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Fakulteta za strojništvo

Use of groundwater flow modelling for assessing environmental scenarios

Diploma thesis.

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Diploma thesis contents

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Use of groundwater flow modelling for assessing environmental scenarios

Key words: groundwater, aquifer, Apace field, FREEWAT, QGIS, hydraulic head, numerical modelling.

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ABSTRACT

The diploma thesis presents a study of the groundwater flow on the aquifer of Apace field through different environmental scenarios. The two pumping stations, Segovci and Podgrad, located on the Apace field, are an important source of drinking water for the north-eastern part of Slovenia. In this study, we investigated the influence of droughts on the groundwater level and groundwater flow and assessed the impact of a newly planned pumping station in the northern part of the aquifer. The new pumping station is planned to mitigate the shortage of drinking water in the summer months and decrease the groundwater deficit in the area of the pumping station Podgrad. The hydrogeological analysis and the groundwater flow modelling was done using the geographical information system QGIS and hydrogeological tool FREEWAT.

Contents

1. Introduction

1.1. Overview of the problem

Groundwater is the most important source of drinking water for almost half of the world's population [1], as well as an alternative to solve the needs of agriculture. On the other hand, this resource has a remarkable effect of sustaining and control of streams, lakes, wetlands, other associated ecosystems.

According to a study by Unesco [1], between 2011 and 2050, the world population is expected to increase by 33%, and food demand will rise by 60% in the same period. Furthermore, it is projected that populations living in urban areas will almost double. As well as, 2.3 billion people expected to be living in areas with severe water stress, especially in North and South Africa and South and Central Asia. Another report predicts the world could face a 40% global water deficit by 2030 under a business-as-usual scenario. That is why groundwater is going to be the key to many water problems now and in the future.

In recent years, there has been some evidence of climate changes and its impacts on water resources. The shortage of water in the swamps, the decrease in rainfall, as well as the increase in desert areas, will oblige us to explore other alternatives for obtaining drinking water. According to Unesco, the most important direct effect of climate change on groundwater is associated with recharge patterns [2]. The spatial and temporal distribution of precipitation, air temperature, evapotranspiration, soil moisture, groundwater levels and response time of aquifers are the main natural factors that control the recharge of groundwater in different climatic zones. The reaction of deep, non-renewable aquifers and fossil aquifers to the impacts of climate change will last for centuries or millennia; the reaction of the surface, karst or coastal aquifers can last, in terms of groundwater recharge, only a matter of weeks, months or years.
It is necessary to analyze and quantify the potential impacts of climate change on the quality and quantity of groundwater in terms of social, economic and environmental effects, as well as risks to the population and ecosystems dependent on underground water resources.

On the other side, groundwater has got a lot of problems with pollution. There are some activities which are not very environmentally friendly, such as landfills of urban waste, leakage of wastewater that seeps into the land, industrial landfills, use of fertilizers and pesticides in agriculture or forestry practices or excessive exploitation of aquifers that facilitate to the intrusion of salt water into the area of sweet waters. So, it is important to have a greater control of the industrial activities, as well as, a good logistic of the use of the groundwater.

Hence, studies and analysis of groundwater management are needed all over the world, especially in areas with more droughts and higher demographic decrease levels. According to the World Water Forum held in San Francisco in 2012 [3], it was stated that through the application of mathematical modelling for groundwater, it was possible to estimate the decrease in local recharge, the decrease in water levels and the change in the hydraulic regime of the water system. With reference to these results, recommendations were made on the management of the aquifer, structural and nonstructural measures and the possibility of joint use of surface and underground water to supply the needs of the area in the future.

In this study, we are going to use a tool to help us build a theoretical model of the groundwater flow. The name of the model is Freewat [4] and it is a free open-source tool for water resource management, created within the frame of *Horizon 2020 project free and open source software tools for water resource management*, financed by the EU Commission. The Freewat platform is an integrated modelling environment for the simulation of water quantity and quality in surface and groundwater, with an integrated water management and planning module.

However, Freewat is not the only groundwater model that exists. Another important tool is Visual Modflow [5]. The objective of the modelling of an underground water system with Visual Modflow is to obtain the evolution of groundwater levels and flow velocities in the environment, defined as the area of interest. It is one of the most widely used and internationally recognized models in hydrogeology for flow simulation.

1.2. Goals and aims

Goals:

- To produce a groundwater flow model.
- To use the model to study environmental scenarios.
- To make an assessment of environmental impact of placing additional pumping stations in the aquifer.

1.3. Assumptions and limitations

Assumptions and limitations:

- We will assume steady state conditions using average environmental data.
- The flow of groundwater is laminar.
- Flow through porous media will be modelled by Darcy equation.

1.4. Foreseen working methods

- Study of literature in the field groundwater.
- Making a model of groundwater.
- Study of environmental scenarios.

- Analysis of results.
- Writing the thesis.

2. Theoretical part

Water is life. From ancient times to the present, and our future, water is and will remain a great pillar of our development. Our existence depends on it. And in many cultures, water is a blessing, a joy and a party that we should remember all those who, fortunately, have access to it. Water is a vital right that everyone should have, but unfortunately, according to the OMS [6], 2100 million people do not have access to this privilege.

All the big civilizations have been developed around water resources such as rivers, lakes or groundwater. When the water ran out or there were great droughts, many people had to migrate to other places to get this precious good. Groundwater has gotten an important role as the principal source for many people of being drinking water, as well as the engine of the ecosystems. These waters, originally used exclusively for drinking, have been incorporated over the centuries into activities such as agriculture or industry. It must be taken into account that groundwater is an irreplaceable resource in a good part of the planet, and essential for health. Therefore, we need to conserve and control the use of it.

2.1. Model of groundwater

2.1.1. Hydrological cycle

For a better understanding of the groundwater and the aquifer, it is important to remember the hydrological cycle, as it is the base of both (Figure 1).
The hydrological cycle involves the constant movement of water, both on the surface of the Earth, as well as above and below it. Its correct knowledge is fundamental to an adequate use and management of water resources. Water can be found in three states: solid (ice or snow), liquid and gas (water vapor). The water is in constant movement and change in the oceans, rivers, rains or clouds. Evaporating from the surface, precipitating from the clouds or infiltrating the earth. But it is important to note that the total amount of water on the planet does not change. The circulation and conservation of water on Earth is called the hydrological cycle.

The hydrological cycle begins with the evaporation of water from the surface (like the oceans, rivers, lakes, reservoirs, etc.). The vegetation also helps in evaporation, by means of perspiration. As the water vapor (gas) rises, it is cooled and slowly transforming into the water. This process is called condensation. The water molecules are joined to each other, forming clouds. Because of their own weight, they fall in the form of precipitation. Depending on the temperature, they can fall in the form of rain when the temperatures are high or, on the contrary, in the form of snow or hail if the temperatures are low. A part of the water that reaches the earth's surface (because not all of it arrives, some of it evaporates in the journey) is used by living beings (humans, vegetation, animals, etc); another part receives the rivers, oceans or lakes. A small percentage of the water will seep into the ground forming aquifers or layers of groundwater, known as groundwater. This process is called infiltration. From the groundwater, water will return to the surface in the form of natural fountains, streams, and rivers, closing the cycle.

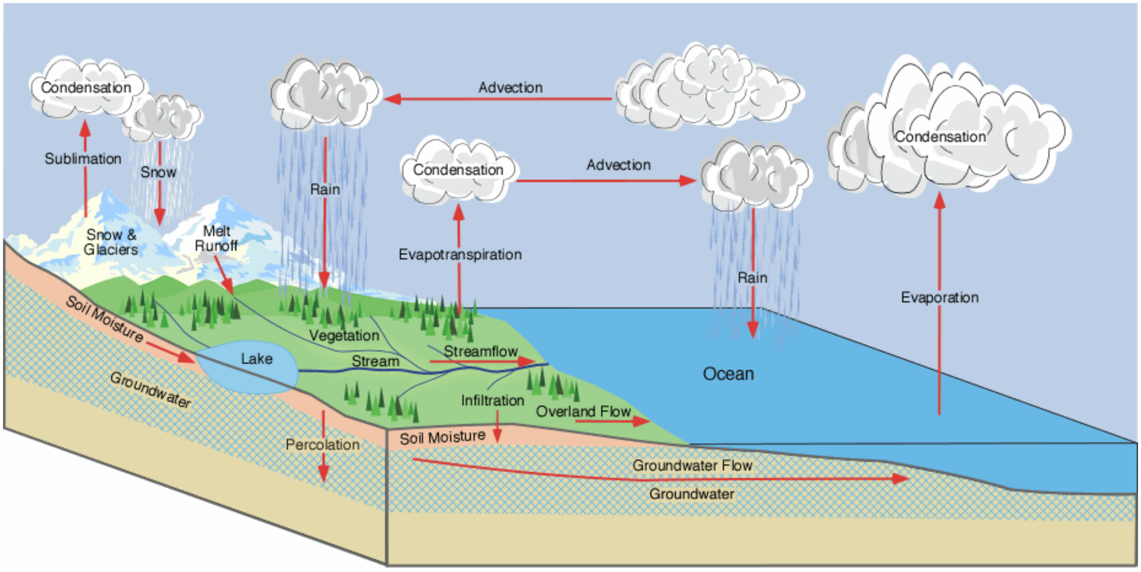

Figure 1. The hydrological cycle [12]

2.1.2. **The groundwater and the aquifer**

Once seen how the water is infiltrated into the ground, we are going to describe what is groundwater and the aquifer.

Underground water occurs in two areas, the vadose zone, and the saturated zone. The first one, the vadose zone (unsaturated zone), is the closest to the land surface and it contains both water and air. The other area of the ground is the saturated zone, which is beneath the vadose zone. Its interconnected openings are full of water. The water located in this zone (saturated zone) is named groundwater. The area between both zones is the water table, which is the surface where the pressure head is equal to the atmospheric one. The best way to show these parts of the ground is in Figure 2.

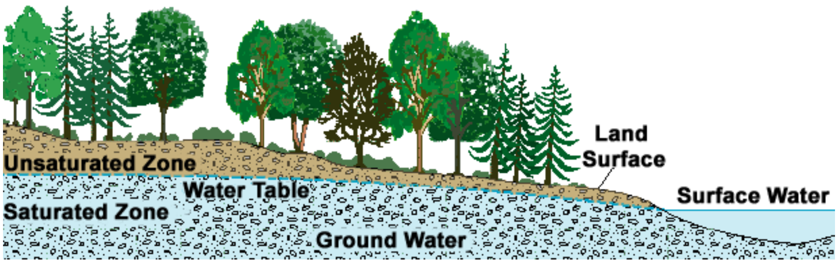

Figure 2. Distribution of underground water [13]

The groundwater moves very slowly through the aquifer. Only in some cases, like karst aquifers or fractured rocks, the water can circulate at higher velocities (like the surface velocities in rivers). The slow movement of the water in the vadose zone and saturated zone, helps in the management and protection of the aquifers. The water that recharges the aquifer, comes from precipitation, rivers or lakes. For the complete recharge, the precipitation must be infiltrated into the root zone. Most groundwater recharge takes part in the wet season when the soil is moist and excess water seeps downward. However, when the soil is dry, water gets tied up in pores, clinging to the solids in the aquifer. On the other side, the water is discharged by flowing into rivers, lakes or oceans, as well as evaporation, pumping wells or through the vegetation. It is possible that groundwater can evaporate, even if the water table is located a few meters below the surface.

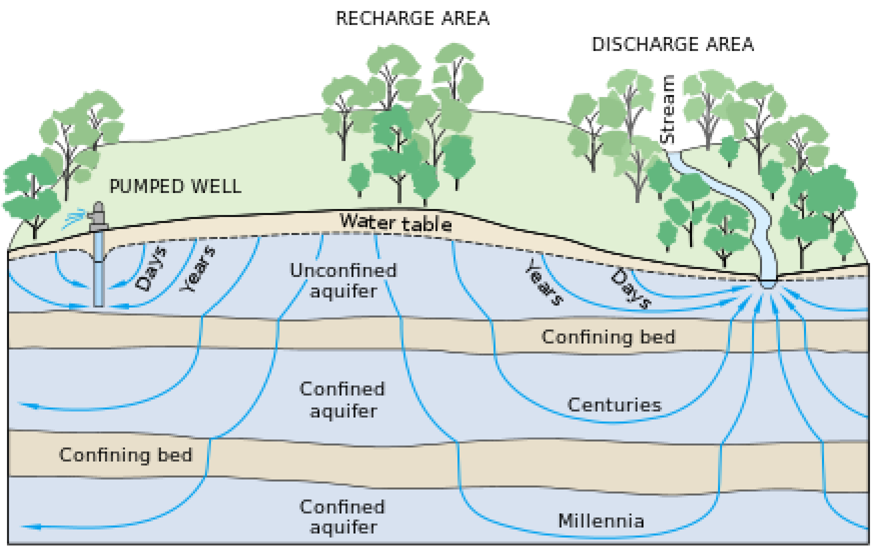

Figure 3. Relative time of groundwater [14]

An aquifer is a body of saturated rock or sediment that has got the capacity of transit a huge amount of water to wells or springs. There are some examples of aquifers like unconsolidated sand and gravel which can be found in alluvial valleys, tectonic valleys and glacial outwash; sandstone and limestone which are common sedimentary rocks forming in some terrestrial, transitional and marine environments; as well as, fractured rocks that cooling magma and tectonic forces normally produce fractures in rocks.

The limits of the aquifer are the confining layers which are geologic units having a low permeability. They restrict the movement of the water between aquifers. It is defined as an unconfined aquifer, the one which is composed of saturated sediment or rock that is not directly overlain by a confining layer. The top of an unconfined aquifer is the water table. The fluid pressure is positive below the water table and negative in the vadose zone. On the other hand, the confined aquifer is composed of permeable rock, and usually, is deeper than the unconfined ones. The groundwater in this type of aquifers is under pressure and the top of it is the cap layer. We can see this type of aquifers in Figure 3, as well.

2.1.3. Physical Properties

We are going to see some physical properties very important in hydrogeology [7]. First of all, hydrogeology is the study of the distribution and movement of underground water in the soil and rocks.

The first concept is going to be the pressure head. The pressure can be measured with a tensiometer in the vadose zone or a piezometer in the saturated zone. The most common tool in hydrogeology is the piezometer, which is a solid vertical pipe. The pressure head [7] (Ψ) is equal to the length of the water column in the pipe. The elevation of the bottom's pipe represents the sea level, which is called elevation head (z). Summing the elevation head and pressure head yields we obtain the hydraulic head (h). The unit of the hydraulic head is the meter. The hydraulic head can be used to calculate the hydraulic gradient between two or more points.

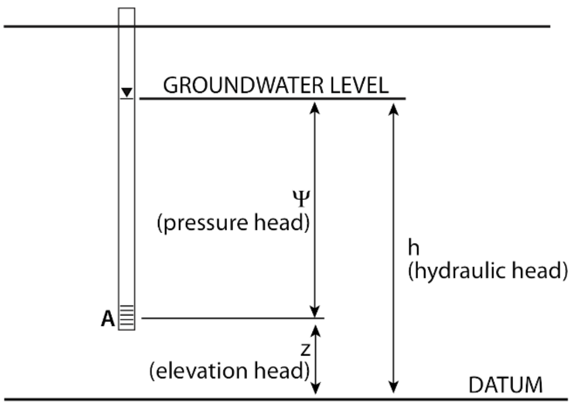

Figure 4. Pressure head [15]

$$h = z + \Psi \tag{2.1}$$

In addition, the important properties that govern the capability of an aquifer (to transmit, store and yield groundwater) are:

The total porosity [7] is the volume percent of a rock or soil sample, that consists of void space. The porosity of the earth material ranges from 0 to 60 %. For unconsolidated sediment, the total porosity is slightly high, but it is low for sedimentary rocks and extremely low in metamorphic rocks. We can estimate the porosity if we know the volume of water, required to saturate the sample. But sometimes, it is difficult to do that (especially in tight clay samples, having tiny pores), so the alternative is using the next equation [2]:

$$n = 1 - \frac{\rho_b}{\rho_s} \tag{2.2}$$

Where ρ_b is the dry bulk density and ρ_s is the particle density.

The effective porosity [7] is the volume percentage of a rock or soil sample that has got interconnected pores where the water can flow. Effective porosity cannot overcome the total porosity. It is measured by the volume of fluid required to saturate a dry sample of known volume (it is done under a vacuum to avoid air).

The intrinsic permeability [7] shows the ability of a porous medium to transmit fluids. It is a property of the medium, independent of the fluid. The Darcy, a popular unit of permeability, is equal to 9.87 x 10^{-9} cm^2.

The Hydraulic conductivity [7] takes into account the permeability of the aquifer, as well as the fluid being transmitted through the aquifer. The equation for it is:

$$K = \frac{k\rho g}{\mu} \tag{2.3}$$

Where ρ is the density, g the acceleration of gravity (9.8 m/s^2) and μ is fluid viscosity (kg/ms). The hydraulic conductivity could be measured in the laboratory.

An aquifer with the hydraulic conductivity equal in all locations is a homogeneous aquifer. Although, when K is variable from one location to other, the aquifer is heterogeneous. In addition, a different term, isotropy, pertains to directional variability in the magnitude of K. Hence, isotropic condition means that the magnitude of K is equal in all directions. In an anisotropic aquifer, K changes with the direction. The vertical hydraulic conductivity is lower than the horizontal one. Fluids move more easily in the direction parallel to elongated grains. In contrast, horizontal and vertical hydraulic conductivity is nearly equal for spherical grains (we can find it in ancient beaches or dune deposits).

The transmissivity [7].This term is very similar to hydraulic conductivity. It quantifies the amount of water that can be transmitted horizontally through the saturated thickness of a unit. Transmissivity (T) is equal to the product of hydraulic conductivity (K) and saturated thickness (b).

$$T = Kb \tag{2.4}$$

The specific yield [7] is the volume of water drained by gravity and divided by the total volume of a saturated aquifer sample. The unit is $m^3_{water}/m^3_{saturated\ sample}$

The storage coefficient [7] is the volume of water released (ΔV), divided per unit area (A) of the aquifer and the variation of the hydraulic head (ΔH). The unit is m^3_{water}/m^2m.

$$S = \frac{\Delta V}{A \cdot \Delta H} \tag{2.4}$$

The storage coefficient of unconfined aquifers are similar to specific yield due to the water is released by gravity drainage. On the other side, confined aquifers released water by compression of aquifer solids and water expansion.

The springs [7] are specific points on the ground surface, where the groundwater seeps out at the land. They were very important years ago when the technologies were not as developed as nowadays. There are several types: depression, contact, fault, sinkhole, and joint, as we can see in Figure 5.

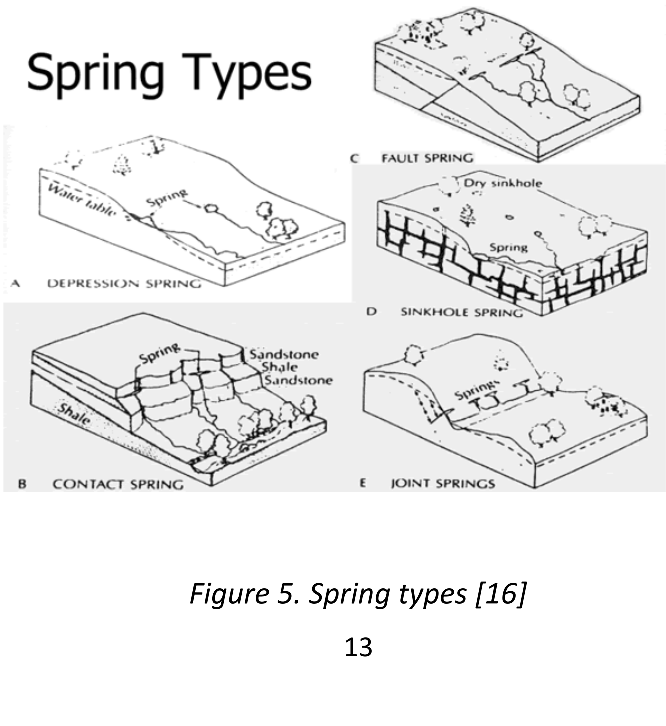

Figure 5. Spring types [16]

2.1.4. Chemical composition and conditions of the groundwater

The water is a universal solvent. It has the capacity to incorporate a high concentration of substances. The groundwater has got a bigger chance to dissolve more materials than the water of the surface, due to the contact with the geological formations where it moves; the presence of CO_2 and O_2 dissolved in the water and the slow water's movement. Hence, the groundwater has got a high concentration of substances.

The result of the composition of the groundwater comes from the next processes [8]:

- The evapo-concentration of atmospheric salts (comes from the water of the rain). Minerals such as calcite and feldspar are dissolved by low pH rainwater in the recharge area.
- The interaction between the water and the minerals of the soil.
- The incorporation of residual salts, because of the temperature, the weather, the terrain, etc.

Also, the human activity can modify the chemical composition of the groundwater with the introduction of solutes (nitrates, salts) and various substances, such as hydrocarbons. The presence of this substances can create an important degradation of the natural characteristics.

The higher concentration of the substances is in the ionic form. The most common ions in the groundwater are calcium, magnesium, sodium, and potassium, as well as the anions, such as bicarbonate, sulfate, and chloride. These substances are conditioned by the pH, the temperature and the concentration of oxygen in the water. The pH is between 6.5 and 8 [8]. The temperature of the groundwater in the top of the aquifer is more or less equal to the average temperature of the atmospheric temperatures of the site and the dissolved oxygen in the water is around 0 and 5 mg/l [8].

2.1.5. Groundwater flow

In this section, the flow of the groundwater is explained. It is very important to know how the water moves and is conducted to have a correct analysis of the aquifer.

Some of the physical properties previously explained and are going to be used are the hydraulic head, hydraulic conductivity, and effective porosity. These concepts control the flow of the groundwater, which generally moves in the direction of the steepest hydraulic gradient.

The hydraulic gradient in an aquifer between two points is the difference of the hydraulic head, divided by the distance between these points. One example of the calculation of the hydraulic gradient in Figure 6.

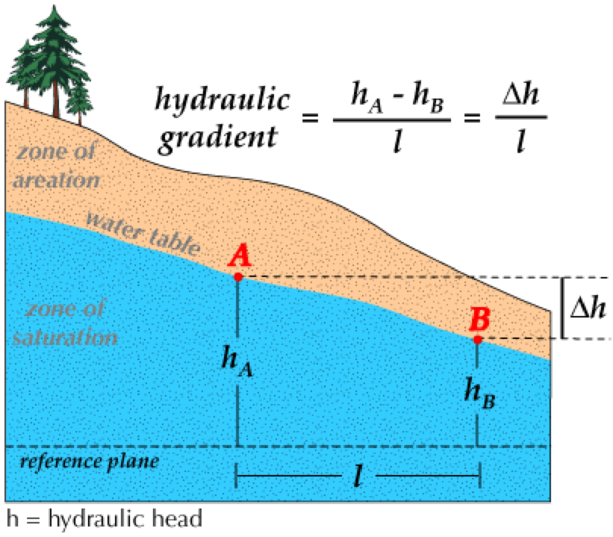

Figure 6. Hydraulic gradient [17]

The next question to explain is how can we determinate the flow direction. We need at least three piezometers to establish the local direction of horizontal flow. In the reality, the flow varies with the location, so more than three wells are necessary to characterize the different flow directions. An example to know a single direction is a three-point method.

The other concept to see is the groundwater velocity (v) [7]. To estimate it, we use the hydraulic gradient (i), the effective porosity (n_e) and the hydraulic conductivity (K). The velocity is defined by the next equation:

$$v = \frac{Ki}{n_e} \tag{2.5}$$

One of the most important principles that we are going to use in this study is the Darcy's Law [7][9]. For the explanation, we are going to refer to Figure 7. It expresses the average linear rate at which groundwater moves through an aquifer. The volumetric rate of flow *Q (m^3/s)* can be obtained by:

$$Q = kiA = k\frac{h_A - h_B}{L}A \tag{2.6}$$

Where k is a coefficient of permeability, which has got a direct relation with the characteristics of the soil; i is the hydraulic gradient and A is the cross-sectional area of the aquifer (including pores and soil).

It is important to know that greater k is, greater is the flow through the soil. The coefficient of permeability influences the water retaining capacity and stability of earth dams, as well as the capacity of pumping installations for the lowering of groundwater table during excavations. On the other side of the equivalence, we have the same constant (the coefficient of permeability) k; h_A is the height of the reference plane that reaches the water in a tube, placed at the entrance of the filter layer; h_B is the height point of the reference plane that reaches the water in a tube placed at the exit of the filter layer; and L is the total length of the sample. We can see this experiment in Figure 7. In the base of the energy relationships, the water moves from higher heights to lower heights. As we can see in Darcy's equation, this term $\frac{h_A - h_B}{L}$ is the hydraulic gradient. We can express it in the followig way q=$\frac{Q}{A} = \frac{\partial h}{\partial z}$, where h is the hydraulic gradient and z, the distance travelled. If we generalize the expression, we obtain $q = -k \cdot \nabla\big(h(x,y,z)\big)$, where k is the coefficient of permeability and the other term is a symmetric tensor diagonalizable to 3 main directions,

$$k = \begin{bmatrix} k_{xx}k_{xy}k_{xz} \\ k_{yx}k_{yy}k_{yz} \\ k_{zx}k_{zy}k_{zz} \end{bmatrix} \rightarrow \begin{bmatrix} k_{xx} & 0 & 0 \\ 0 & k_{yy} & 0 \\ 0 & 0 & k_{zz} \end{bmatrix}$$

The water will move in the direction which has more permeability, and at the same time, the direction will indicate the water's velocity in unit conditions of the gradient. In isotropic conditions, the three principal permeabilities will be the same.

The Darcy Law is only valid for saturated, continuous, homogeneous, isotropic soil; when the inertial forces are negligible (Re<1); and with slow, viscous flow.

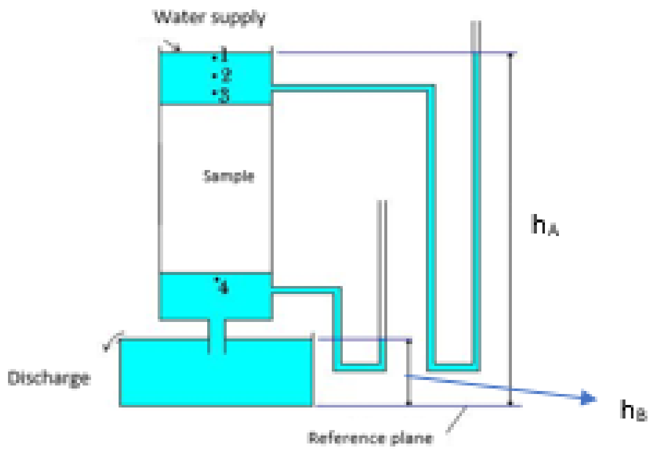

Figure 7. Darcy's experiment [9]

Another concept that it is going to be explained is the flow nets [7]. The flow nets show in a graphically form the steady-state groundwater flow in two dimensions. A flow net is formed by equipotential lines and flow lines. The equipotential lines connect points of equal hydraulic heads. The flow lines represent paths of the water molecules movement. In an isotropic aquifer, the groundwater flows in the direction of the steepest hydraulic gradient, and flow lines cross equipotential lines at right angles. In Figure 8 we can see an example of flow nets.

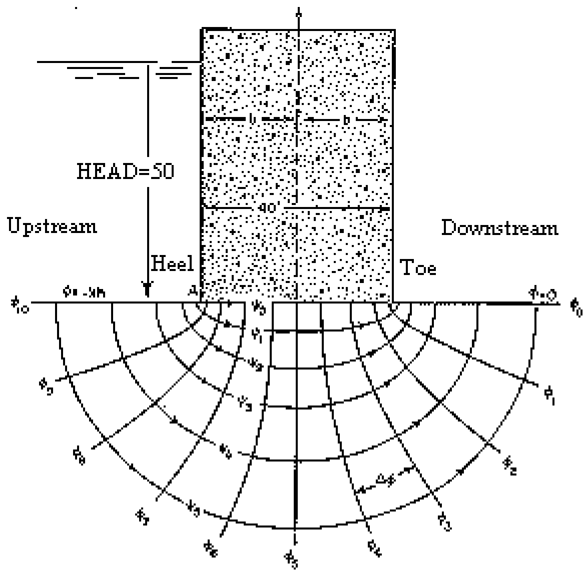

Figure 8. Flow nets [18]

The last concept that it is explained is the flow net boundaries [7] (it is a specific case of the flow nets, normally they are used in the upstream and downstream ends). They are the edges of flow nets. An arbitrary boundary is one, that does not coincide with any feature of a flow system. The hydraulic head is variable in this boundary. One example of this case is the water table, which pressure head is zero. On the other side, a constant hydraulic head boundary has a single hydraulic head value. One example of this case is the level of a regulated reservoir.

2.2. Description of the hydrological tool FREEWAT

FREEWAT (Free and open source software tools for WATer resource management) [4] is a project financed by the EU Commission under the call Water Innovation: Boosting its value for Europe. It is a computer program which is designed for the simulation of water quantity and quality in surface water and groundwater, with the help of an integrated water management and planning module.

FREEWAT has the main objective of promoting water resource management by simplifying the application of the Water Framework Directive and other EU water-related Directives; as well as, to coordinate and organize the water's management and the EU's researchers in one platform (FREEWAT).

FREEWAT groundwater flow modelling is based on a computer program called MODFLOW [10]. This programme is the base of FREEWAT and in the next chapters, we are going to see the principles of MODFLOW (that are the same for FREEWAT) to understand how it works.

2.2.1. Mathematical model and discretization convention

The next differential-partial equation defines a three-dimensional model of groundwater movement with a constant density, through a permeable material [10]:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) + W = S_s \frac{\partial h}{\partial t} \tag{2.7}$$

Where K_x, $K_{Y,}$ and K_Z are the permeability coefficient in the x, y and z coordinate axes (m/s); h the hydraulic potential (m); W is the volume flow per unit of volume represented by sources and sinks of water (1/s); S_S specific storage of permeable material (1/m); and t is time (s).

These terms (K_x, $K_{Y,}$ and K_Z) and S_S represent the functions of the space (S_S=S_S(x,y,z)) and W is a function of the space and time (W=W(x,y,z,t)). This equation is for groundwater flow without equilibrium conditions in a heterogeneous and anisotropic medium. An analytical solution of the above equation is often only possible for simple systems. If there are more demanding systems, an approximation must be used. And if there are more demanding systems, the final differences method is often employed. This system describes linear algebraic equations that give results for individual points at a given place and time.

In Figure 9*,* we can see a spatial discretization of an aquifer system into a network of cubes, which are called cells. The network is described in three directions, with rows, columns, and layers. In each cell, it exists a node that can be positioned at different points. In the case of equations of final differences, the node is located at the center of each point.

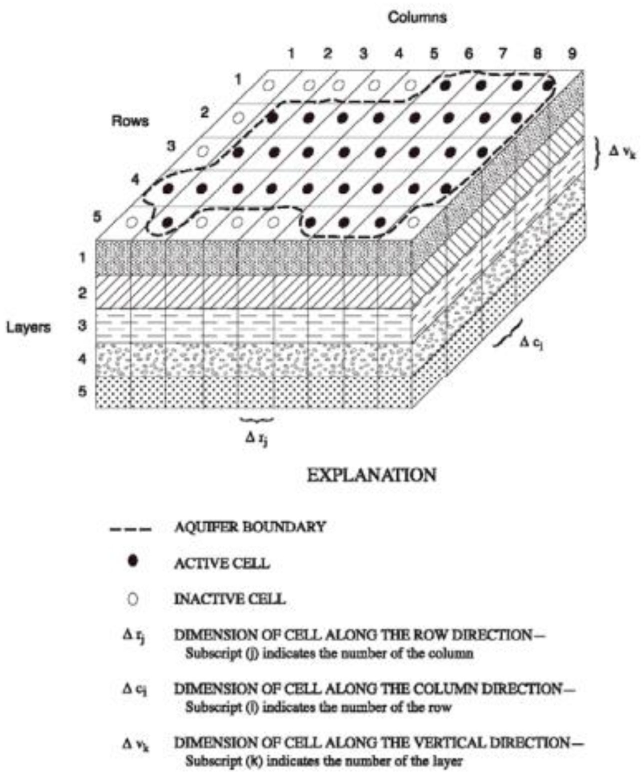

Figure 9. A discretized aquifer system [11]

2.2.2. Flow into a cell

Development of the groundwater flow equation under the assumption of constant density, the sum of the current in the cell and the current form must be the same, as the change in the cell's storage. The continuity equation expressing this balance of the water is,

$$\sum Q_i = S_S \frac{\Delta h}{\Delta t} \Delta V \tag{2.8}$$

Where Q_i is the flow rate in the cell (m^3/s), S_S is the volume of water that can be introduced into the aquifer material (1/m) and ΔV is the cell volume (m^3).

In general, the cells of the network are divided into two groups: one are cells with a constant value and others with varied value. But in steady-state, it is used the active and unactive cells.

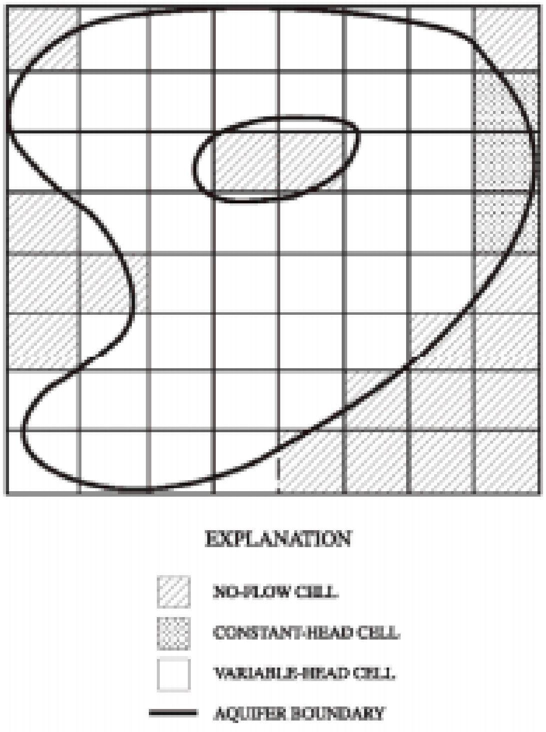

Figure 10. Cells designations [11]

2.2.3. Boundary condition packages

The FREEWAT software works as a complement of QGIS tool. It allows the processing of data bases of measurements or monitoring of groundwater, the preparation of input data and boundary conditions for the establishment of the desired mathematical model of groundwater and the presentation of the results obtained from the derived model. To build the model, the following somewhat more detailed software packages were taken into account:

WELL package

The MODFLOW WEL package simulates aquifer recharge or groundwater extraction by pumping or filling water from the aquifer through wells or similar systems shown in Figure 11. A positive or negative flow Q (m^3 / s) is defined per individual cell of the model through n periods of time [4].

The user must define in the network of the model the column, the line and the layer in which the hole is, for each period of time, and the amount of water filled or pumping Q. The negative values of Q indicate well the pump and the positive filling.

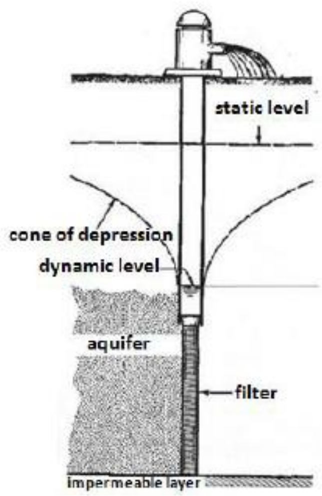

Figure 11: The relationship between the pumping well and the aquifer. [4]

RIV package

MODFLOW RIV package The river pack simulates water penetration between the river bed and the aquifer.

The equation that shows the current between the aquifer and the river at the n cell is:

$$Q = C^{RIV}{}_{n}(H^{RIV}{}_{n} - h_{i,j,k}) \quad (2.9)$$

Where the $C^{RIV}{}_{n}$ is the conductivity of the river bed material (m^2/s), the $H^{RIV}{}_{n}$ is the river stage (m), and the head at the node of the cell (m). The system is shown in Figure 12.

The $C^{RIV}{}_{n}$ or the permeability of the riverbed depends on the coefficient of permeability of the river bed and its geometry. It is calculated using the following equation:

$$C^{RIV}{}_{n} = K_n L_n W_n / M_n \quad (2.10)$$

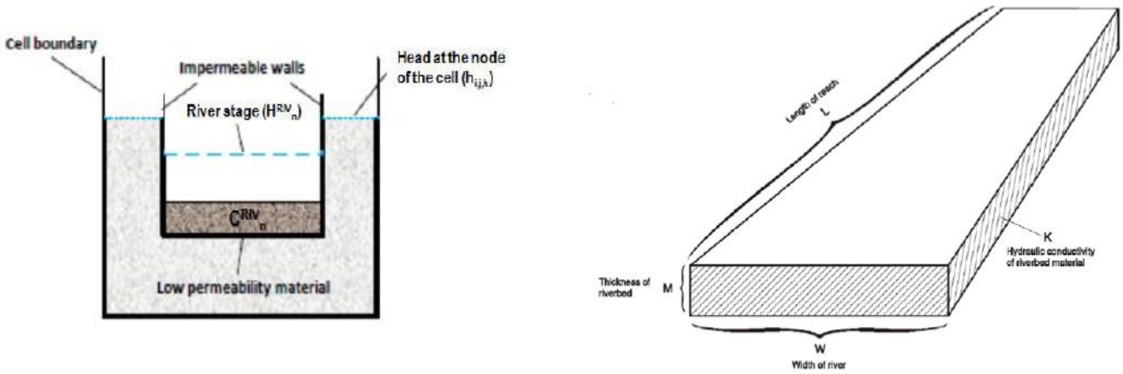

Figure 12. View RIV package model cell. [4]

RCH package

This package simulates areally-distributed direct recharge to groundwater, usually used for rainfall recharge.

It is necessary to determine the amount of charge over the desired territory (m/s). This flow is then multiplied within the model by the surface of each model cell in order to obtain a charging current in each cell, which then has a unit (m^3/s).

3. Groundwater modelling

Modelling is a very important tool to know the state of the water, as well as the water balance for its protection. In addition, a study can be made on the impact of certain activities through various simulations, such as a change in the pumping system or amount of water that can be extracted from them. With these simulations, the response of the groundwater system can be better understood with respect to external changes that can occur and be able to manage it. Groundwater modelling is a tool for protecting the environment.

3.1. Apace field

Apace field is a plain in the northwestern part of Slovenia. Bordered in the North by the river Mura, which represents the state border between the Republic of Slovenia and the Republic of Austria, and South with the foothills of Slovenske gorice.

Figure 13. Apace field

In this area, there is a local aquifer with large amounts of groundwater. The Apace aquifer represents a very important water resource for this country. In Slovenia, groundwater is the main source of drinking water supply, representing more than 90% [11].

Apace field is between 230 and 210 m high, with an area of 49 km^2[12]. The aquifer has a thickness ranging from 4 to 12 m and in the central part, it contains a depth that goes from 2.5 m at 3.5 m and is in direct contact with the river. For water management, the aquifer is divided into three zones that are protected. The current of the aquifer goes from the southwest part to the central zone of the field and then towards the northwest edge

A part of Apace's field groundwater is fed by rainfall, another part of the surrounding hills and by the Mura river. The nearby hills with internal flows contribute between 12 and 14 L/s per km, while the Mura River can contribute up to 8 L/s per km [11].

The area of modelling covers the Apace field, the city of Cmurek (which belongs to Austria) and borders the north along with the Mura river, and Slovenske gorice. The limits used were data obtained on the surveying website of the Slovenian Republic. We divided the area of the aquifer to 245,216 [11] cells whose size is 20 x 20 meters each and of which 115,890 are active (the rest are inactive cells and in the calculations are not taken into account).
In the modelling process, the coordinates of the terrain are the following X: 560 386; Y: 169 466 and in the northwest, X = 575905; Y = 175785.

The model is divided into one layer. The impermeable base was made from data from research wells and piezometers (found in the area). In areas where these studies cannot be carried out, the data is obtained by interpolation of adjacent measurements.

At the highest point, the impermeable base is at 226 meters above sea level. The height of the impermeable base is falling towards the south-east, until 202 meters. The thickness of the aquifer (between the impermeable layer and the surface) varies between 0.6 m to 15 m (in the widest wall).

On the other hand, the permeability coefficients (K) vary greatly, because the geological structure of Apace's terrain is very diverse. The geological structure on the slopes is composed of sand and gravel. The permeability coefficients are between $8.3 \cdot 10^{-3}$ and $-3.8 \cdot 10^{-3}$ m / s. The values of transmissivity in this zone vary between $1.52 \cdot 10^2$ and $8.9 \cdot 10^2$ m / s^2, although the latter transmissivity data are not necessary for the design of the computational model.

The computational model has some boundary conditions that are the following:

- Mura River (drainage and irrigation).
- Recharge of the aquifer with precipitation.
- The inlet of hinterland waters of Slovenske Gorice.
- Pumping water from Segovci and Podgrad.

The Mura River is modelled with the FREEWAT RIV (river) package. The package has the ability to connect the river and the aquifer because the water of the river can recharge the underground water. The Mura River is represented by a line between Cmurek and Gornja Radgona. In these two places, there are also hydrological measurement stations to obtain data and be able to put them in the program. The representation of Mura river with the RIV package includes 6426 [11] cells that reflect the path of the river (in Figure 14, we can see the path of the river and the green cells). For the operation of the package, it is necessary to know the coefficient of permeability of the lower part of the Mura River, where an approximate value of 0.0864 m^2/day was used since there are no studies or resources necessary to determine it exactly.
Using the coefficient of permeability, the package calculates the hydraulic conductivity according to the equation:

$$K = k\gamma / \mu \tag{3.1}$$

where k is the coefficient of permeability (m/s), γ is the density (kg/m^3), the viscosity μ (kg/ms) and K is the hydraulic conductivity (m/day).

In addition to the permeability, it is necessary to know the water level and altitude of the Mura River. The package only works when inserting the start and end data, the intermediate values are automatically interpolated within the package.

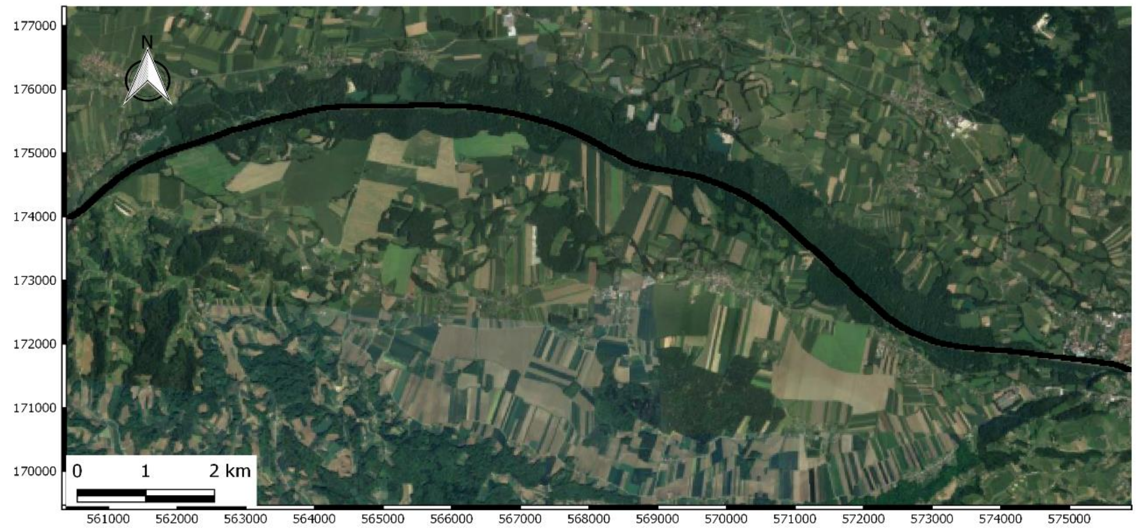

Figure 14. River Mura

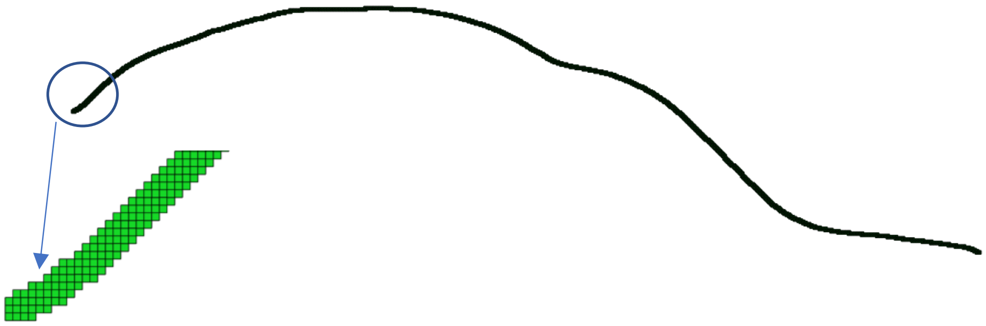

Figure 15. River in FREEWAT

The precipitation is modelled with the RCH package (recharge) in FREEWAT. The package includes 115,890 active cells that comprise the Apace field. The data used for this package has been obtained from the Gornja Radgona station (since there is no measuring station in the Apace field). The average precipitation in the Apace field is 937 mm of rain per year. The precipitation in the aquifer contributes around 8.9 l/s per km^2 of water. The maximum annual precipitation is 1213mm and minimum 514mm [19].

With the WELL package, the supply of the aquifer in the catchment area of Slovenske Gorice can be reflected. The calculation carried out in this package is based on the principle that the quantity of water that flows outside the catchment area, is then distributed in the cells at the southern end of the model. This is reflected with WELL cells located around the southern edge of the Apace field (we can see in Figure 13), on the slopes of Slovenske gorice. The package calculates the flow in the following way:

$$Q = Aic \tag{3.3}$$

Where Q is the flow from the drainage area (m^3/dan), A area (m^2), i amount of rainfall (mm/day) and c drainage coefficient that depends on the vegetation. The values that have been used to make the model are c of 0.15 [11], the precipitation value of 937 mm/day (it was taken by the Gornja Radgona station) and the size of the area is 10.13 km^2. The flow calculated with the equation previously exposed is distributed in the model through 1118 cells. The flow of a cell is 3.45 m^3/day and it is the same for each of them at the edge of the zone [11].

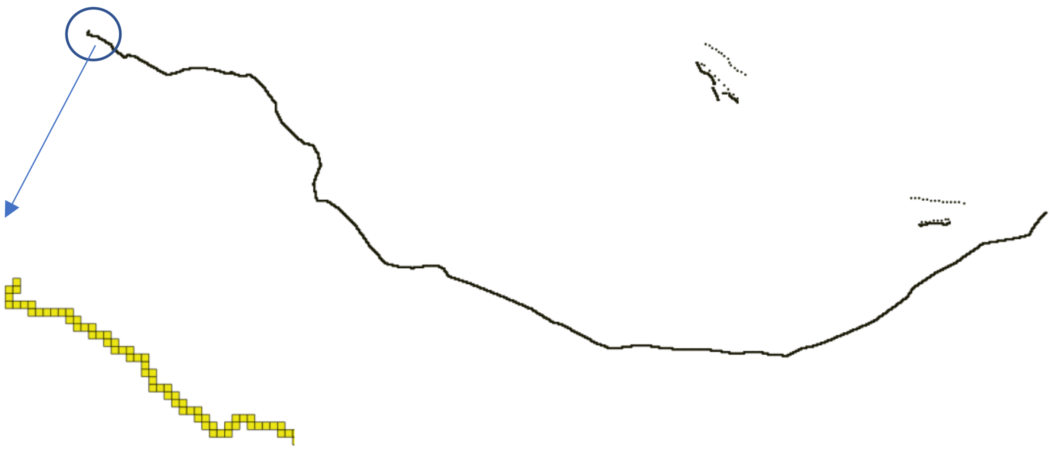

Figure 16. Representation of Slovenske Gorice in FREEWAT

The WELL package also includes the pumping of the two pumping stations, Segovci and Podgrad, with 140 active cells. The model works according to the equation:

$$\frac{Q_n}{Q_w} = \frac{T_n}{\Sigma T} \tag{3.4}$$

Where Qn is the pumping flow in a given layer (m^3 / s), Q_W total flow rate (m^3 / s), Tn permeability for a given layer (m^2 / s), ΣT sum of all permeability (m^2 / s). The Segovci pumping station consists of 14 wells along the Mura, which have the function of pumping or filling (artificial enrichment) of the aquifer, 9 pumping wells and an infiltration ditch to avoid contamination. The Podgrad pumping station has 14 pumping/drainage wells, 8 pumping wells, and an infiltration ditch. In the model, the amount of pumping or filling was constant at 50 l/s [11].

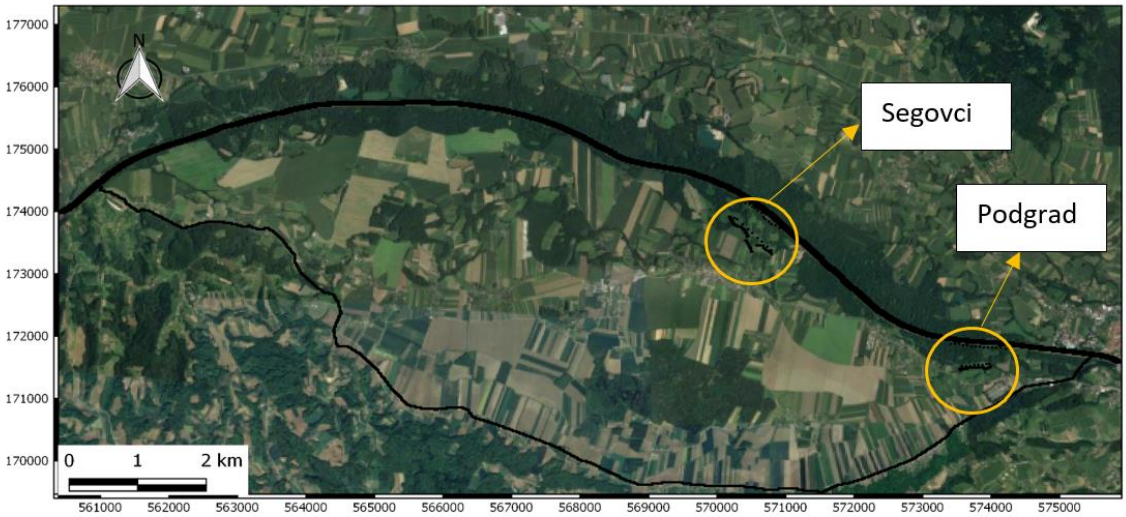

Figure 17. Podgrad and Segovci pumping station in FREEWAT

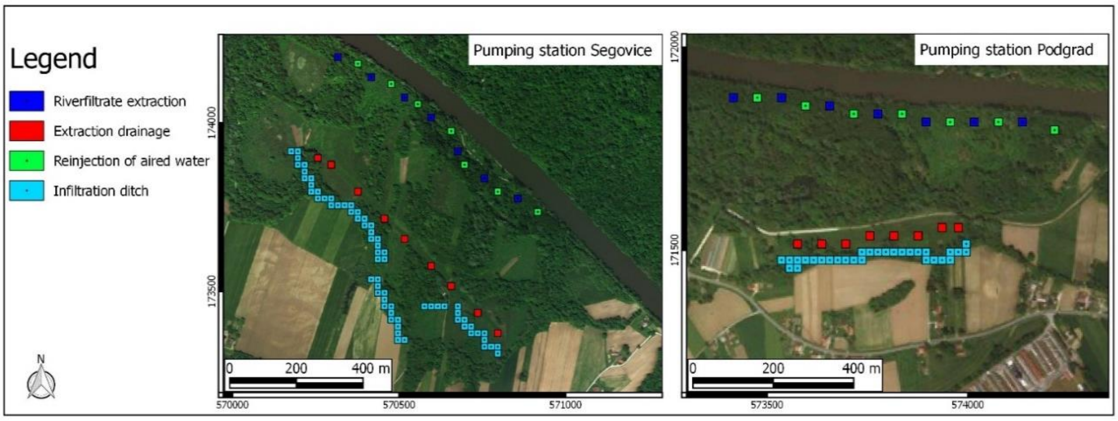

Figure 18. Pumping station Segovci and Podgrad

The scenarios that are going to be carried out are represented in Figure 19.

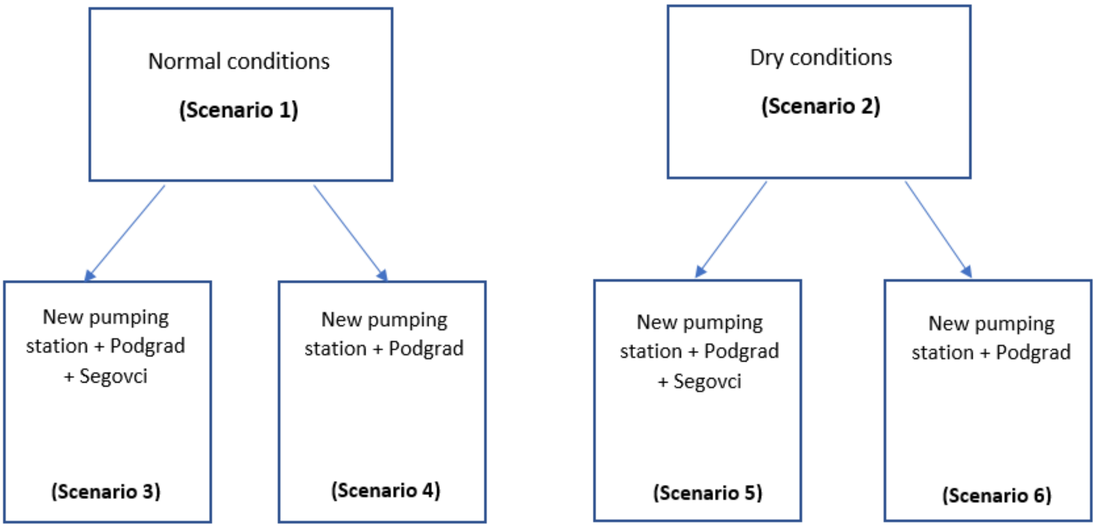

Figure 19. Presentation of the scenarios.

3.2. Scenario 1

Scenario 1, includes the simulation of the groundwater flow in Apace field with the included pumping stations (Segovci and Podgrad) that can also inject the groundwater, the river Mura that provides water to the aquifer and the hinterland waters of Slovenske gorice. The simulation considered yearly averaged precipitation values, pumping values and inflow values of the hinterland waters of Slovenske gorice.

A. Boundary conditions

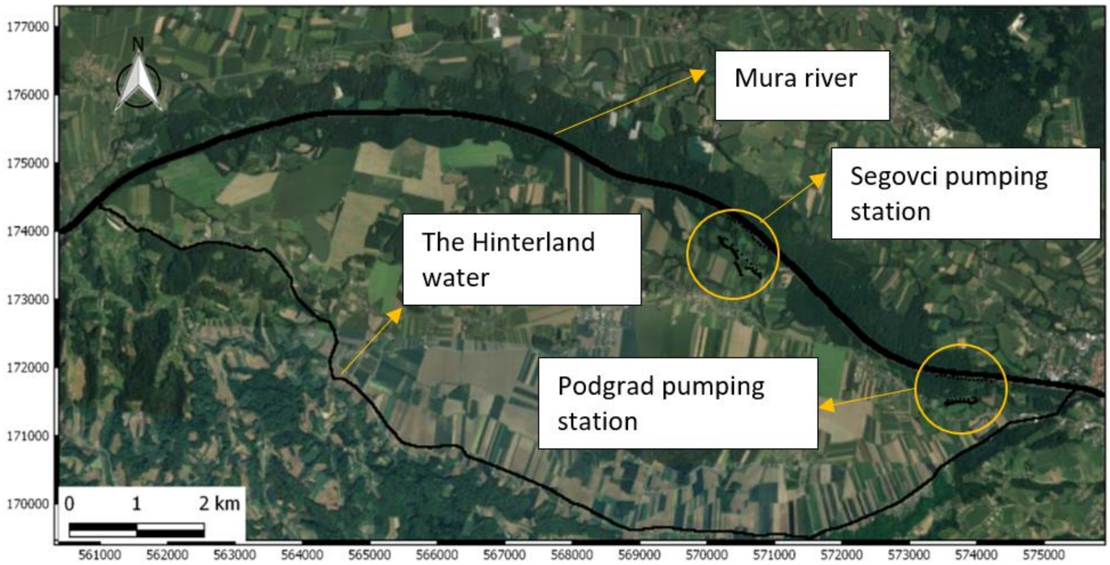

Figure 20. Apace field.

Each cell, representing the <u>hinterland water flow from Slovenske gorice</u>, has a flow rate of 3.45 $\frac{m^3}{day}$ base [11].

<u>Mura river </u>(In Figure 21 we could see the level of Mura river in m.a.s.l.)

Figure 21. Boundary conditions of Mura river

Precipitation

$$1.37\ 10^{-4}\frac{m}{day} \rightarrow 50\frac{mm}{year}$$

This data [11] is the calculated water balance in the area of Apace field, which means that it is the difference between precipitation and evapotranspiration. The water balance was calculated using the Thornthwaitu method, which uses the monthly average temperature, caloric index and precipitation values to calculate the water balance.

Calculations of the flow for Segovci and Podgrad pumping stations.

Scenario 1	Q (l/s)
Segovci	50
Podgrad	50

- Segovci: (Figure 18.)

- For the purple cells, seven of them extract 70 l/s (it is negative) from the Mura river and the other seven (in green colour) inject 20 l/s (it is positive). We have to change the units because FREEWAT uses m^3/day.

$$\frac{70\,\frac{\mathrm{l}}{\mathrm{s}}}{7\ \mathrm{wells}} = 10\,\frac{\mathrm{l}}{\mathrm{s}}\ (\text{each cell}) \rightarrow -864\ \frac{\mathrm{m}^3}{\mathrm{day}}(\text{each cell})$$

$$\frac{20\,\frac{\mathrm{l}}{\mathrm{s}}}{7\ \mathrm{wells}} = 2.86\,\frac{\mathrm{l}}{\mathrm{s}}\ (\text{each cell}) \rightarrow 247\ \frac{\mathrm{m}^3}{\mathrm{day}}(\text{each cell})$$

- For the blue cells, we have got the same total flow as the other ones (50 l/s) but the function of this cells is the recharge of the aquifer.

$$\frac{50\,\frac{\mathrm{l}}{\mathrm{s}}}{65\ \mathrm{wells}} = 0.77\,\frac{\mathrm{l}}{\mathrm{s}}\ (\text{each cell}) \rightarrow 66.5\ \frac{\mathrm{m}^3}{\mathrm{day}}(\text{each cell})$$

- For the red cells, we have also 50 l/s, but this water is extracted from the aquifer.

$$\frac{50\,\frac{\mathrm{l}}{\mathrm{s}}}{9\ \mathrm{wells}} = 5.56\,\frac{\mathrm{l}}{\mathrm{s}}\ (\text{each cell}) \rightarrow -480\ \frac{\mathrm{m}^3}{\mathrm{day}}(\text{each cell})$$

- Podgrad: (Figure 18.)

- For the purple cells, seven of them extract 70 l/s from the Mura river and the other seven (in green colour) inject 20 l/s. We have to change the units because FREEWAT uses m^3/day.

$$\frac{70\,\frac{\mathrm{l}}{\mathrm{s}}}{7\ \text{wells}} = 10\,\frac{\mathrm{l}}{\mathrm{s}}\ \text{(each cell)} \rightarrow -864\ \frac{\mathrm{m}^3}{\mathrm{day}}\,\text{(each cell)}$$

$$\frac{20\,\frac{\mathrm{l}}{\mathrm{s}}}{7\ \text{wells}} = 2.86\,\frac{\mathrm{l}}{\mathrm{s}}\ \text{(each cell)} \rightarrow 247\ \frac{\mathrm{m}^3}{\mathrm{day}}\,\text{(each cell)}$$

- For the blue cells, we have got the same total flow as the other ones (50 l/s) but the function of this cells is the recharge of the aquifer.

$$\frac{50\,\frac{\mathrm{l}}{\mathrm{s}}}{30\ \text{wells}} = 1.67\,\frac{\mathrm{l}}{\mathrm{s}}\ \text{(each cell)} \rightarrow 144\ \frac{\mathrm{m}^3}{\mathrm{day}}\,\text{(each cell)}$$

- For the red cells, we have also 50 l/s but this water is extracted from the aquifer.

$$\frac{50\,\frac{\mathrm{l}}{\mathrm{s}}}{8\ \text{wells}} = 6.25\,\frac{\mathrm{l}}{\mathrm{s}}\ \text{(each cell)} \rightarrow -540\ \frac{\mathrm{m}^3}{\mathrm{day}}\,\text{(each cell)}$$

B. Results

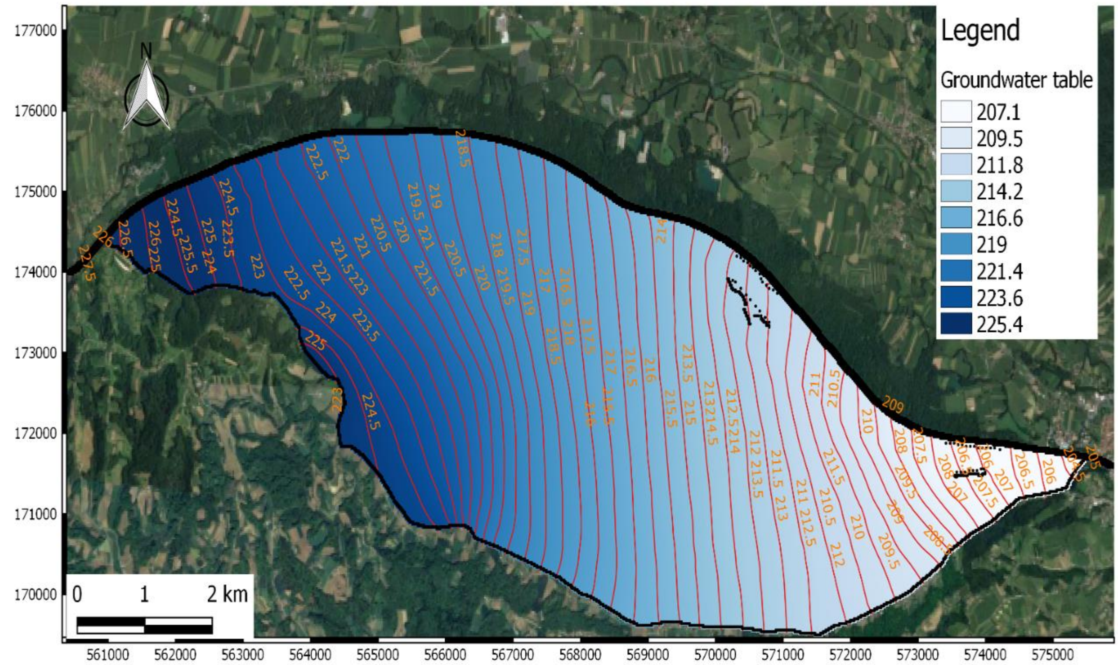

Figure 22. Results of scenario number 1

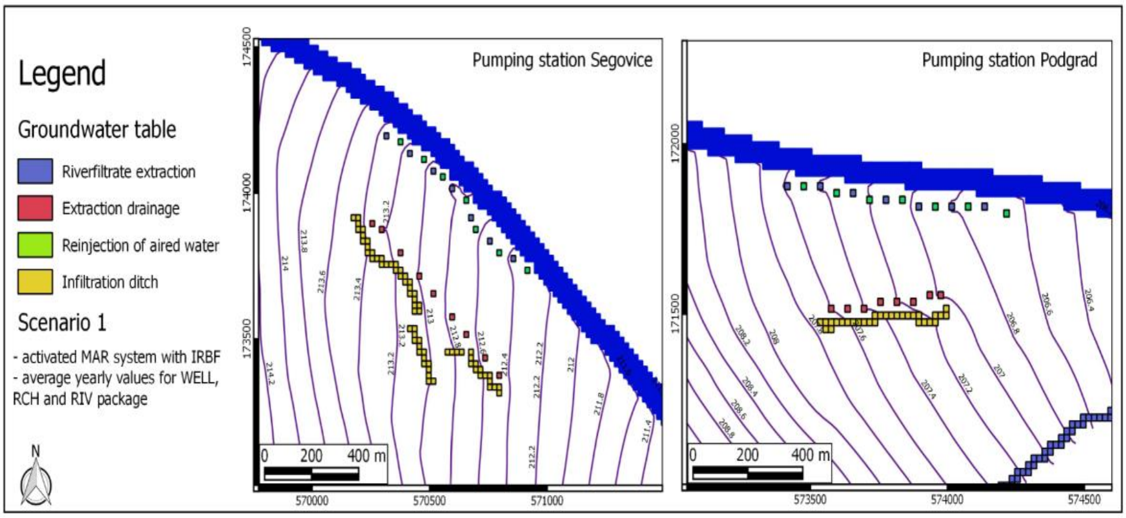

Figure 23. Results from Segovci and Podgrad

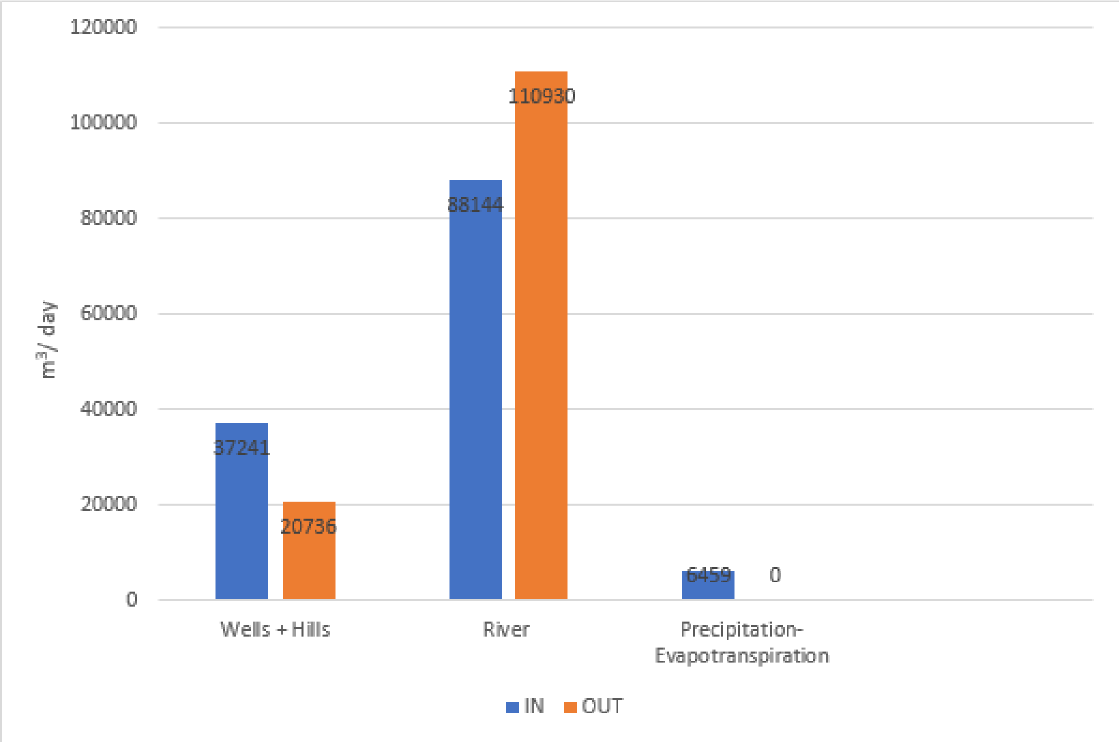

Diagram 1. Volumetric flow comparison the scenario 1

In Figure 22, we can see that the hydraulic contours have the values from 226.5 m to 205.5 m, for normal conditions. From the results of the groundwater model (Figure 22), we can see that most of the water comes from the river Mura and Hinterlands waters of Slovenske gorice. In Figure 23, we can observe that the lines are not straight, but they make a kind of curve next to the cells of the pumping wells and that is because of the extraction of water.

The report that we obtain in FREEWAT contains information about the model setting and the model balance of the simulated period. The model balance is presented in flow rates (m^3/day), which are represented in the diagrams of each scenario. In this diagrams, we can observe the inflow and the outflow of the river, the precipitation, the hills and the wells. The net inflow/outflow of groundwater to/from the domain is represented by the value IN-OUT. Since the mass conservation principle applies, this value must be as low as possible.

In addition, we obtain the results of the report in the graph below. As we can see, the river is very important to the recharge of the aquifer. Also, the wells and the recharge of the rain contributes to increasing the level of the aquifer.
If we see the part of the water balance's recharge, there are only flow(IN) because in normal conditions, the water balance is positive due to the precipitation in this months is higher than evapotranspiration. So there is only filtrated water that comes from the rain.

3.3. Scenario 2

Scenario 2, includes the simulation of the groundwater flow in Apace field in dry conditions. The simulation includes an increase of 10 % of the pumping quantities in the pumping stations of Segovci and Podgrad. The simulation of dry conditions foresees a decrease in the water level of river Mura by one meter. The flow of the hinterland waters from Slovenske gorice is decreased by half, with respect to the normal conditions (scenario 1). The precipitation value used is the average value for the months June, July and August.

A. Boundary conditions

Each cell, representing the hinterland water flow from Slovenske gorice, has a flow rate of 1.725 $\frac{m^3}{day}$.

Mura river (In the Figure 24 we could see the level of Mura river in m.a.s.l.)

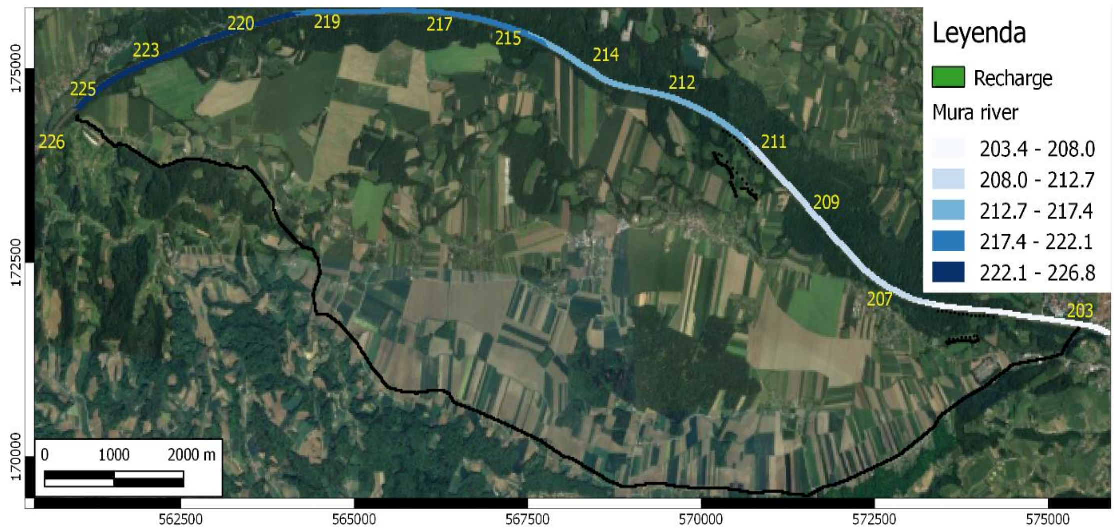

Figure 24. Boundary conditions of Mura river

Precipitation

$$-7.6\ 10^{-5}\ \frac{m}{day} \rightarrow -27.7\frac{mm}{year}$$

This data [11] is the calculated water balance in the area of Apace field, which means that it is the difference between precipitation and evapotranspiration. It is used as the input data for the RCH package. This balance is negative because in June, July and August the evapotranspiration is higher than the precipitation.

Calculations of the flow for Segovci and Podgrad pumping stations.

Scenario 2	Q (l/s)
Segovci	55
Podgrad	55

- Segovci: (Figure 18.)

- For the purple cells, seven of them extract 75 l/s) from the Mura river and the other seven (in green colour) inject 20 l/s. We have to change the units because FREEWAT uses m^3/day.

$$\frac{75\frac{\mathrm{l}}{\mathrm{s}}}{7\text{ wells}} = 10.71\frac{\mathrm{l}}{\mathrm{s}}\ (\text{each cell}) \rightarrow -925.71\ \frac{\mathrm{m}^3}{\mathrm{day}}(\text{each cell})$$

$$\frac{20\frac{\mathrm{l}}{\mathrm{s}}}{7\text{ wells}} = 2.86\frac{\mathrm{l}}{\mathrm{s}}\ (\text{each cell}) \rightarrow 247\ \frac{\mathrm{m}^3}{\mathrm{day}}(\text{each cell})$$

- For the blue cells, we have got the same total flow as the other ones (55 l/s) but the function of this cells is the recharge of the aquifer.

$$\frac{55\frac{\mathrm{l}}{\mathrm{s}}}{65\text{ wells}} = 0.85\frac{\mathrm{l}}{\mathrm{s}}\ (\text{each cell}) \rightarrow 73.15\ \frac{\mathrm{m}^3}{\mathrm{day}}(\text{each cell})$$

- For the red cells, we have also 55 l/s but this water is extracted from the aquifer.

$$\frac{55\frac{\mathrm{l}}{\mathrm{s}}}{9\text{ wells}} = 6.11\frac{\mathrm{l}}{\mathrm{s}}\ (\text{each cell}) \rightarrow -528\ \frac{\mathrm{m}^3}{\mathrm{day}}(\text{each cell})$$

- Podgrad: (Figure 18.)

- For the purple cells, seven of them extract 75 l/s from the Mura river and the other seven (in colour green) inject 20 l/s. We have to change the units because FREEWAT uses m^3/day.

$$\frac{75\frac{\mathrm{l}}{\mathrm{s}}}{7\text{ wells}} = 10.71\frac{\mathrm{l}}{\mathrm{s}}\ (\text{each cell}) \rightarrow -925.71\ \frac{\mathrm{m}^3}{\mathrm{day}}(\text{each cell})$$

$$\frac{20\frac{\mathrm{l}}{\mathrm{s}}}{7\text{ wells}} = 2.86\frac{\mathrm{l}}{\mathrm{s}}\ (\text{each cell}) \rightarrow 247\ \frac{\mathrm{m}^3}{\mathrm{day}}(\text{each cell})$$

- For the blue cells, we have got the same total flow as the other ones (55 l/s) but the function of this cells is the recharge of the aquifer.

$$\frac{55\,\frac{\mathrm{l}}{\mathrm{s}}}{30\text{ wells}} = 1.83\,\frac{\mathrm{l}}{\mathrm{s}}\ (\text{each cell}) \rightarrow 158.4\ \frac{\mathrm{m}^3}{\mathrm{day}}(\text{each cell})$$

- For the red cells, we have also 55 l/s but this water is extracted from the aquifer.

$$\frac{55\,\frac{\mathrm{l}}{\mathrm{s}}}{8\text{ wells}} = 6.875\,\frac{\mathrm{l}}{\mathrm{s}}\ (\text{each cell}) \rightarrow -594\ \frac{\mathrm{m}^3}{\mathrm{day}}(\text{each cell})$$

B. Results

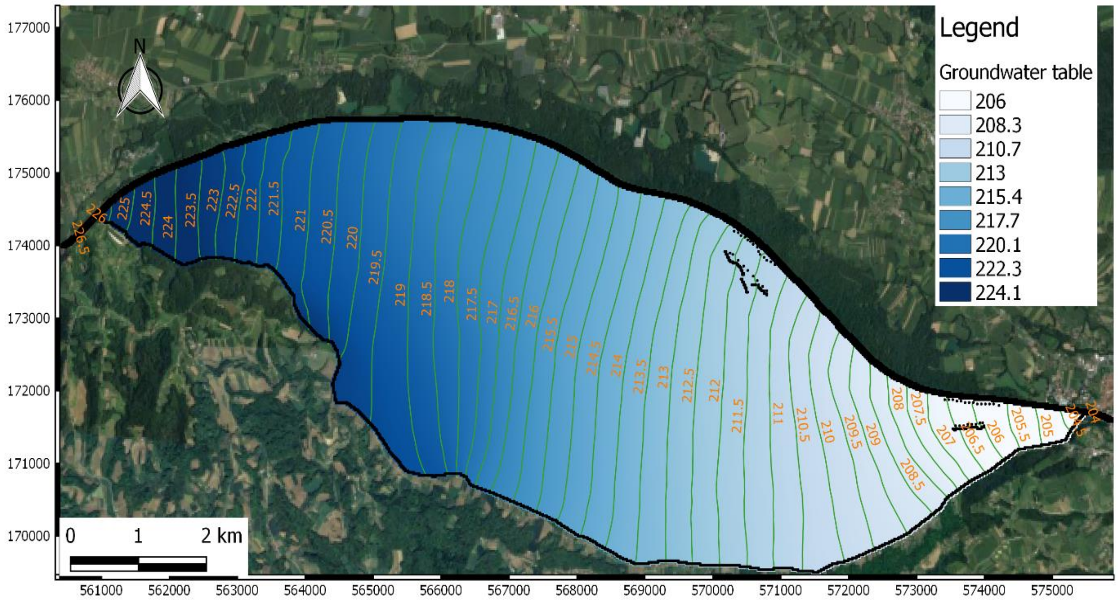

Figure 25. Results of scenario number 2

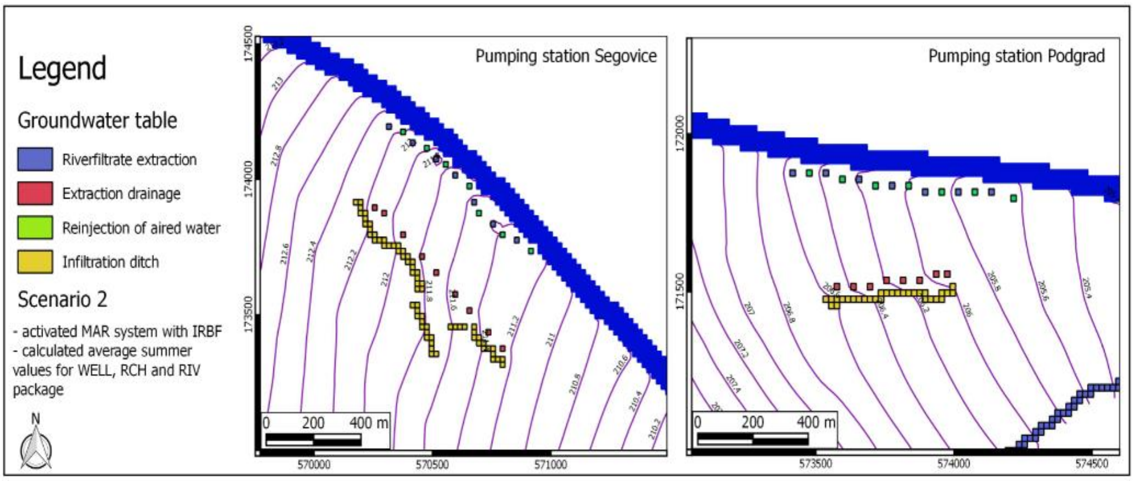

Figure 26. Results from Segovci and Podgrad

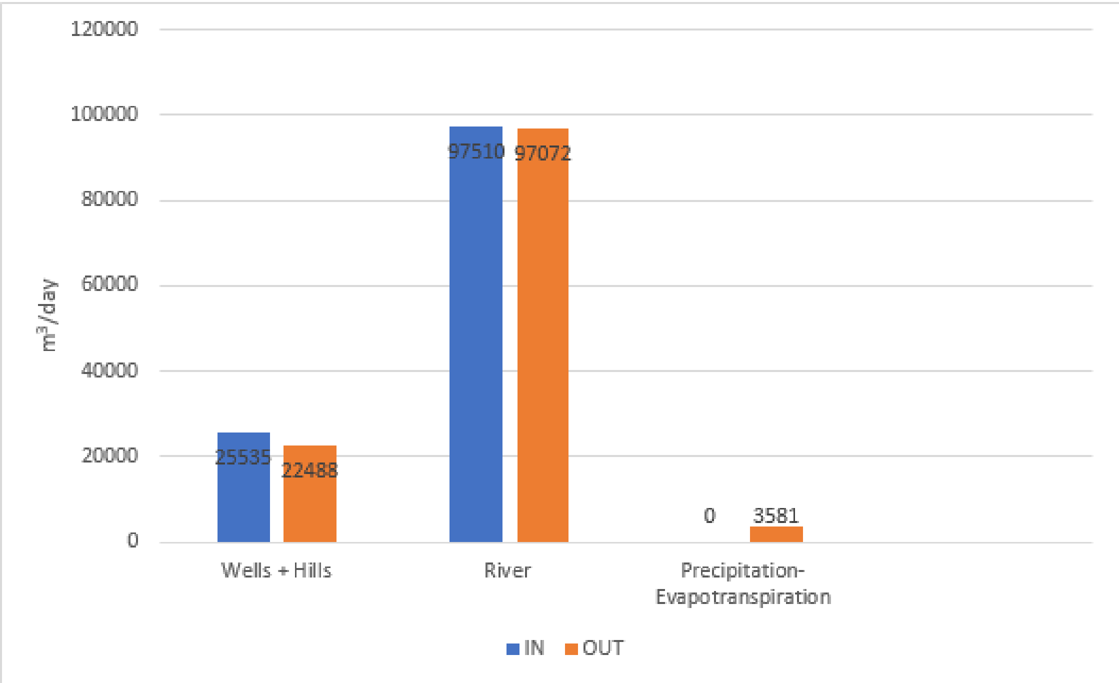

Diagram 2. Volumetric flow comparison for the scenario 2

In Figure 25, we can see that the hydraulic contours have the values from 226.5 m to 205.5 m, for dry conditions. From the results of the groundwater model (Figure 25) we can see that less water is coming from the Hinterlands waters. The contour lines have a new orientation. In addition, in Figure 26, we can observe that the lines are not straight, but they make a kind of curve next to the cells of the pumping wells and that is because of the extraction of water.

On the other hand, in the graph below, the values of extraction and drain are very similar in the wells and the river. Also, if we see the part of the water balance's recharge, there are only flow(OUT) because in dry conditions, the water balance is negative due to the evapotranspiration in summer are higher than precipitation. So there is only extracted water that comes from the aquifer.

3.4. Scenario 3

Scenario 3, includes the simulation of the groundwater flow in Apace field in normal conditions, but with a new pumping station. This simulation includes the pumping stations Segovci, Podgrad and a new pumping station planned in the northern area of Apace field. The input data for Mura river, the inflow from the hinterland waters of Slovenske gorice and the precipitation is the same as in scenario 1.

It has been decided to build a new pumping station, because of the possibility of increasing water consumption in that area (due to the increase in population), in addition to the fact, that the Segovci station does not work very well.

A. Boundary conditions

Each cell, representing the hinterland water flow from Slovenske gorice, has a flow rate of 3.45 $\frac{m^3}{day}$[11].

Mura river (In the Figure 21 we could see the level of Mura river in m.a.s.l.)

Precipitation

$$1.37\ 10^{-4}\frac{m}{day} \rightarrow 50\frac{mm}{year}$$

Flow for Segovci and Podgrad pumping stations (the same as the situation 1).

Scenario 3	Q (l/s)
Segovci	50
Podgrad	50

Flow for the new pumping station.

The pumping station is planned to be constructed in the northern part of Apace field, where the saturated thickness of the aquifer reaches it's maximum. The pumping station will be located between the edge of the forest and a clean surface, so we will not have to cut down trees that could generate environmental problems.

Scenario 3	Q(l/s)
New pumping well	20.83

In each cell, representing the newly constructed well, the pumping quantity is:

$$\frac{20.83\,\frac{\mathrm{l}}{\mathrm{s}}}{3\mathrm{wells}} = 6.94\,\frac{\mathrm{l}}{\mathrm{s}}\ (\text{each cell}) \rightarrow -600\ \frac{\mathrm{m}^3}{\mathrm{day}}(\text{each cell})$$

B. Results

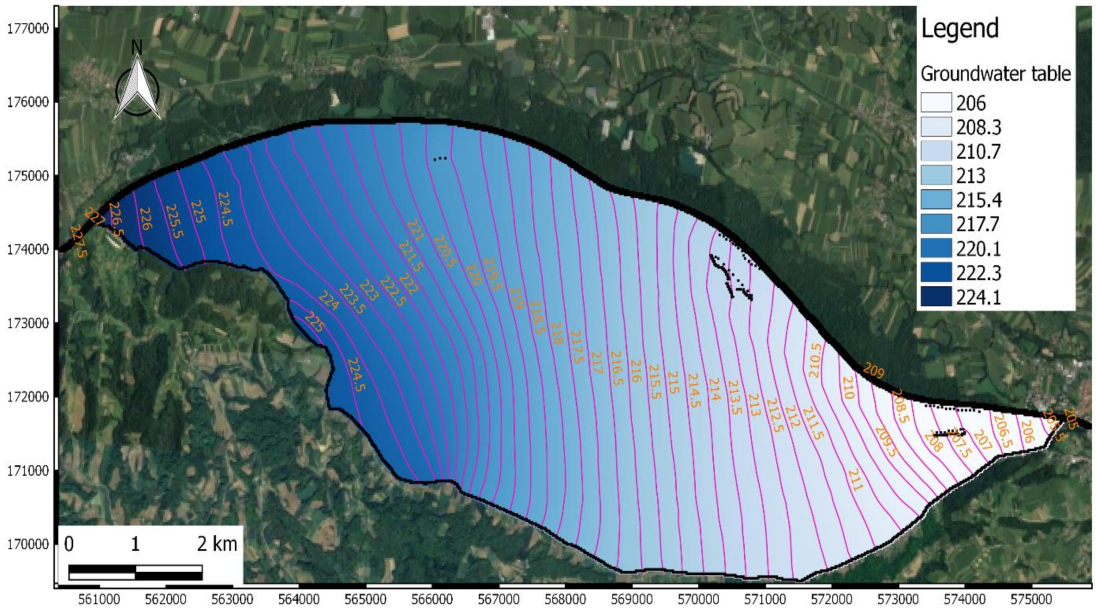

Figure 27. Results of scenario number 3

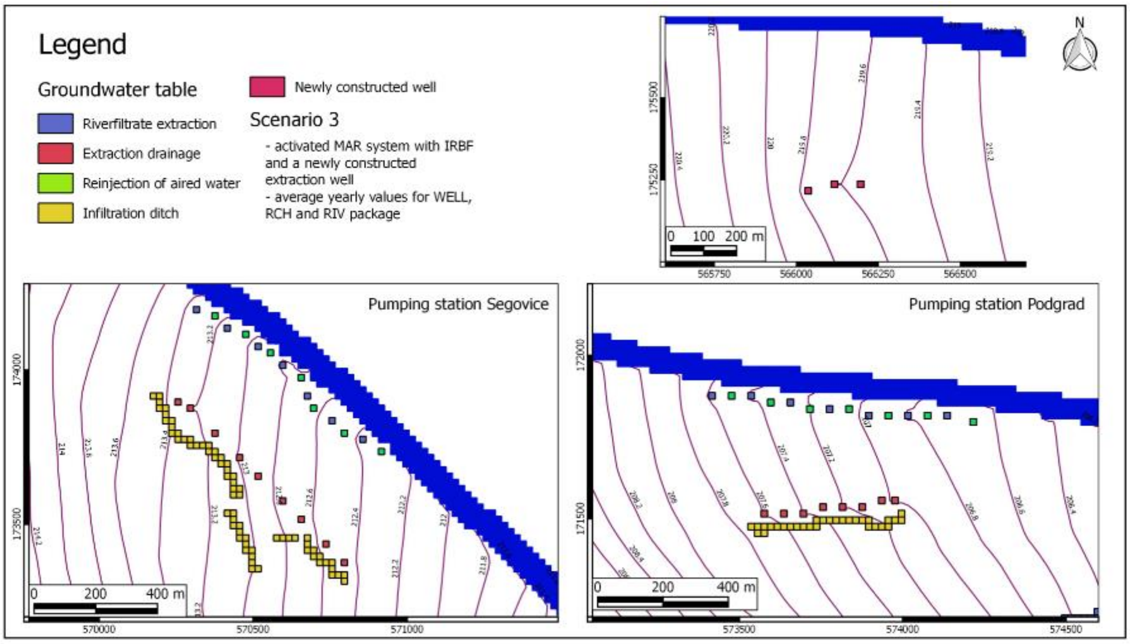

Figure 28. Results from the new pumping station, Segovci and Podgrad

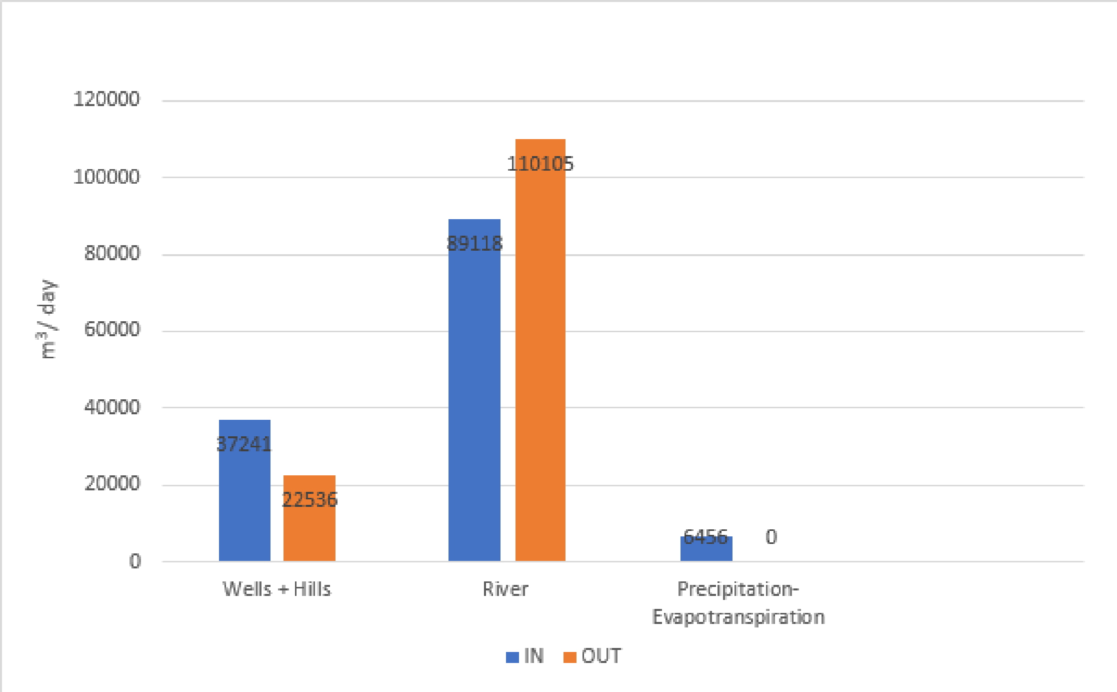

Diagram 3. Volumetric flow comparison for the scenario 3

In Figure 27, we can see that the hydraulic contours have the values from 226.5 m to 205.5 m, for normal conditions From the results of the groundwater model (Figure 27) we can still see that most of the water comes from the river Mura and Hinterlands waters of Slovenske gorice. In the Figure 28, we can observate that the lines are not straight, but they make a kind of curve next to the cells of the pumping wells and that is because of the extraction of water.

In the graph, we can observe the results of the simulation. There is more extracted water than the second simulation because of the new pumping station, but the balance is that there is more drained water than extracted, for the wells. Also, as we commented, in the normal conditions, the water balance is positive and there is only filtrated water, flow(IN).

3.5. Scenario 4

Scenario 4, includes the simulation of the groundwater flow in Apace field in normal conditions, but with only two operating pumping stations, the new pumping station and the pumping station Podgrad. It has been decided to take this situation, because the pumped water at the Podgrad pumping station has higher quality of water than Segovci. The scnenario foresees that the new pumping station will pump the same amount of water, as pumping station Segovci before.

$$50\ \frac{l}{s}\ \text{(Segovci)} + 50\ \frac{l}{s}\ \text{(Podgrad)} = 100\ \frac{l}{s}$$

A. Boundary conditions

Each cell, representing the hinterland water flow from Slovenske gorice, has a flow rate of 3.45 m^3/ day. It is a data base.

Mura river (In the Figure 21 we could see the level of Mura river in m.a.s.l.)

Precipitation

$$1.37\ 10^{-4}\frac{m}{day} \rightarrow 50\frac{mm}{year}$$

Flow for Podgrad pumping station (the same as in situation 1)

Scenario 4	Q (l/s)
Podgrad	50

Flow for the new pumping station.

Scenario 4	Q(l/s)
New pumping well	50

In each cell, representing the newly constructed well, the pumping quantity is:

$$\frac{50\frac{\mathrm{l}}{\mathrm{s}}}{3\mathrm{wells}} = 16.67\frac{\mathrm{l}}{\mathrm{s}}\ \text{(each cell)} \rightarrow -1440\ \frac{\mathrm{m}^3}{\mathrm{day}}\text{(each cell)}$$

B. Results

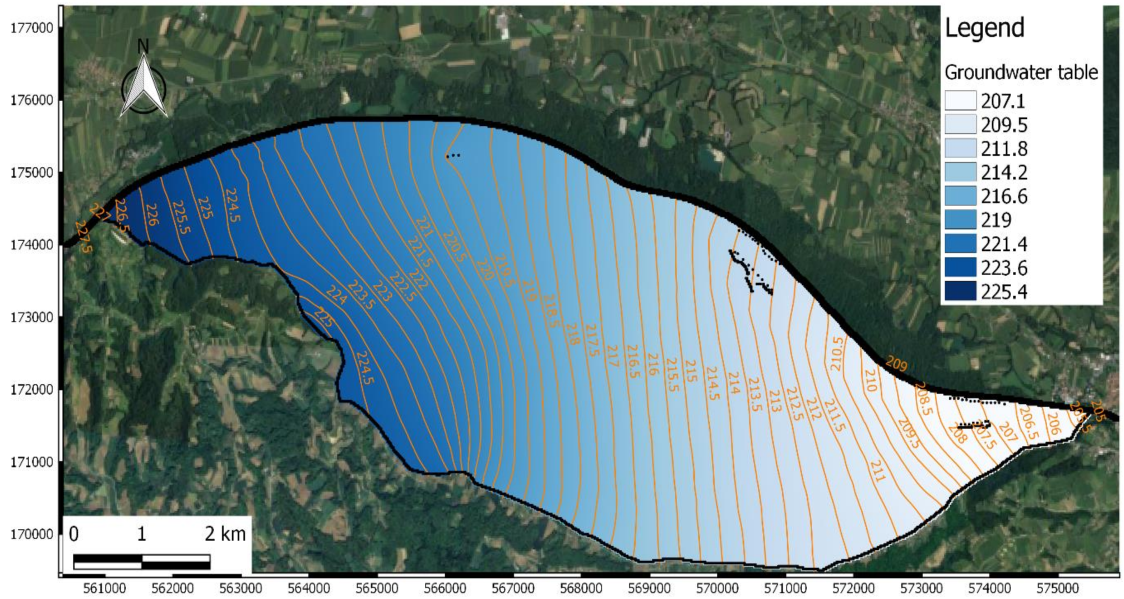

Figure 29 . Results of scenario number 4

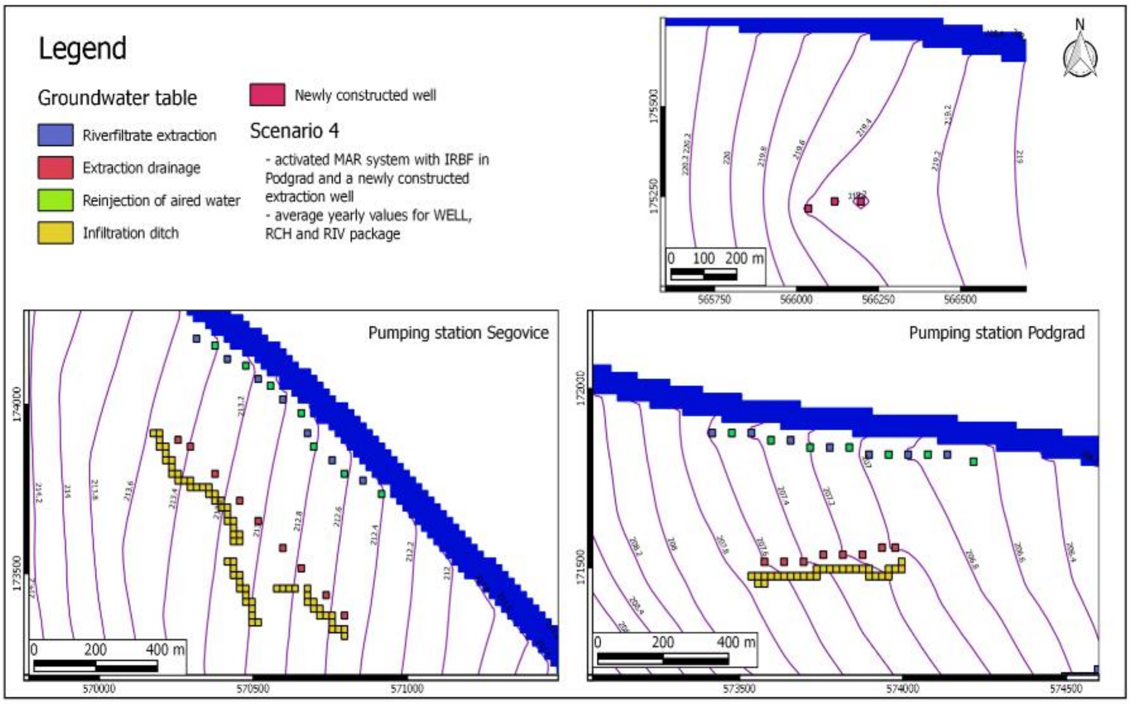

Figure 30. Results from the new pumping station, Segovci and Podgrad

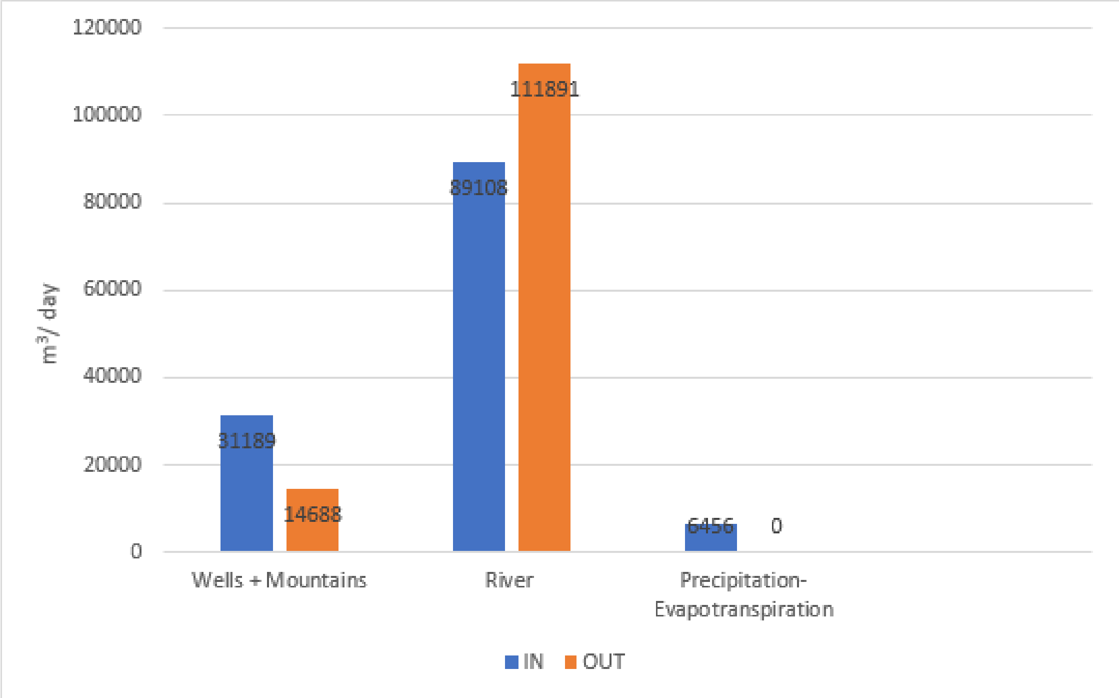

Diagram 4. Volumetric flow comparison for the scenario 4

In Figure 29, we can see that the hydaulic countours have the values from 226.5 m to 205.5 m, for normal conditions. From the results of the groundwater model (Figure 29) we can see that most of the water comes from the river Mura and Hinterlands waters of Slovenske gorice. In Figure 30 we can observate that the lines are not straight, but they make a kind of curve next to the cells only in the new pumping station and Podgrad because of the extraction of water. On the other side, for Segovci the lines are straight, because the pumping station doesn't operate.

In the results of the simulation, we obtain that there is less water extraction from the wells (if we compare with the situation of the three working pumping stations). As the other situation, there is only flow(IN) for the water balance because, in the normal conditions, we have a positive balance. In addition, the recharge of the river is very important, but there is more extracted water than drained.

3.6. Scenario 5

Scenario 5, , includes the simulation of the groundwater flow in Apace field in dry conditions, but with a new pumping. It means, that the new pumping station works with Podgrad and Segovci but with dry conditions: 10% increase of pumping quantity in each pumping station. The simulation of dry conditions foresees a decrease in the water level of river Mura by one meter. The flow of the hinterland waters from Slovenske gorice is decreased by half, with respect to the normal conditions (scenario 1). The precipitation value used is the average value of the months June, July and August.

A. Boundary conditions

Each cell, representing the hinterland water flow from Slovenske gorice, has a flow rate of $1.725\,\frac{m^3}{day}$.

Mura river (In the Figure 24 we could see the level of Mura river in m.a.s.l.)

Precipitation

$$-7.6\;10^{-5}\;\frac{m}{day} \rightarrow -27.7\,\frac{mm}{year}$$

Flow for Segovci and Podgrad pumping stations

Scenario 5	Q (l/s)
Segovci	55
Podgrad	55

Flow for the new pumping station.

Scenario 5	Q(l/s)
New pumping well	22.91

In each cell, representing the newly constructed well, the pumping quantity is:

$$\frac{22.91\,\frac{\mathrm{l}}{\mathrm{s}}}{3\mathrm{wells}} = 7.64\,\frac{\mathrm{l}}{\mathrm{s}}\;(\text{each cell}) \rightarrow -660\;\frac{\mathrm{m}^3}{\mathrm{day}}(\text{each cell})$$

B. Results

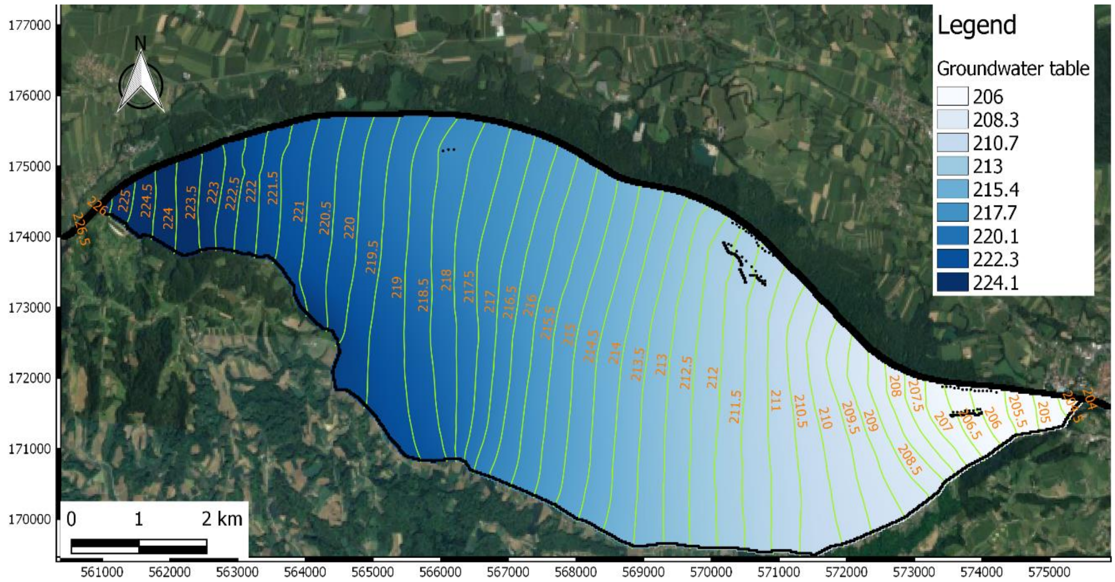

Figure 31. Results of scenario number 5

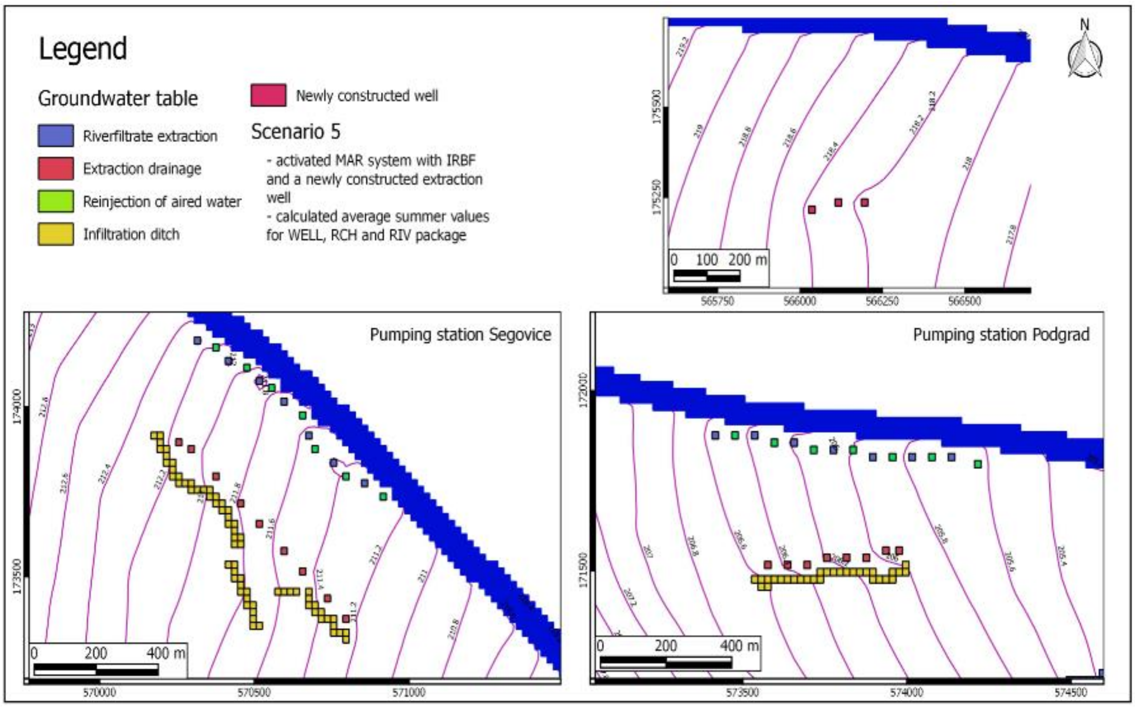

Figure 32. Results from the new pumping station, Segovci and Podgrad

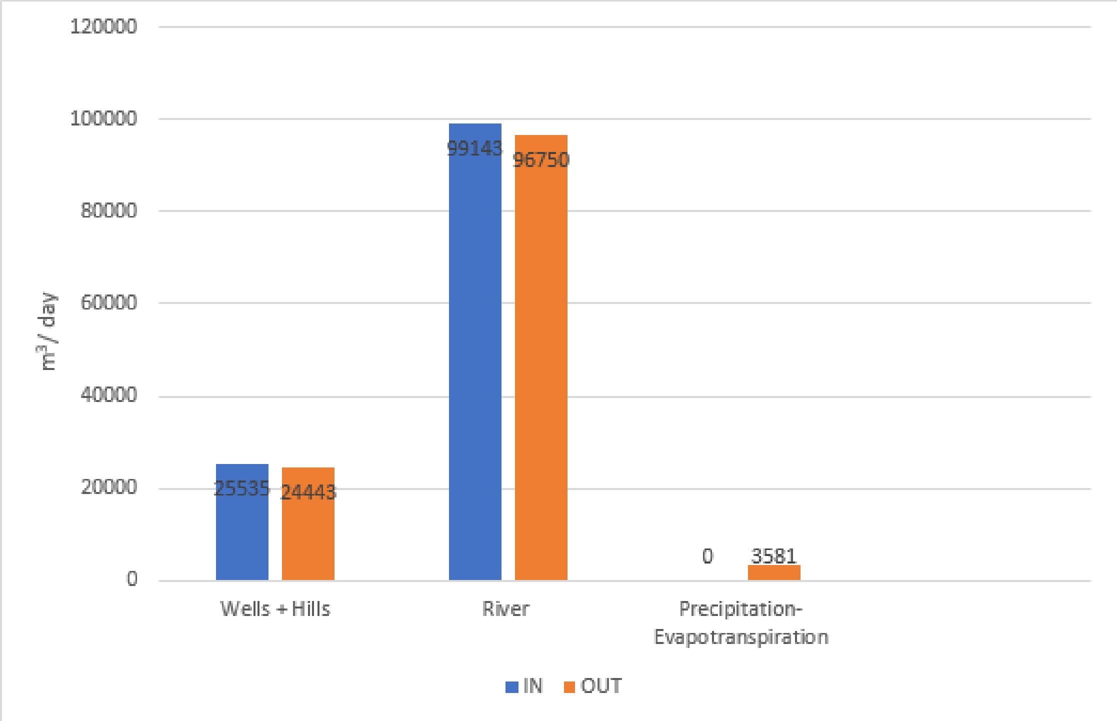

Diagram 5. Volumetric flow comparison for the scenario 5

In Figure 31, we can see that the hydaulic countours have the values from 226.5 m to 205.5 m, for dry conditions. From the results of the groundwater model (Figure 31) we can see that less of the water comes Hinterlands waters of Slovenske gorice than in Scenario 3. In the Figure 32 we can observate that the lines are not straight, but they make a kind of curve next to the cells the pumping statios because of the extraction of water.

In Diagram 5, we can see that we are in dry conditions and that's why there is more flow out (due to the evapotranspiration is higher than the precipitation, having a negative water balance) and the program extracted water from the aquifer due to this fact. Also, we can observe that there are less difference between drained and extracted water for the wells and the river (if we compare with the normal conditions).

3.7. Scenario 6

Scenario 6, includes the simulation of the groundwater flow in Apace field in dry conditions, but with only two operating pumping stations, the new pumping station and the pumping station Podgrad. The scenario 6 is an addition to the scenario 4.
The scnenario foresees that the new pumping station will pump the same amount of water, as pumping station Segovci before.

A. Boundary conditions

Each cell, representing the hinterland water flow from Slovenske gorice, has a flow rate of 1.725 $\frac{m^3}{day}$.

Mura river (In Figure 24 we could see the level of Mura river in m.a.s.l.)

Precipitation

$$-7.6\ 10^{-5}\ \frac{m}{day} \rightarrow -27.7\frac{mm}{year}$$

Flow for Podgrad pumping station.

Scenario 6	Q (l/s)
Podgrad	55

Flow for the new pumping station.

Scenario 6	Q(l/s)
New pumping well	55

In each cell, representing the newly constructed well, the pumping quantity is:

$$\frac{55\,\frac{\mathrm{l}}{\mathrm{s}}}{3\mathrm{wells}} = 18.33\,\frac{\mathrm{l}}{\mathrm{s}}\ (\text{each cell}) \rightarrow -1584\ \frac{\mathrm{m}^3}{\mathrm{day}}(\text{each cell})$$

B. Results

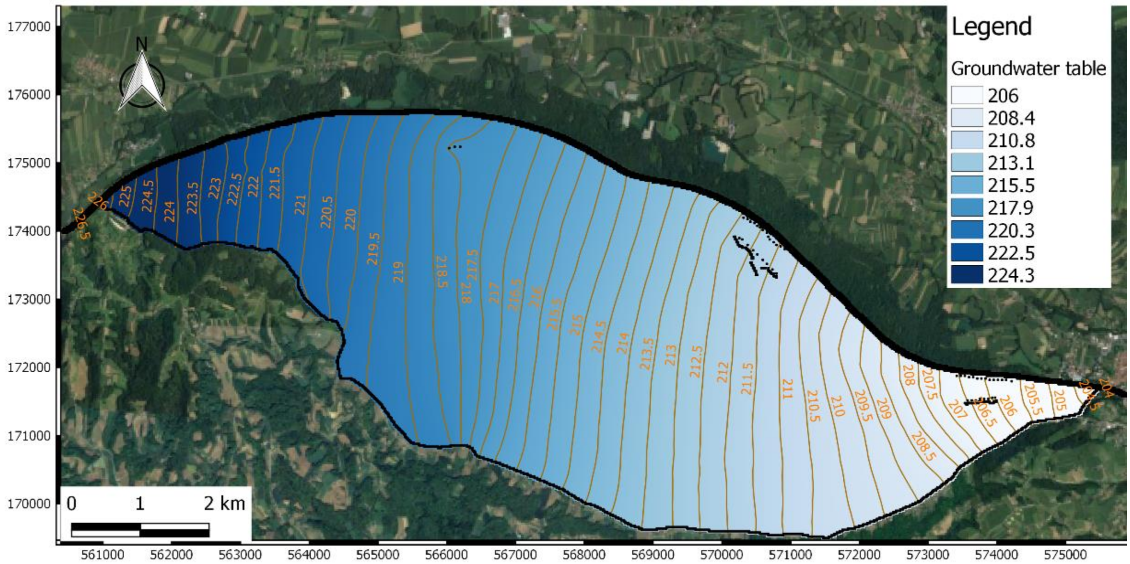

Figure 33. Results of scenario number 6

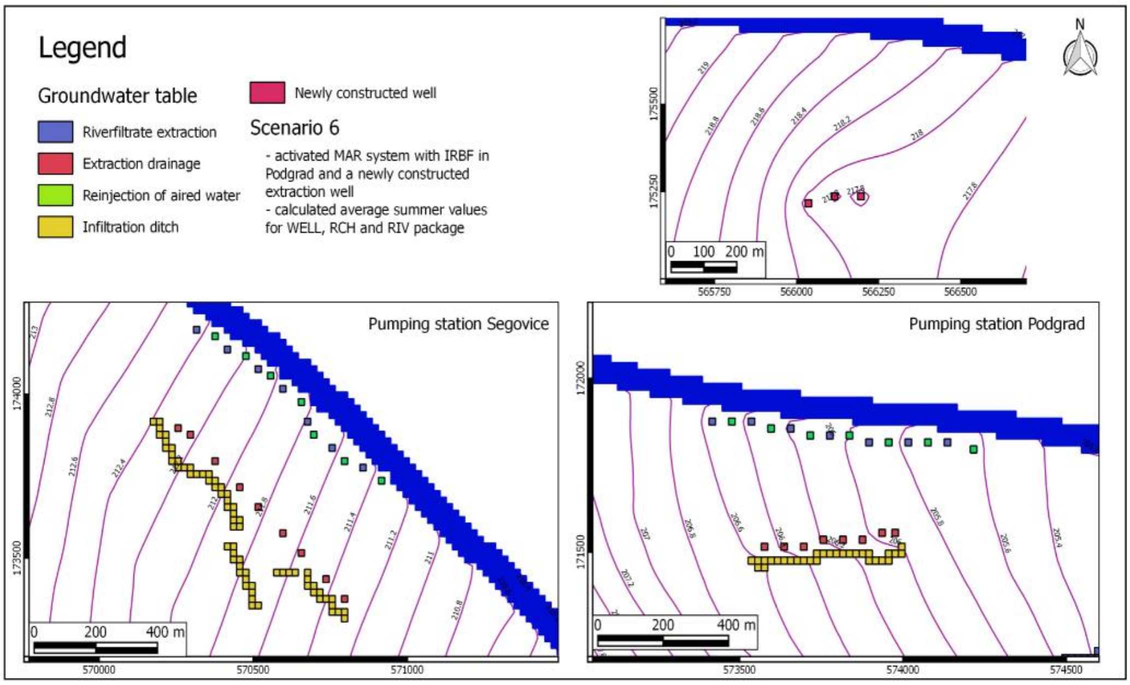

Figure 34. Results from the new pumping station, Segovci and Podgrad

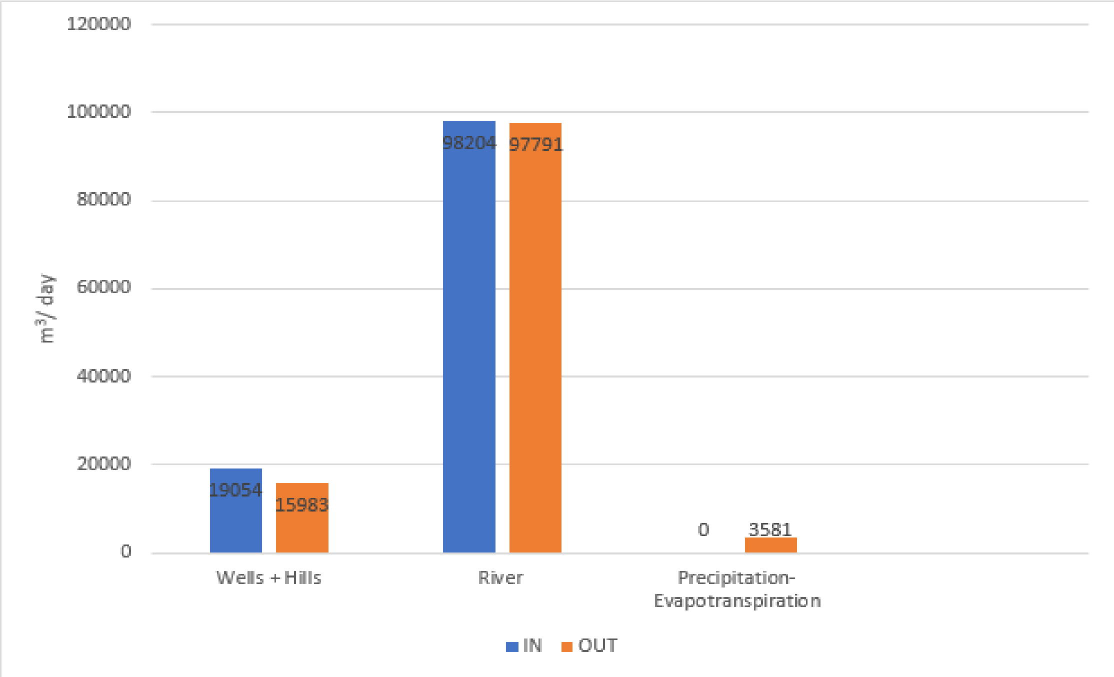

Diagram 6. Volumetric flow comparison for the scenario 6

In Figure 33 we can see that the hydaulic countours have the values from 226.5 m to 205.5 m, for dry conditions. From the results of the groundwater model (Figure 33) we can see that less of the water comes from the hinterland waters of Slovenske gorice than in scenario 4. In Figure 34 we can observate that the lines are not straight, but they make a kind of curve next to the cells the pumping statios because of the extraction of water.

In the results of the simulation (Diagram 6), we observe the consequences of dry conditions that means a water balance negative. So, the evapotranspiration is higher than precipitation and the total effect is the extraction of water from the aquifer. By only working two pumping stations, the extraction of water is less than in the other scenarios. The only thing in common is the importance of the recharge from the river Mura.

4. Results comparison

- **Comparison scenario 1 with 2**

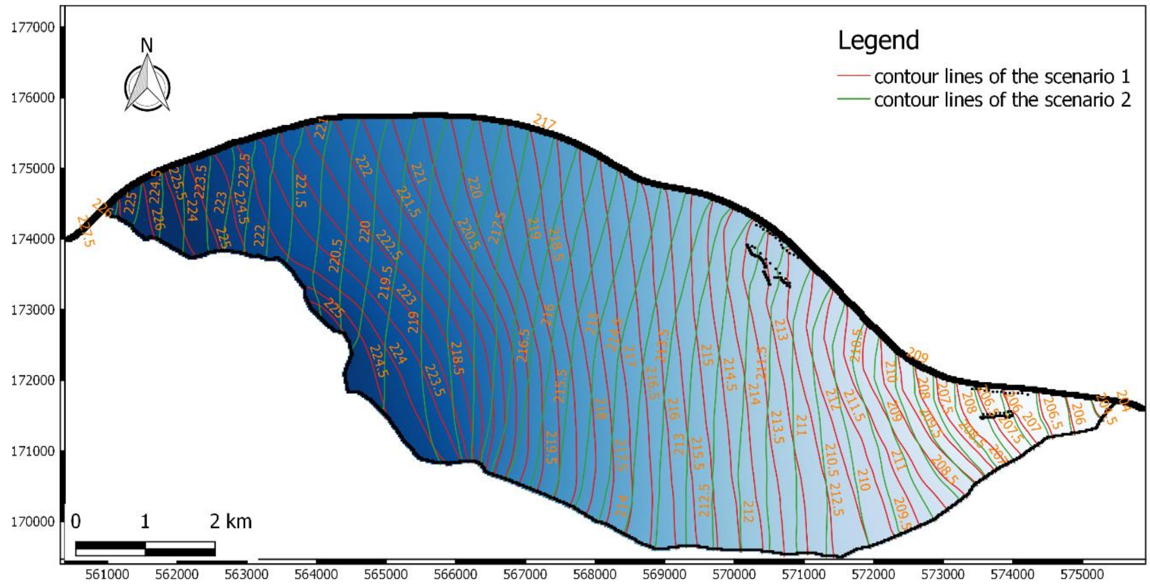

Figure 35. Comparison of the results between scenario 1 and 2

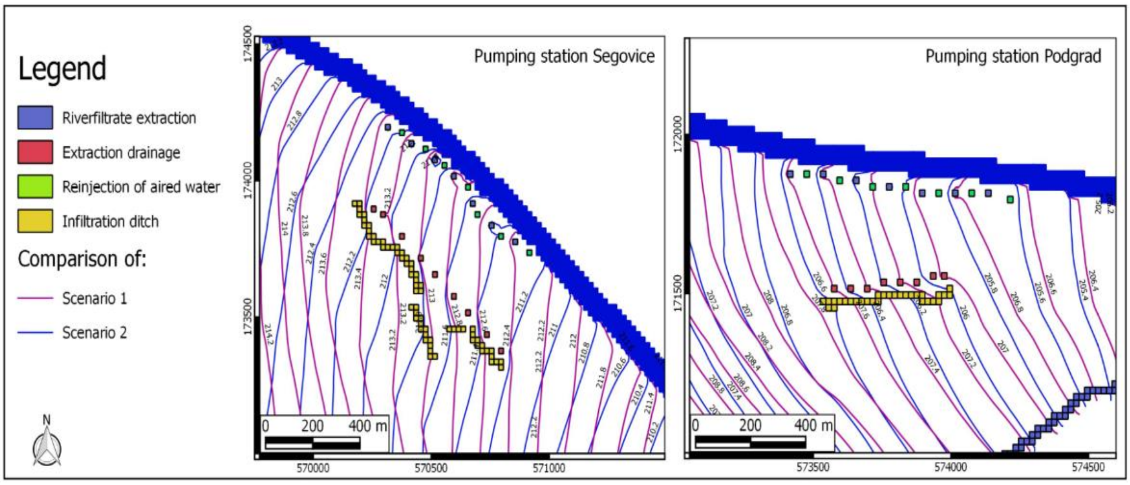

Figure 36. Comparison of the results between scenario 1 and 2 of the pumping areas

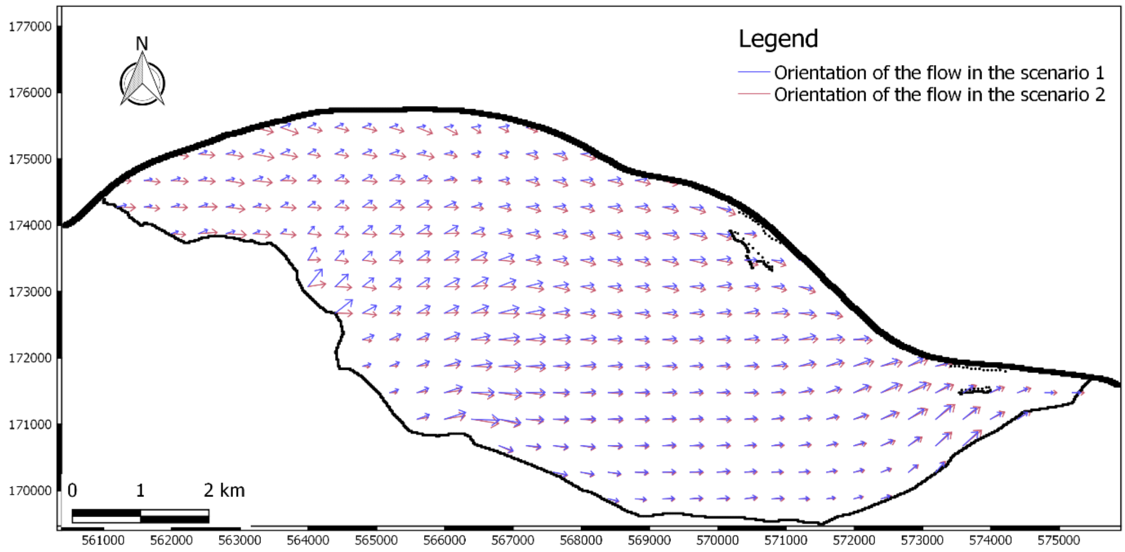

Figure 37. Groundwater orientation flow

In Figures 35 and 36, we can see the great difference that exists between the normal conditions (scenario 1 (red contour lines)) and the dry conditions (scenario 2 (green contour lines)). In scenario 1, the orientation of the flow (Figure 37) goes from the mountains to the northwest. This is due to the increase flow from the mountains to the aquifer. On the other hand, in scenario 2 the flow goes from east to west, due to the drought and the decrease in the inflow of hinterland waters from Slovenske gorice. Also if we observe, the water level drops by one meter. This is a big difference that should be taken into account. This is due to the fact that the water level of the Mura River has dropped by one meter and that, being a dry season, the population uses more water for their daily uses in addition to the need for agriculture. On the other hand, you can also observe that water level drop in the pumping areas.

- **Comparison scenario 1 with 3**

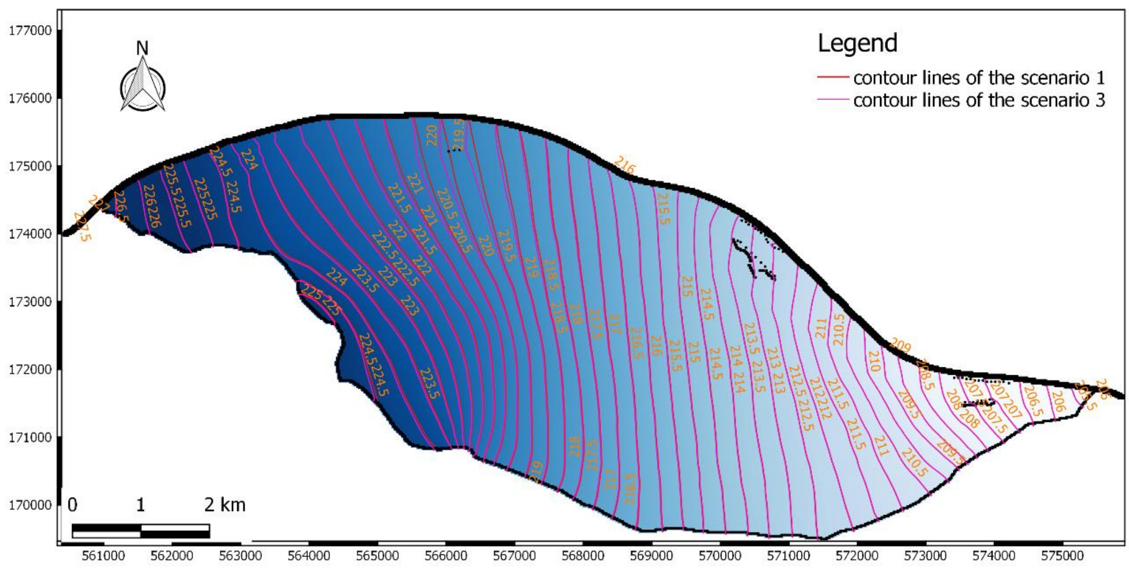

Figure 38. Comparison of the results between scenario 1 and 3

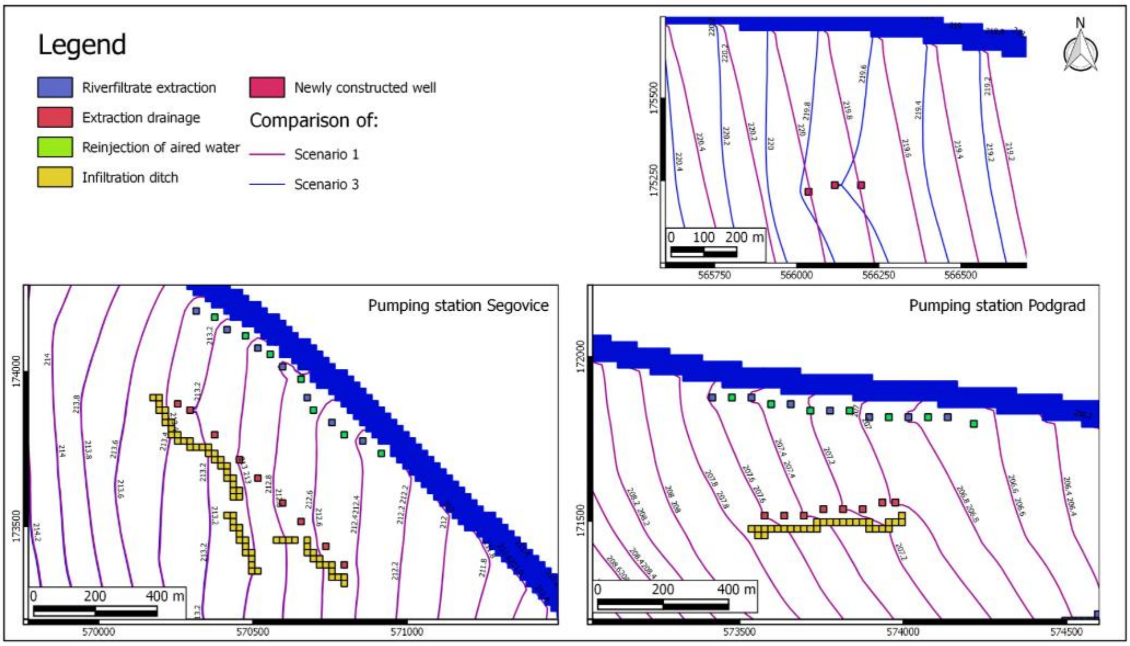

Figure 39. Comparison of the results between scenario 1 and 3 of the pumping areas

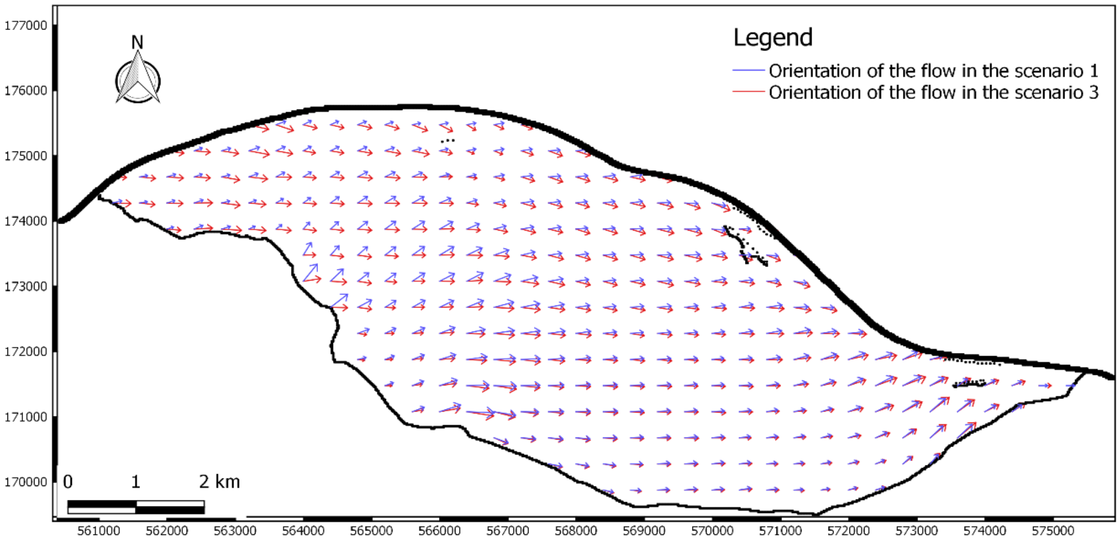

Figure 40. Groundwater orientation flow

In Figures 38 and 39, we see that the difference is not as excessive as in the previous comparison since we are in the same conditions (the normal ones). The orientation of the flow changes, we can see this difference in Figure 40 because of the new pumping station working. And the water levels are similar. But it is true that if we look at Figure 39, for the new pumping station, when extracting water, the contour lines vary enough for this fact.

- **Comparison scenario 1 with 4**

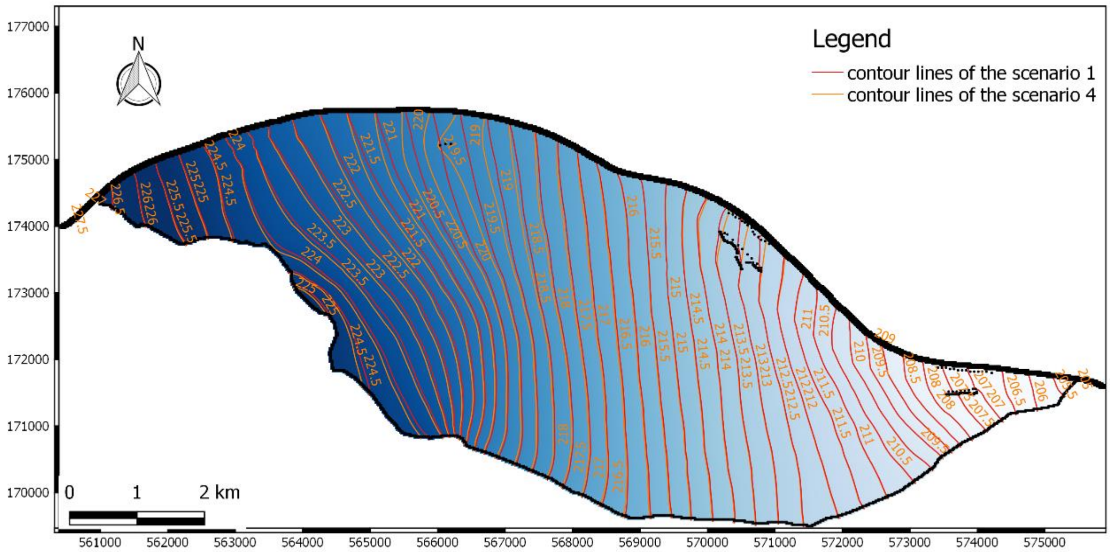

Figure 41. Comparison of the results between scenario 1 and 4

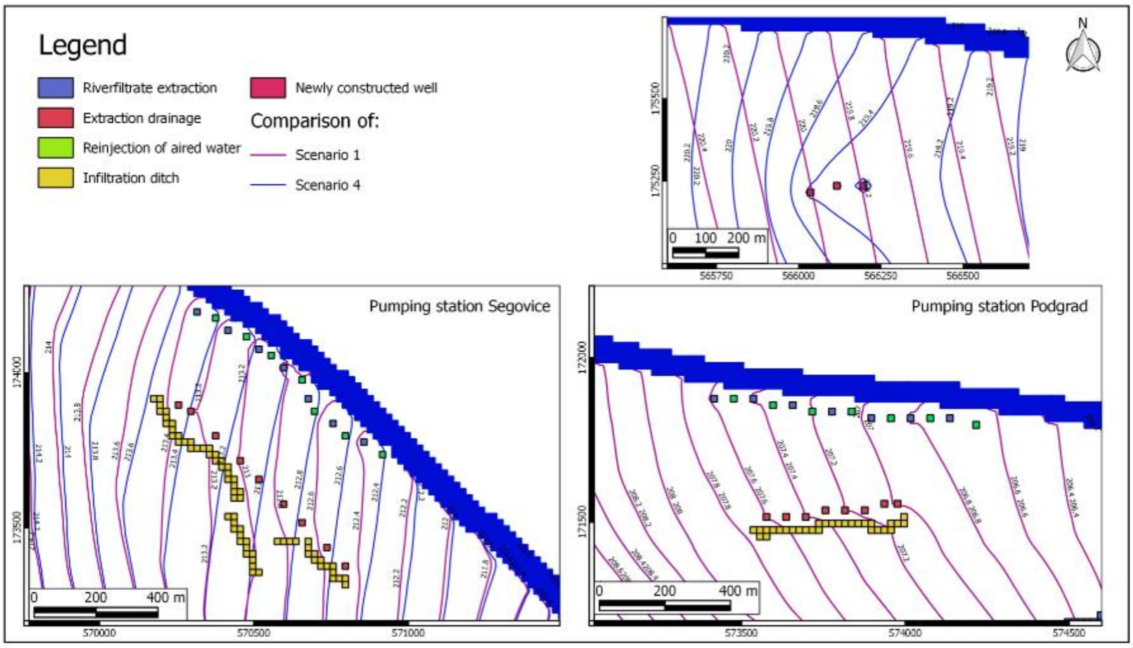

Figure 42. Comparison of the results between scenario 1 and 4 of the pumping areas

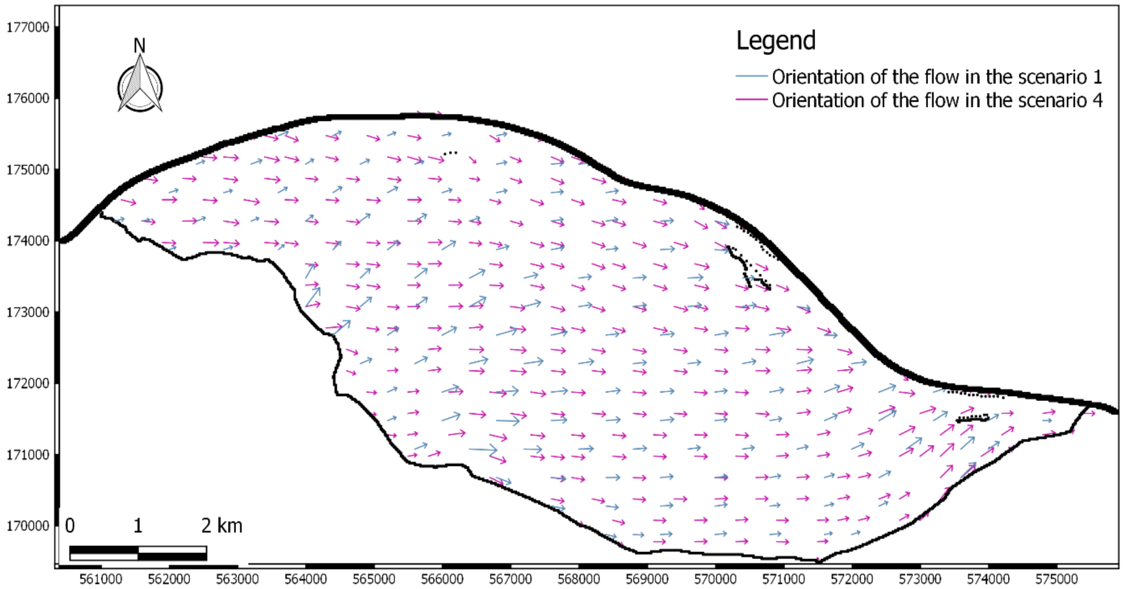

Figure 43. Groundwater orientation flow

In Figures 41 and 42, we see that the water level is similar, although it varies a little because of the new pumping situations that has been simulated. The orientation of the water flow varies, as we can see in the Figure 43, due to the change of the working pumping station. For Segovci, the contour lines change a lot because in the scenario 1, one extracts water but in scenario 4 this pumping station does not work. On the other hand, for Podgrad the contour lines are identical since they are working with the same conditions and flows. However, for the new pumping station it varies a lot because it has increased almost twice its flow extraction (if we compare scenario 3 with 4).

- **Comparison scenario 2 with 5**

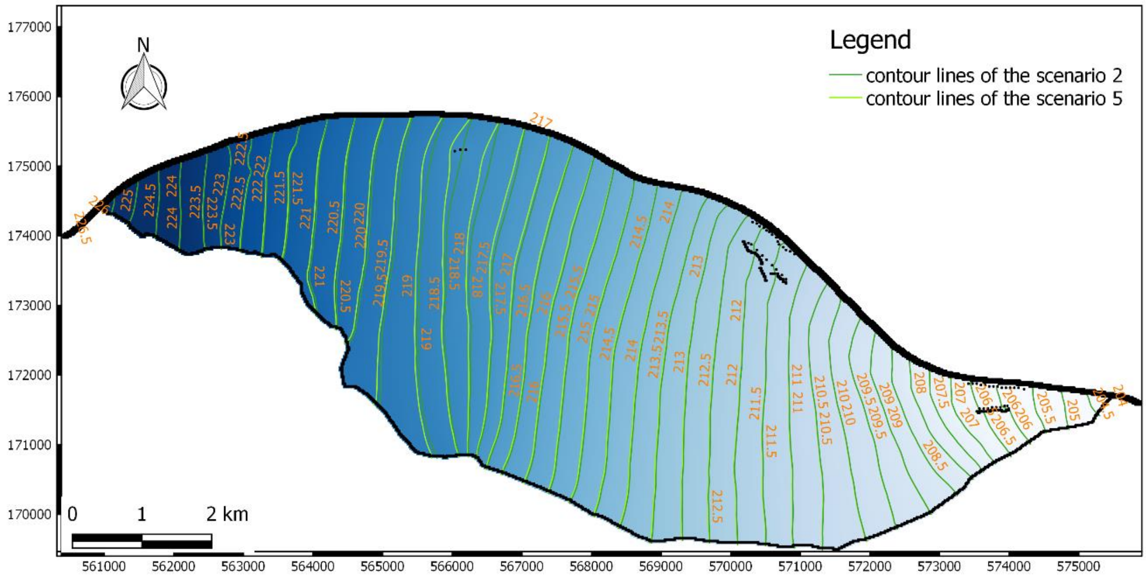

Figure 44. Comparison of the results between scenario 2 and 5

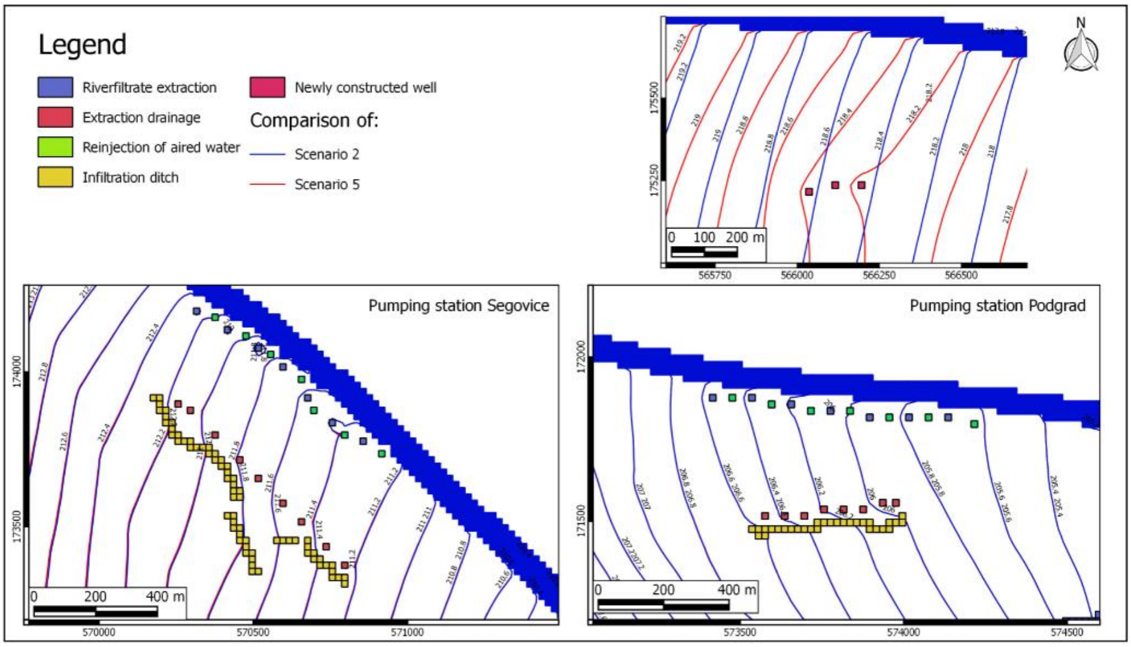

Figure 45. Comparison of the results between scenario 2 and 5 of the pumping areas

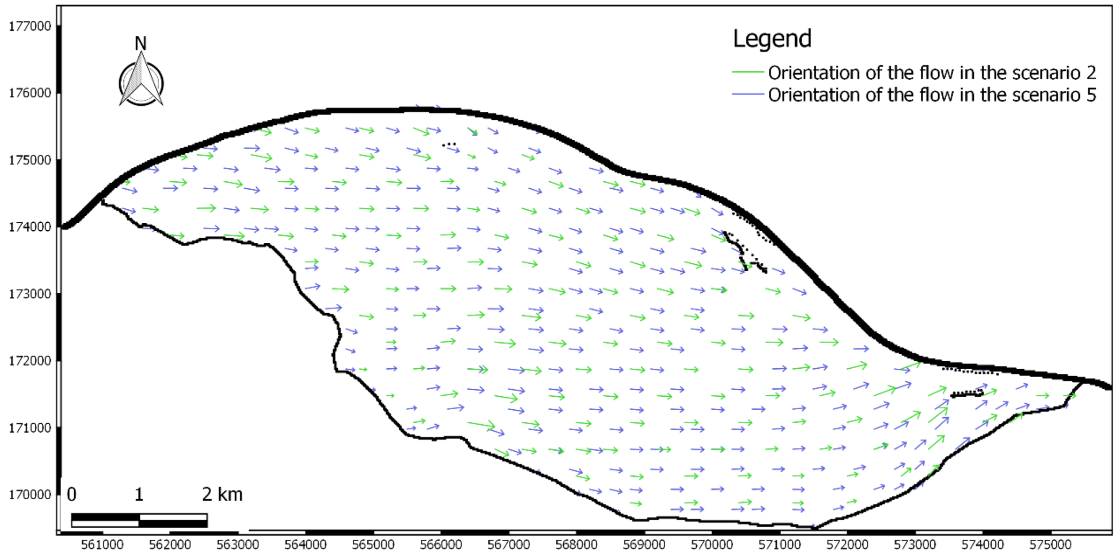

Figure 46. Groundwater orientation flow

In this comparison, we see the effects of the drought (the level of the river descends one meter, as the extraction of water in the pumping zones increases by 10% and the precipitation values are used for the summer months). In Figures 44, 45 and 46, we see that the water goes from east to west, since the water comes from the mountains of Slovenske gorice. The contour levels are very similar, but in the pumping zone of the new station, we can see more difference, than in the extraction of scenario 5.

- **Scenario 2 and 6**

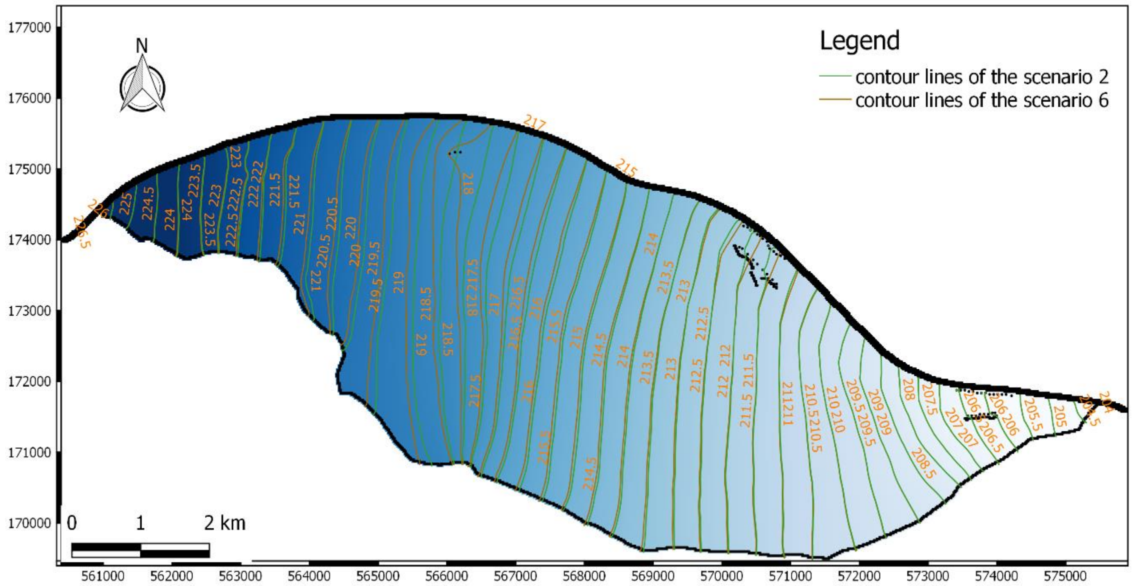

Figure 47. Comparison of the results between scenario 2 and 6

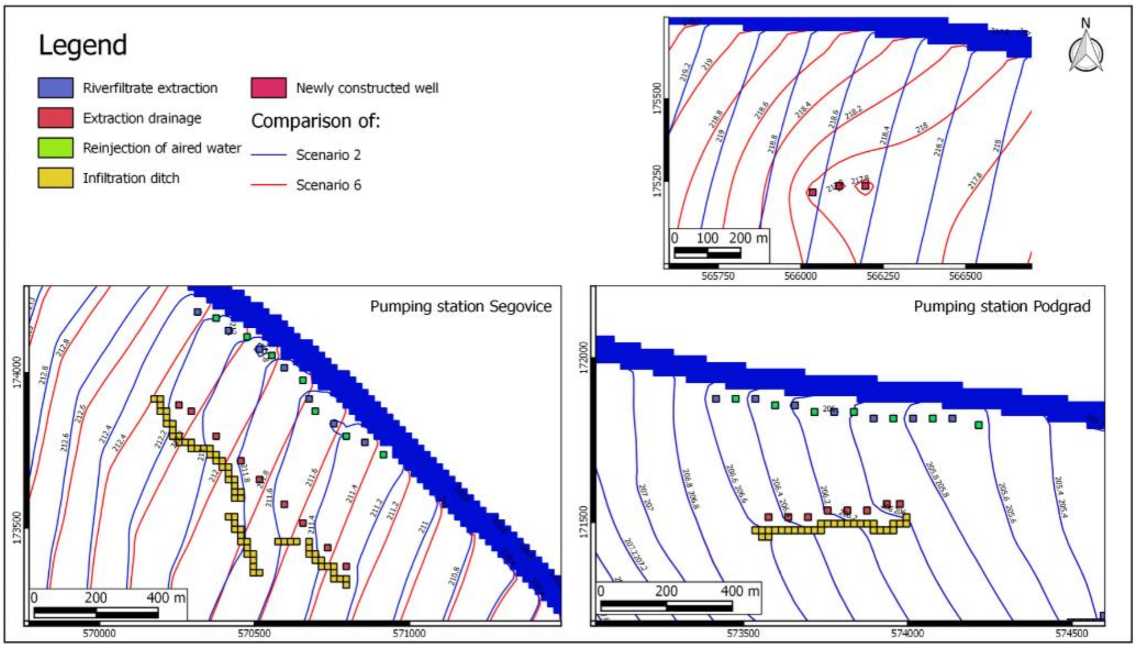

Figure 48. Comparison of the results between scenario 2 and 6 of the pumping areas

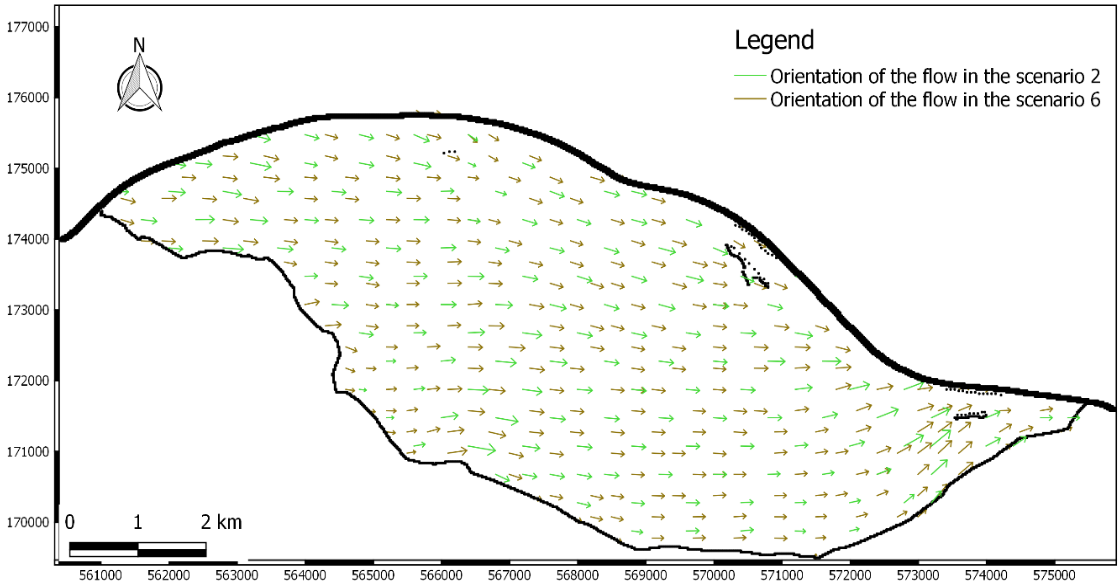

Figure 49. Groundwater orientation flow

In this comparison of scenarios 2 and 6, we see that the water level drops and the orientation of the flow (Figure 49) is the same, given that both situations are in drought conditions. We can observe bigger differences in the areas of pumping. Since the pumping station Segovci in scenario 6 does not work, while in the two remaining stations work but with a greater flow of water with respect to scenario 2, hence the differences in contour lines is more noticeable.

5. Conclusions

After having carried out this study with different scenarios, we can draw several conclusions about the water level and the external influences that affect the groundwater.

In the first place, the climate change that our planet is suffering is an evident fact nowadays, causing that in some areas, there are more periods of drought. This is a very important and worrying fact, at the same time since water is the engine for human life. As it has been observed in scenario 2 and in the comparison with scenario 1, the change suffered by the aquifer is very large, losing almost one meter of the water level (a very drastic change). In addition, the drought not only affects that there is less precipitation but also affects the level and quality of water from the Mura River that infiltrates into the aquifer.

Secondly, we can observe that in all the scenarios, the aquifer state is greatly depended on the Mura River. The less water level there is in the river, the less water the aquifer will have. In addition, there is a current problem with the Mura River, as it is losing sediments due to the hydropower plants that are located upstream in Austria. The hydropower plant is obstructing the flow that goes directly to the Mura river, making the water levels of the river lower. Therefore, a conclusion can be drawn that the protection of the Mura River is critical for the protection of the aquifer's state.

In third place, we can also observe, the dependence of the aquifer to the hinterland waters from Slovenske gorice. When there is little water coming from the mountains (scenario 2,5,6), the orientation of the aquifer water flow changes a lot compared to normal conditions.

Finally, it should be noted that this study has been carried out within a steady state groundwater model. That means, that there have been no data changes over time. This makes the results obtained from the different scenarios very general. To obtain much more detailed conclusions about how the water level and aquifer state can evolve, the transient state would have to be used. In which, we would use different input data for the boundary conditions in different time periods. This implies, that the calculations would take much longer than in the steady-state model, but the results of the groundwater model would be much more accurate than those with the steady-state model.

6. Literature

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