged directly from precipitations and discharged by the river and streams. The lower aquifers are recharged by leakage of water from the upper aquifer or directly through the hydrogeological windows. The general groundwater flow direction is towards the north.

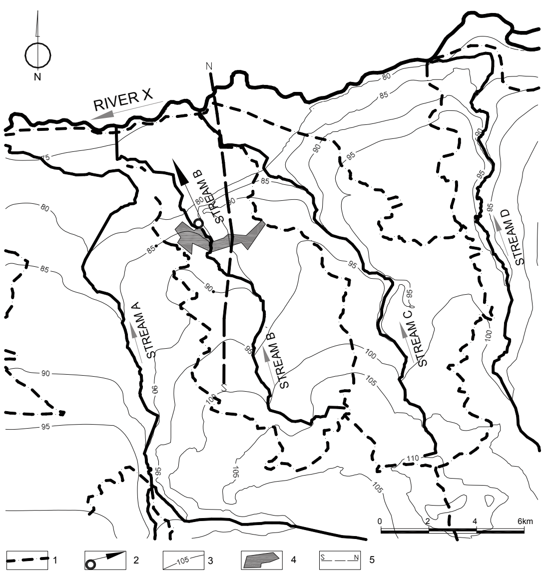


*Fig. 1 Hydroizohipses of the water table quaternary aquifer. Explanations: 1 – watershed, 2 – mine water discharge direction, 3 – hydroisohipses, 4 – open pit area, 5 – hydrogeological cross-section*

## Methods

A 3-dimensional finite difference model has been used based on MODFLOW code (McDonald and Harbaugh 1988) in conjunction with the MODFLOW-Surfact (Version 3) code to allow for both saturated and unsaturated flow conditions. The modeling has been undertaken using the Groundwater Vistas (Version 5.36) software package (ESI 2006). The concep-

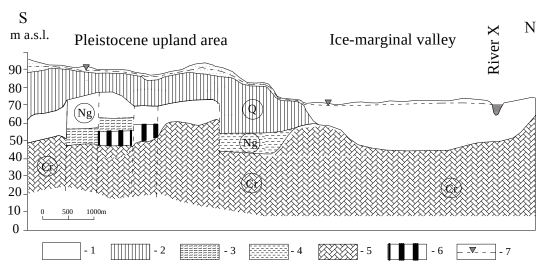


*Fig. 2 The hydrogeological cross-section through the deposit area (S–N). Explanations: 1 – fine and medium sands, 2 – clays, 3 – silts, 4 – argils, 5 – marls, 6 – deposit, 7 – quaternary water table in natural conditions, Q – Quaternary; Ng – Neogene; Cr – Cretaceous*

tual model for the area is based on investigations undertaken by the Geological Institute and mining company. A three-dimensional five-layered numerical model has been developed, which covers an area of 660 $km^2$. The model is discretized with a uniform 100 m by 100 m grid, which gives a grid mesh of 255 rows and 300 columns. It is divided into five vertical layers – three aquifers and two aquitards. The aquifers represent: 1. the water table quaternary aquifer, 2. the neogen-paleogen over-deposit porous aquifer and 3. the porous – interstice aquifer which includes the cretaceous marls and mudstones. Between the aquifers, there are two layers represented by aquitards comprised of clays and silts. The effective infiltration $Q$ = const. varies over the area from 4.6 to 15.3 % of average annual precipitation. Head dependent flow boundaries (MODFLOW GHB cells) have been used in all layers to represent external regional flows into and out of the model domain. The River X on the north has been represented using Modflow's River cells. The water level in the River X has been set from the topographic map 1: 25 000.

All streams in the study area including the Stream B flowing through the deposit area, were simulated only in the layer I by mixed boundary condition represented by the Stream Package. This package enables computing the flow between the stream and aquifer using Darcy's law as presented by McDonald and Harbaugh (1988; 1). The value of leakage between the aquifer and the stream is added to or subtracted from the flow of the stream, which allows calculating the water level in each cell representing the stream, using the Manning formula as described by Ozbilgin and Dickerman (1984; 2, 3). All parameters for using the Stream Package – stage of stream, width of stream, streambed elevation, slope of stream channel and streambed conductance – have been collected during the field investigation. Roughness coefficient was estimated from the tables (White 1979).

$$Q = \mathrm{CSTR}\left(H_s - H_a\right) \tag{1}$$

where:

$Q$ – leakage to or from the aquifer through the streambed, ($L^3/T$),

$H_s$ – head in the stream, (L),

$H_a$ – head in aquifer side of streambed, (L),

CSTR – conductance of the streambed, ($L^2/T$).

$$Q = \frac{C}{n}\left(AR^{\frac{2}{3}}S^{\frac{1}{2}}\right) \tag{2}$$

where:

$Q$ – stream discharge, ($L^3/T$),

$n$ – Manning's roughness coefficient, dimensionless,

$A$ – cross-sectional area of the stream, ($L^2$),

$R$ – hydraulic radius, (L),

$S$ – slope of the stream channel, (L/L),

$C$ – a constant, ($L^{1/3}/T$), which is 1.486 for units of cubic feet per second or 1.0 for cubic meters per second.

$$d = \left[\frac{Qn}{\sqrt{Cws}}\right]^{\frac{3}{5}} \tag{3}$$

where:

$d$ – depth of the water in the stream, (L),

$w$ – width of the channel, (L).

The groundwater model was developed in steady state mode. Steady state calibration has been based on the available water level data recorded during field investigations in 450 dug wells located in the water table aquifer. The water level data from deeper aquifers represents long term average aquifer conditions. The steady state conditions were achieved with sequential model runs by manually adjusting the horizontal and vertical conductivity and recharge values until the best fit between the simulated and measured water levels was attained. Transient model calibration was not run but the heads from steady-state runs calculated for pre-mining conditions were used as initial conditions for the transient simulation. The predictive simulation has been carried out in transient conditions for the 8-year period of the open pit dewatering, by lowering the groundwater level within the deposit area of 30 – 45 m. The dewatering operation was modeled by progressive assignment of Modflow the Time-Variant Specified Head cells $H = f(t)$ to active mining areas in accordance with the respective project mine plans. It was assumed that the mine water from the pit dewatering will be discharged into the Stream B.

## Results and Discussion

For the average Stream B parameters obtained during field investigations – channel width of 4 m, riverbed conductance of $1.2 \times 10^{-6}$ m/s, hydraulic gradient of $1.6 \times 10^{-3}$ and roughness coefficient of 0.01 as well as taking into account measurements of the stream stage and groundwater level in 450 wells – the Stream Package enables simulating its total streamflow (0.07 $m^3/s$) in the steady state conditions. Moreover it evaluated the interaction between the stream and the aquifer in each cell (Fig. 3). The results of the modeling study reveal that the streamflow occurs 3000 m downstream from the beginning of the streambed, which confirms the field investigation (Fig. 4).

In the next step, the streamflow and flow between the stream and the aquifer has been simulated in mining conditions under transient conditions. In this case the Stream B, regarded as a body of water where the discharge from the dewatering system will be released, has been divided into two segments. The first segment covered a section of the Stream B located upstream of the proposed pit. The second segment involved a part of the Stream B situated downstream.

Two variants have been analyzed. The first one assumed that the mine water will not be discharged into the Stream B. In this case the streambed will be out of water at a range of 4500 m from the pit. When the groundwater level is above the bottom of the streambed, the process of groundwater drainage by the Stream B will begin and the streamflow will start (Fig. 5).

In the second scenario mine water will be discharged into the Stream B downstream of the pit at the rate of 0.5 $m^3/s$. In this case stream-

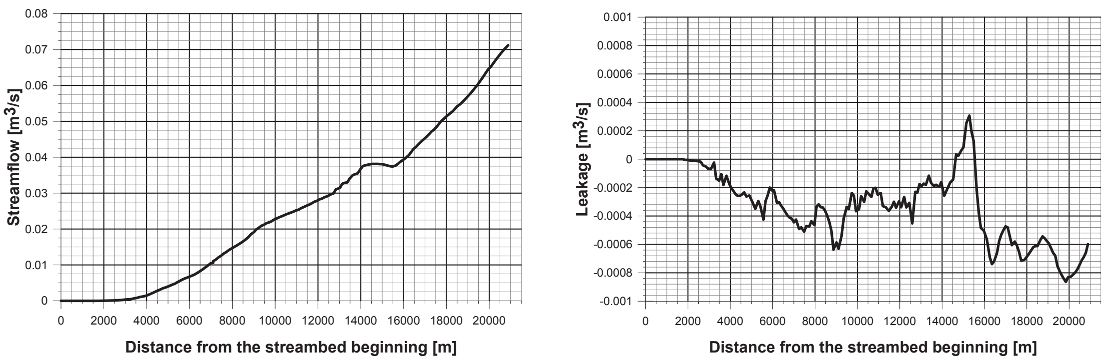


***Fig. 3*** *Streamflow (left) and leakage between the Stream B and the aquifer (right) in natural condition*

***Fig. 4*** *The Stream B – streambed (left) and streamflow (right)*

flow was accounted for by specifying flow for the first cell in the segment located downstream from the dewatering system (north boundary of the pit), and then computing the streamflow to adjacent downstream cells as equal to the inflow in the upstream cell plus or minus leakage from or to the aquifer in the upstream cell (Prudic 1988). In this case the highest streamflow will take place right in the first cell downstream the north boundary of the pit. In the cells located downstream, the flow will decrease because of the aquifer recharge with surface water (Fig. 6). Groundwater recharge from the surface water reduced the range of the cone of depression of 1000 m. The simulation revealed that due to mine water discharge the water stage in the Stream B will increase by 0.1 m, compared to natural conditions.

In both of simulated variants, south from the open pit boundary *i.e.* in a segment of the Stream B located upstream of the proposed pit, the Stream B changes from a gaining into a losing stream. At a distance of 4000 m from the south edge of the pit the streamflow in the Stream B will stop due to mine dewatering impact (Fig. 7).

## Conclusions

The impact of mine drainage on the surface water results in streamflow reduction, and even drying up. On the other hand, discharge of mine water to streams increases the streamflow, stream stage and can reduce the cone depression by interaction with the aquifer. In order to assess stream-aquifer interaction the Stream Package can be used. It is a lot more powerful than the commonly used River Package and Drain Package, allowing calculation of the streamflow and water stage change as well allowing estimating the lengths of the

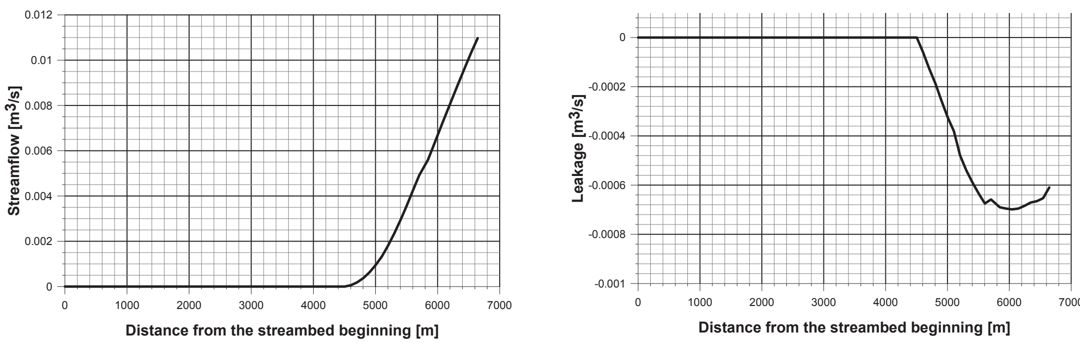


***Fig. 5*** *Streamflow (left) and leakage between the Stream B and the aquifer (right) in dewatering conditions, downstream of the open pit without mine water discharge*

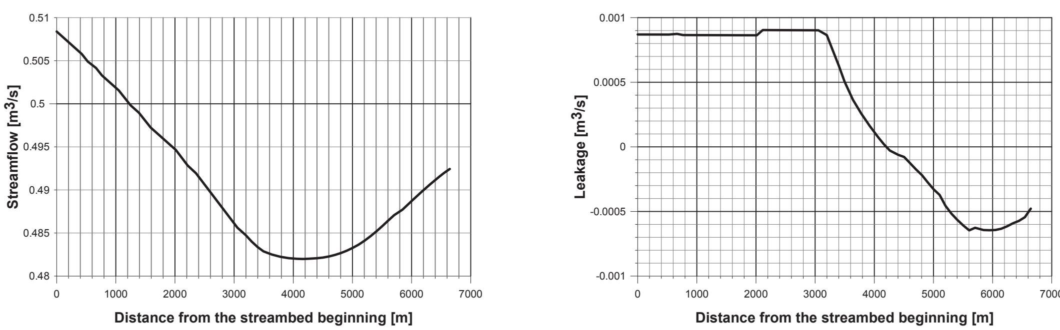


***Fig. 6*** *Streamflow (left) and leakage between the Stream B and the aquifer (right) in dewatering conditions, downstream of the open pit with mine water discharge 0.5 $m^3/s$*

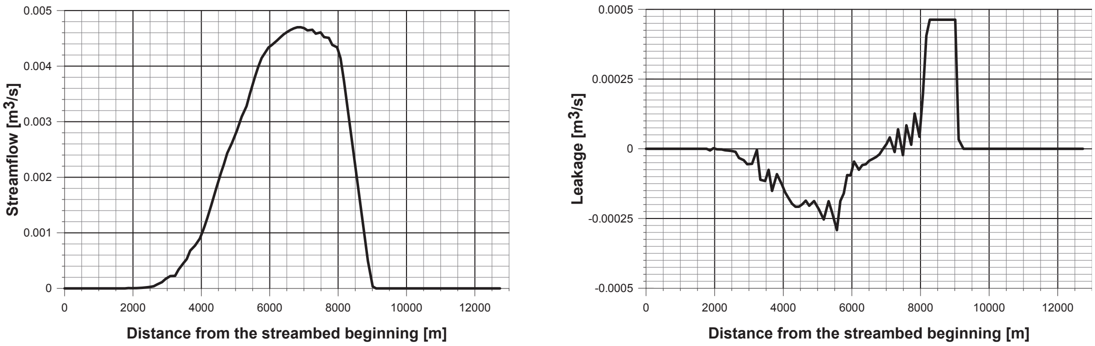


***Fig. 7*** *Streamflow (left) and leakage between the Stream B and the aquifer (right) in dewatering conditions, upstream of the open pit*

streambed subject to a total loss of water. However, to get a feasible solution it is necessary to acquire additional data: stream parameters (width of stream, roughness coefficient, slope of stream channel), stream stage and the groundwater level in the upper aquifer, essential for the stream-aquifer relations. The results of the modeling study reveal that the Stream Package is particularly useful in areas under the influence of mine drainage and mine water discharge. In addition to calculating the streamflow, flow between stream and aquifer and the stream stage, it permits streams to go dry during a given period of simulation as well as to simulate subtraction or additional inflow to surface water, which is not included in the River Package. The Stream Package has some limitations that may affect the solution (Prudic 1989). It does not include a time function for routing flows specified for the first cell; it calculates the water level in the stream assuming a rectangular channel and constant streambed conductance and makes the assumption of the instantaneous leakage from the stream to the aquifer. Some of these restrictions have been removed in newer versions of the Stream Package. The possibility of varying the geometry of the streambed in its cross section has been included in the Streamflow-Routing Package (SFR1) Package (Prudic *et al.* 2004), and the presence of the unsaturated zone beneath the streambed, in a subsequent modification – in the Streamflow-Routing Package (SRF2) Package (Niswonger and Prudic 2006).

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