**Numerical Modelling of Groundwater-Surface Water Hydrogeological and Hydraulic Connectivity in a Floodplain Hyporheic Zone**

**Kurgatt Geoffrey1, Philip Kibet Langat 2\* Richard Koech3 Andrea Tóth4**

1 Faculty of Earth Sciences and Engineering, University of Miskolc – Hungary, 3515 Miskolc, A/4 building, ground floor 26-28 | Email: [kurgatt.geoffrey@student.uni-miskolc.hu](mailto:kurgatt.geoffrey@student.uni-miskolc.hu); geffkur@gmail.com

2 School of Engineering and Technology, Central Queensland University Australia, Bruce Highway, Rockhampton North QLD 4701, Email: [p.langat@cqu.edu.au](mailto:p.langat@cqu.edu.au)

3 College of Science and Sustainability, Central Queensland University, Australia, Bundaberg Campus, Building 8, University Drive, Bundaberg QLD 4670. | E [r.koech@cqu.edu.au](mailto:r.koech@cqu.edu.au)

4 Institute of Water Resources and Environmental Management, Faculty of Earth Sciences and Engineering, University of Miskolc – Hungary, 3515 Miskolc, A/4 building, ground floor 26-28 | E-mail: [andrea.toth@uni-miskolc.hu](mailto:andrea.toth@uni-miskolc.hu)

\* Corresponding Author: Central Queensland *University Australia, .* *E-Mail: p.* [*p.langat@cqu.edu.au*](mailto:p.langat@cqu.edu.au)

# **Abstract**

Transient numerical flow models were developed and calibrated in Processing MODFLOW to quantitatively examine the groundwater-surface water interaction in a floodplain hyporheic zone. Although understanding of groundwater–surface water flux exchange in a hyporheic zone is crucial for effective water management and a variety of scientific purposes, it is a difficult place to study. Our numerical modelling of Danube River and Surány aquifers interaction revealed that there was a strong relationship between the response time lag (of river level change and groundwater level change) and the distance of wells from the river; the response time between a river rise (flooding) and GW level rise increased with increasing distance from the river and vice versa. Further, there were bigger depressions due to pumping in production wells located farther away from the river as a result of decreasing recharge from the river. The water budget from the models showed that the river seepage was the biggest contributor of inflow into the aquifer with over 70% contribution. The analysis of bank filtrate demonstrated that the level of river stage influenced the length of particle travel time; higher river stages led to shorter particle travel times. For the wells closer to the Danube River, the calculated travel times were shorter and increased with wells located farther away from the river. The numerical modelling results imply a strong hydraulic and hydrogeological connection between the permanent river and the adjacent alluvial aquifer. This investigation directly contributes to the implementation of the Danube River basin-wide water resources management and Flood Risk Management Plan developed in 2015 and the European Union Floods Directive requirements. Our models may be used in advancing understanding of the groundwater-surface water hydrogeological and hydraulic connectivity processes and mechanisms in floodplain environments.

**Key words**: Groundwater–surface water; (GW-SW) connectivity; numerical modelling; Processing MODFLOW; floodplain

# **1.0 INTRODUCTION**

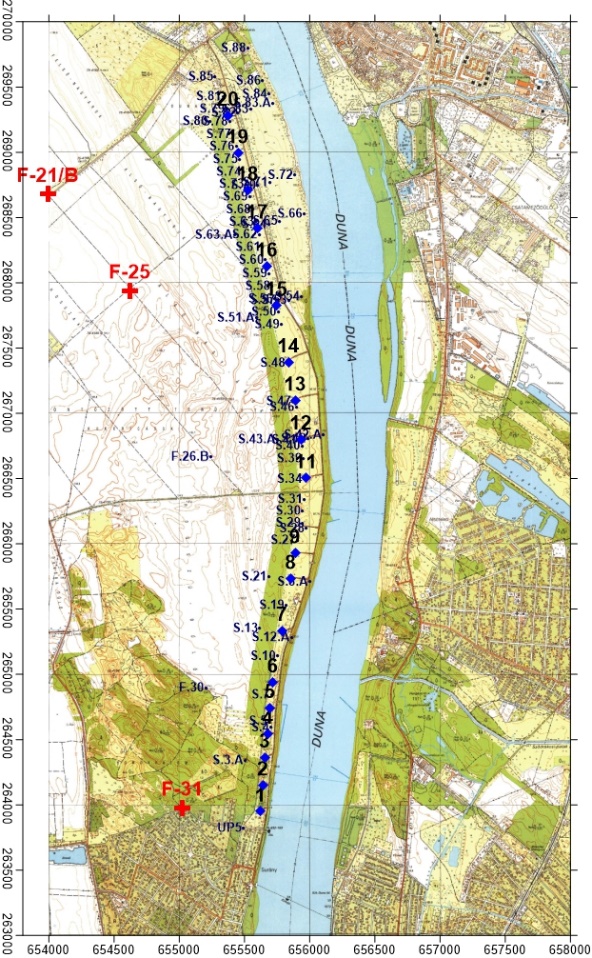
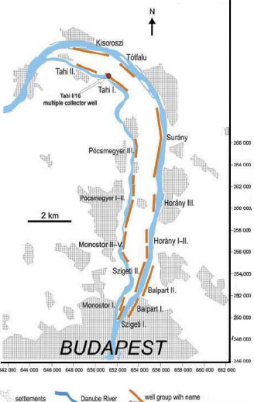
Groundwater (GW) constitutes up to 97% of the global available freshwater reserves and has been extensively abstracted all over the world. Sustainable Development Goals (SDGs), notably SDG 6, and parts of SDGs 12 and 13 underscore the importance of protecting, conserving, restoring and sustainably using water-related ecosystems. The understanding of groundwater GW and surface water (SW) interaction and hydraulic processes is vital especially for the coordinated use of groundwater and surface waters, flood attenuation within a floodplain, control of water logging conditions, sustenance of wetlands and the protection of aquatic life (El-Rawy et al., 2020; Zhang & Sato, 2024). The hyporheic zone flow dynamics and behaviour are recognized as an important for GW-SW interactions (Banks et al., 2019). Hyporheic interstices serve to connect the biological transition boundary between a river and groundwater ecosystems and mediate the bio-chemical exchange processes between both ecosystems (Banerjee & Ganguly, 2023). In floodplain environments, investigating and quantifying the spatial and temporal groundwater-surface water interactions (GW-SW) is complex because of heterogeneity in hydraulic and reactive processes across a range of spatial and temporal breadths. However, understanding the extent of connectivity between groundwater and surface water is crucial for the overall water resource sustainable management and ecosystem health (Zhang et al. al 2024).

A number of techniques and methods have been used to investigate and quantify the GW-SW hydraulic interaction including field-based methods (chemical, thermal and electrical), and analytical and numerical modelling methods (El-Rawy et al., 2020; Bui et al.; 2020). Each technique available for investigating GW-SW interactions provides key information about a single or a few processes of interest, and each method has unique characteristics and limitations (González-Pinzón et al., 2015; Ntona, et al., 2022). Field-based measurement studies are considerably costly, labour and data intensive and often time consuming (Blume and van Meerveld, 2015). Analytical models require less data but may not be applicable to more complex problems. Additionally, they oversimplify the natural system by making many assumptions, for example isotropy and homogeneity of a groundwater storage system (aquifer) which in most cases is far from the reality (Baalousha, 2011). On the other hand, numerical models can solve more complex and complicated problems by closely simulating the natural environments and integrating variables and conditions for understanding groundwater dynamics. Numerical models are techniques frequently used to analyse and simulate groundwater flow conditions and are valuable tools for validating GW-SW connectivity and hydraulic gradient interpretations (Lakshmanan, 2005; Bonduà et al., 2023; Jafari et al., 2021; Bailey et al., 2022; Felfelani et al., 2024). The solutions for the GW-SW interactions are derived from the Darcy’s law and the law of conservation of mass i.e. the continuity equation (Gadadhara & Krámer, 2021). The Darcy equation describes the flow of a fluid through a porous media while the law of conservation of mass states that the net flow rate of fluid mass into an elemental volume of aquifer is equal to the time rate of change of fluid mass storage within the element. A numerical groundwater model is a simplified mathematical representation of the complex system involving the flow of groundwater through an aquifer which constitutes saturated sediments and fractured rock (Elango, 2005). A powerful groundwater model is one that quantitatively represents the spatial and temporal hydraulic heads in a simplified representation of the complex hydrogeological conditions in the subsurface (Anderson, Woessner & Hunt, 2015).

Although the Surány aquifer along the Danube River is strategically important with respect to SW and GW interaction because of water supply, the observation network and stage level data do not necessarily adequately address the potential water quality risks. Earlier studies showed that the Surány aquifers are recharged up to 96 – 97% by the Danube River through the river bed, while precipitation accounts for only 3 – 4% (Kármán et al., 2014). The water gets into the production wells mainly from the Danube River as well as from recharge due to precipitation. Nyiri et al. (2023) examined the processes that take place between the Danube River and the production wells within the Surány well group in order to explore the effects that threaten the safety of drinking water supply in Budapest from water extraction to the consumers. Using field measurements such as water levels, stable isotopes, temperature, and electrical conductivity, Nyiri et al. (2023) concluded that the Danube River played a significant role in the evolution of the production and monitoring wells’ levels located in Surány of Szentendre Island and that the water levels and parameters measured in the monitoring wells reacted with a delay to the changes that occurred in the Danube River. However, their study was not able to determine the actual arrival time of bank filtrate into the wells which is important in periodical management activities in relation to GW-SW connectivity (Bara et al., 2024). The hyporheic zone is a difficult location to study and often, estimations of groundwater budgets and their variability across multiple spatial and temporals cales rely on numerical modelling. This study builds numerical groundwater flow models using Processing MODFLOW for simulating the groundwater-surface water flow regimes within the Surány aquifer along the Danube River in Hungary. We also use the calibrated models to calculate the water budget within the aquifer and estimate the travel times of bank filtrate from the river to the studied wells. This study is useful in groundwater–surface water monitoring and provides a better understanding of the hydrological and hydraulic connectivity of GW-SW in floodplain hyporheic zones.

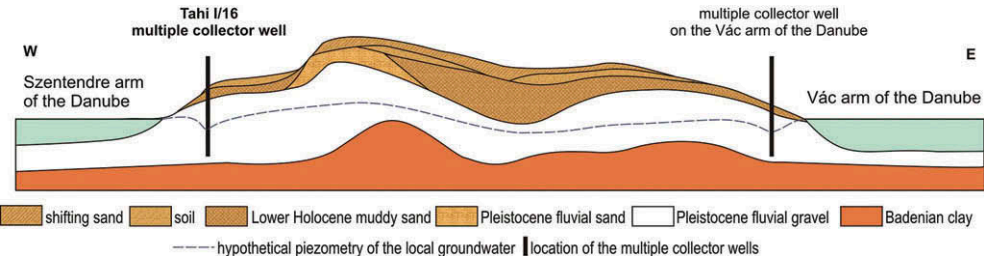
# **2.0 THE STUDY AREA**

The study site is located along Danube River in Surány village inside Szentendre Island. The island is situated between the [Danube River Bend](https://en.wikipedia.org/wiki/Danube_Bend) and [Budapest](https://en.wikipedia.org/wiki/Budapest) in Hungary. The island forms part of the [Szentendre District](https://en.wikipedia.org/wiki/Szentendre_District) of [Pest County](https://en.wikipedia.org/wiki/Pest_County). The site is composed of 20 production wells (riverbank filtered – RBF wells) drilled along the river with distances ranging from 75m to 450m away from the banks of the Danube River (Figure 1). Riverbank filtration (RBF) is a form of technology that involves extracting water through pumping wells drilled into an alluvial aquifer adjacent to a river. (Jaramillo, 2012). If the aquifer and the river are hydraulically connected, pumping the wells creates a hydraulic gradient that forces water to flow from the river in the direction of the wells. The data used in the investigation was obtained from the Budapest Waterworks, which is a company mandated with the provision of water production and supply and wastewater disposal and treatment services to the inhabitants of Budapest City and its environs. Szentendre Island, with an area of 56km2 lies to the North of Budapest, Hungary’s capital. It is situated within two branches of the Danube River (**Figure 1)**. The island has a length of 31km and a width that varies between 2.3km and 3.5km (Kármán et al*.*, 2014). The elevation of the island ranges from 100m to 124m. Farmlands and forests cover the land surface of the island. The island is also home to 25 protected plant species and 205 migratory bird species. The island has parts that belong to the Natura 2000 network of breeding and resting sites for rare and threatened species. The Natura 2000 is a network of protected areas in Europe consisting of the most valuable and threatened species and habitats, both at sea and land. It covers all the 27 EU Member States (Kreft & Güngöroglu, 2018). The climate in the study area is humid continental. The island has an average annual temperature of 10°C; averages of slightly above 0°C in the coldest months of winter and above 22°C in the warmest months. The average annual precipitation is 600–650 mm. (Tóth et al., 2015).



**Figure 1**. A georeferenced map showing the location of the study site with the Riverbank filtrated (RBF) Production wells and Monitoring wells in Surány village, Szentendre Island – Hungary. The numbers from 1 - 20 represent the number of the RBF wells in Surány which forms the Surány well group (Appendix 8.1). Only wells 1 - 18 were studied. Surány well group is one of the 20 well groups in Szentendre Island which cumulatively consist of over 500 drilled wells.

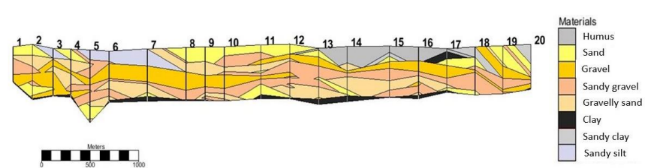
Geologically, the basement of the island consists of Tertiary marine sediments, Upper Oligocene clay and Lower Miocene clayey, sandy layers (**Figure 2**). The thickness of the basement formation varies from 90 and 130 m. No significant groundwater yield is expected in this formation. The basement formation is overlain by fluvial gravels and sands that formed from the beginning of the Pleistocene age. The thickness of the fluvial sediments ranges from 3.5 to 10m (Szabó, 2021). This is the formation which contains the high-yielding aquifers. The fluvial sediments are overlain in the immediate subsurface by only 3 – 5m of Pleistocene and Holocene casting sand layers separated by lenses of clayey-silty-sand and muddy layers. Semi-consolidated shifting sand layers are also found in this formation.



**Location of the Surány wells**

**Figure 2.** Conceptual geological model of the Szentendre Island (modified after Góczán, 1955)

The significance of the study area, Surány village within the Szentendre Island, is that over 90% of the drinking water supply in Hungary originates from groundwater and 95% of the 165 million m3 annual water production in Budapest city comes from riverbank-filtrated (RBF) wells drilled along the Danube River which includes the Surány well group (Budapest Water Works Report, 2018). Budapest Water Works company operates 756 Riverbank Filtered wells to supply water to a population of 1.89 million in Budapest. The drinking water production is provided by the bank-filtrated wells in Szentendre (**Figure 3**) and Csepel Islands (Kármán et al., 2014). There are 20 RBF wells within the Surány well field that is part of the 756 wells supplying the entire Budapest City. The numbers from 1 – 20 in **Figure 3** represent the number of the RBF wells in Surány. The basic data for the 20 Surány wells are shown in appendix 8.1. The other important consideration for the investigation of the Szentendre Island is because the island is a lowland within the Danube River basin and as such among the areas greatly affected by floods. According to Kádár (2015), Hungary’s biggest natural hazard is flooding owing to 23% of the country’s territory being situated in a flood plain. Szentendre Island is among the 23% areas located within a flood plain.



The numbers correspond to the number of RBF wells in Surány

**Figure 3.** Cross section of the Surány well group (Used with permission from *Nyiri et al*., 2023). Wells 19 and 20 were not used during the investigation due to lack of adequate data. The basic data for the 20 Surány wells are shown in appendix 8.1.

# **3.0 Data and Method**

## **3.1 Data sets**

A three-year daily data series of the changing Danube River stage (height) and the water levels of the 18 production wells in Surány well field were obtained from the Budapest Waterworks Ltd. The datasets also included daily pumping rates in m3 from each of the wells for the three-year period. The data series covered the period between 01/01/2018 and 31/12/2020. This time interval covers the periods of June 2019 and June 2020 where there were flash floods experienced in Hungary. Data from the network of monitoring wells around the Surány well field were also used in the analysis.

## **3.2 Methods**

### **3.2.1 *Processing MODFLOW***

Numerical modelling was performed using the finite difference code Processing MODFLOW developed by the USGS for simulating and predicting groundwater conditions and groundwater-surface water interactions. Processing MODFLOW 8.0 application was used to build the hydrodynamic flow models. Calibration of the models was done using the in-built parameter estimation package (PEST) and calculation of the groundwater flow paths and travel times was performed using the particle-tracking model PMPATH. Golden Software Surfer 2021 was used to develop digital maps of the study area and to create the interpolated grids of the model layer surfaces for input into Processing MODFLOW. The objectives of building and calibrating the numerical flow models were In a stage time series. because there were extreme high flows and low flows in the River Danube to examine and quantify the GW-SW connectivity between the Surány aquifer and the Danube River through; - head-time curves and head distribution contours generated from the models, to calculate the water budget for the Surány aquifer within the modelled areas and to determine the average travel time of bank filtrate from the Danube River to the production wells under transient flow conditions using particle tracking in PMPATH. Three basic flow models were built using an average of initial parameters obtained from literature for similar alluvial formations, which were later refined based on the calibration results from PEST.

The groundwater flow governing equations for a three-dimensional system applied by the Processing MODFLOW code in its computations is given by equation (1) as derived from the Darcy’s law and the Continuity equation. The partial-differential equation describes the distribution of hydraulic head in space and time {h (x, y, z, t)} for transient groundwater flow in a heterogeneous and anisotropic medium.

(1)

Where;

*– A volumetric flux per unit volume (i.e. sources and sinks of GW) (T-1)*

*– Specific storage of the porous material (L-1)*

*Time (T)*

Equation (1) must be accompanied by a specification of the initial head conditions and the boundary conditions of flow and head in an aquifer system. Both the energy of flow and the volume of water in storage can be measured and calculation of the directions and rates of movement of water can be done.

In terms of confined and unconfined aquifers, equation (1) is represented in the following simplified versions when the aquifers are assumed to be homogeneous and isotropic.

1. Confined and confined aquifers under steady state condition

(2)

1. Unconfined aquifer (under transient state) – which applies to the shallow Surány aquifer under study.

(3)

1. Confined aquifer (under transient state).

(4)

Where:

*Transmissivity {= Kb} (T-1)*

*Aquifer thickness (L)*

*Specific yield (of an unconfined aquifer) (-)*

*Specific storage (of a confined aquifer) (T-1)*

Numerical methods try to simulate and predict complex river-aquifer interaction situations even for cases with complicated boundary conditions, heterogeneity in the aquifer and the transient flow and stage relationships. The methods combine both the equations of open channel flow and the groundwater flow equation to simultaneously solve for the river stage and the water table (Gadadhara & Krámer, 2021).

#### **3.2.2.1 Conceptual Models for the Surány aquifer**

To simulate the Surány aquifer, three transient models were set up. The first model encompassed the Surány water works production wells number 1, 2 and 3 which are within 75m and 95m distance from the Danube River; the second model encompassed wells 11, 12, 13 with distances of between 195m to 232m from the Danube River; and the third model encompassed wells 16, 17, and 18 with distances of 352m to 438m from the Danube River (refer to **Figure 3)**. The well levels and pumping data sets for the first 18 wells were available; the data for wells 19 and 20 could not be obtained. The aim of this well group selection was to examine the differences between aspects of the three models with regards to increasing lateral distances from the river. Each model was spatially discretised to cover 1100m in the x-direction (East-West) and 900m in the y-direction (North -South) as shown in the maps in Figures 6 and 7. The models were discretised vertically into two layers with depths obtained from interpolation of the production and monitoring wells data within the model area. The two layers have different hydraulic and storage properties. The upper layer had a silty-sand formation, and the underlying layer (aquifer) was composed of sandy gravel sediments as obtained from the hydro-stratigraphic descriptions of the wells. The grid size ranged from 20m x 22m to 4m x 4.4m around the production wells. The ground surface, aquifer top and aquifer bottom surface elevations were calculated by interpolation of the production and monitoring wells data using Surfer and exported into the Processing MODFLOW. In terms of temporal discretisation, the models were set in transient states with a total simulation period of 795 days. The stress period begins from 12/07/2018 to 13/09/2020 of the production wells time series. This period was selected owing to the extreme high flows and low flows in the Danube River stage time series. The simulation time was divided into 20 stress periods each with lengths ranging from 9 to 77 days as shown in **Table 2**. The number of time steps was set to 1 in each stress period. This was done to make it easy to compare the calculated and observed hydraulic heads during the calibration process. The starting hydraulic heads were obtained from interpolating the starting heads of the wells within each model area at the beginning of the stress period i.e. 12/07/2018. As for the boundary conditions, the Northern and Southern boundaries of the models were assigned active cells while the Western boundary was assigned fixed/constant head cells because of the assumed continuous GW flow from the background into the aquifer. The Eastern boundary was represented by the “River” package to simulate the head-dependent flux boundary as a result of the Danube River. The CRIV parameter (riverbed conductance) was used to represent the flux through the riverbed. All other cells inside the model boundary were assigned active cells and the head distribution changed with time during the transient simulation. The three production wells in each of the models were used during simulation both as production sources and later as observation wells for the hydraulic heads. The transient simulation time was set to run according to the normal waterworks production schedule for the period from 12/07/2018 to 13/09/2020 according to the production time series data. The summary of the initial input data/parameters into the models as obtained from literature for similar alluvial formations (sandy gravel and silty sand) is shown in Table 1.

**Table 1.** Summary of the initial input parameters of the GW models (Anderson et al., 2015; Lakshmanan, 2005)

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Model Layers** |  | **Soil type** | **Khorizontal (m/day)** | **Kvertical (m/day)** | **Effective porosity**  **(-)** | **Specific yield, Sy**  **(-)** | **Specific storage**  **(m-1)** | **Recharge (m/day)** |
| Top (1) |  | Silty sand | 2 | 0.2 | 0.20 | 0.18 | 0.0001 | 2.1x10-4 |
| Bottom (2) |  | Sandy gravel | 100 | 10 | 0.25 | 0.23 | 0.0001 |

Key assumptions that were made in building up the GW-SW models in the Surány aquifer were: a) the model areas are a representation of the whole Surány aquifer in terms of geology, stratigraphy and groundwater flow conditions; b) the unconfined alluvial aquifer in the models is homogeneous, isotropic and of finite extent and therefore hydraulic conductivity and effective porosity values are assumed to be constant throughout the aquifer layer; c) the Danube River (the branch along which the 20 Surány well group is located) is assumed to be a rectangular channel with vertical banks and the flow transmits through the channel bed; d) the representation of the collector wells using single cells via the Well package is an over simplification of the reality due to the capability of the Processing MODFLOW version used and therefore more accurate results may be obtained by using a more specialized package like the Multi-Node Well package; e) the riverbed’s hydraulic conductance is assumed to be constant throughout the length and breadth of the river within the models because data collection on the thickness and hydraulic conductivity of the riverbed sediments was not practically possible within the framework of this study; f) the three-year measurements of the groundwater levels and river stage are assumed to represent the long-term averages; and, g) the Dupuit-Forchheimer conditions are valid, i.e.: (i) in any vertical section of the subsurface, the groundwater flow is horizontal; (ii) the velocity profile is uniform along the depth/vertical axis; and (iii) the slope (α) of the free surface (for unconfined flow) is small enough than α = sin(α) (in radians); the river fully penetrates the aquifer; the flow is saturated (Ferraz & Krámer, 2022).

**Table 2.** Summary of the transient simulation period divided into 20 stress periods with the average river stage and production rates for wells 16, 17, and 18 during the period, as an example. The rest (1, 2, 3, 11, 12, 13) are included in the appendix 8.2.

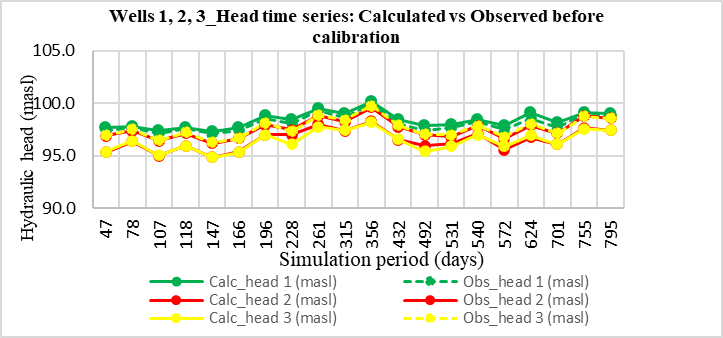
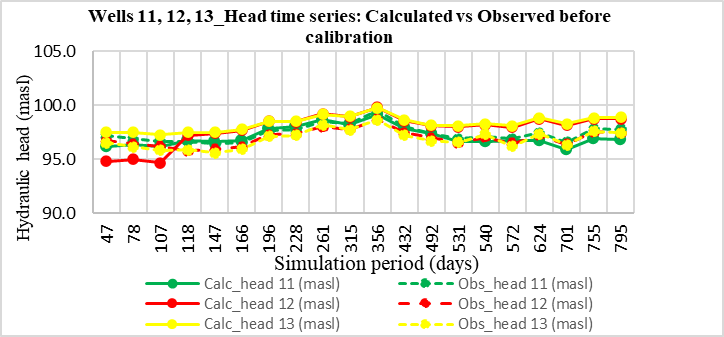
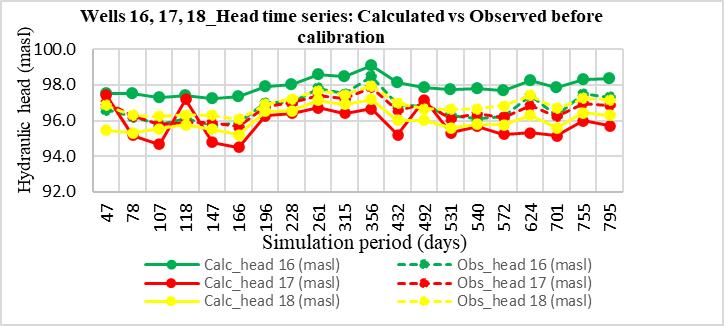
|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Stress Period** | **Simulation period** | | **Period length (days)** | **River stage, Hd\_average (masl)** | **Average pumping rate, Q\_av (m3/day)** | | |
| **Start** | **End** | **Well 16** | **Well 17** | **Well 18** |
| 1 | 2018/07/12 | 2018/08/27 | 47 | 98.01 | 3173 | 7 | 2114 |
| 2 | 2018/08/28 | 2018/09/27 | 31 | 98.19 | 2919 | 1544 | 2096 |
| 3 | 2018/09/28 | 2018/10/26 | 29 | 97.60 | 2870 | 1621 | 1610 |
| 4 | 2018/10/27 | 2018/11/06 | 11 | 98.31 | 2247 | 2 | 1528 |
| 5 | 2018/11/07 | 2018/12/05 | 29 | 97.55 | 2972 | 1568 | 1629 |
| 6 | 2018/12/06 | 2018/12/24 | 19 | 98.31 | 2670 | 1694 | 2032 |
| 7 | 2018/12/25 | 2019/01/23 | 30 | 99.65 | 2082 | 1116 | 1410 |
| 8 | 2019/01/24 | 2019/02/24 | 32 | 98.92 | 2253 | 1138 | 1476 |
| 9 | 2019/02/25 | 2019/03/29 | 33 | 100.36 | 1934 | 1354 | 1492 |
| 10 | 2019/03/30 | 2019/05/22 | 54 | 99.53 | 2491 | 1501 | 1551 |
| 11 | 2019/05/23 | 2019/07/02 | 41 | 101.12 | 3088 | 1831 | 1929 |
| 12 | 2019/07/03 | 2019/09/16 | 76 | 98.79 | 3059 | 1939 | 2015 |
| 13 | 2019/09/17 | 2019/11/15 | 60 | 98.20 | 2117 | 495 | 1734 |
| 14 | 2019/11/16 | 2019/12/24 | 39 | 98.40 | 2995 | 1627 | 2017 |
| 15 | 2019/12/25 | 2020/01/02 | 9 | 99.20 | 3397 | 1437 | 1899 |
| 16 | 2020/01/03 | 2020/02/03 | 32 | 98.19 | 2967 | 1582 | 1761 |
| 17 | 2020/02/04 | 2020/03/26 | 52 | 99.92 | 2597 | 1940 | 1974 |
| 18 | 2020/03/27 | 2020/06/11 | 77 | 98.59 | 2988 | 1747 | 2147 |
| 19 | 2020/06/12 | 2020/08/04 | 54 | 99.78 | 2315 | 1609 | 1877 |
| 20 | 2020/08/05 | 2020/09/13 | 40 | 99.60 | 2612 | 1827 | 2083 |

# **4.0 RESULTS AND DISCUSSIONS**

## ***Modelling Outputs***

### ***Time Series Curves Before Calibration***

After inputting the initial parameters (obtained from literature) into the models, the transient models were run and head-time curves extracted before performing calibration. The time series curves are as illustrated in **Figure 4**.



**Figure 4.** Combined head-time curves for the wells before calibration

### ***Model Calibration***

Calibration of the models was done using PEST which is an in-built parameter estimation software package in Processing MODFLOW. PEST interacts with a numerical model through the model’s own input and output files and adjusts the parameters by running several times. In the course of a parameter estimation process, PEST searches for optimum parameter values whose sum of squared deviations between model-calculated and observed values of hydraulic heads (or drawdowns) at observation boreholes is reduced to a minimum (Simcore Software, 2012). Since the Block-Centered Flow (BCF) package was used with layer type 3 in the current models, the values of horizontal hydraulic conductivity (HK), vertical hydraulic conductivity (VCONT), storage coefficient (S) and the specific yield (Sy) were estimated using the PEST package.

The parameter estimation process was run for each of the three models and the final estimated values of the parameters that were adjusted by the software are given in **Table 3**.

**Table 3.** The values of adjusted parameters after calibration with the Parameter Estimation program – PEST which is in-built within the Processing MODFLOW modeling software.

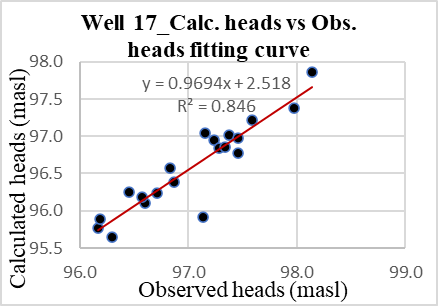
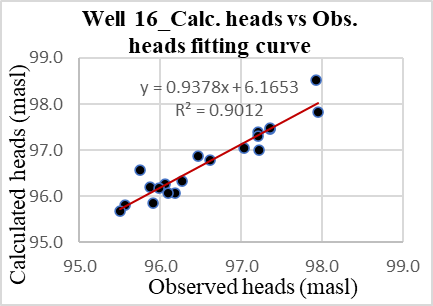
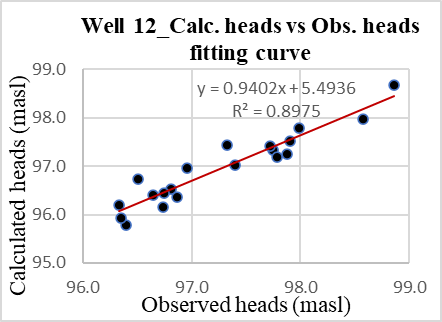
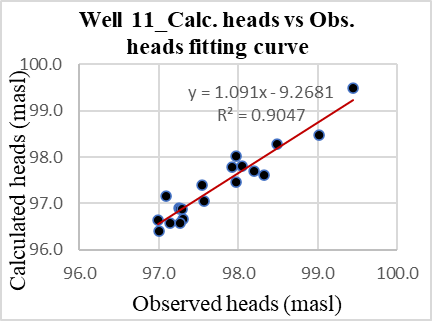
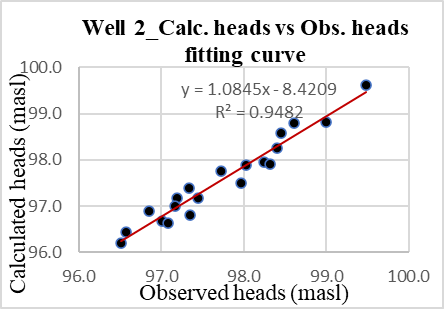
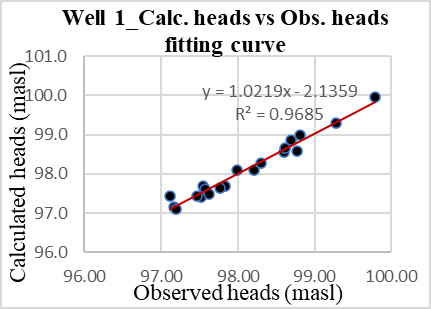
|  |  |  |  |
| --- | --- | --- | --- |
| **Well groups** | **Horizontal hydraulic conductivity Kh (m/day)** | **Specific yield layer\_2**  **(-)** | **Effective porosity layer\_2 (-)** |
| Wells 1, 2, 3 | 260 | 0.19 | 0.22 |
| Wells 11, 12, 13 | 260 | 0.20 | 0.23 |
| Wells 16, 17, 18 | 303 | 0.20 | 0.23 |

### ***Head-Time Series Curves After Calibration***

The calculated hydraulic heads were compared with the observed average hydraulic heads for all the studied wells and the error was calculated. The results of the calculated error are as shown in **Table 4** and the fitting curves are displayed in **Figure 5.** The fitting curves show that the closeness between the calculated and observed heads is reducing with distance away from the river i.e. from well 1 to well 17.

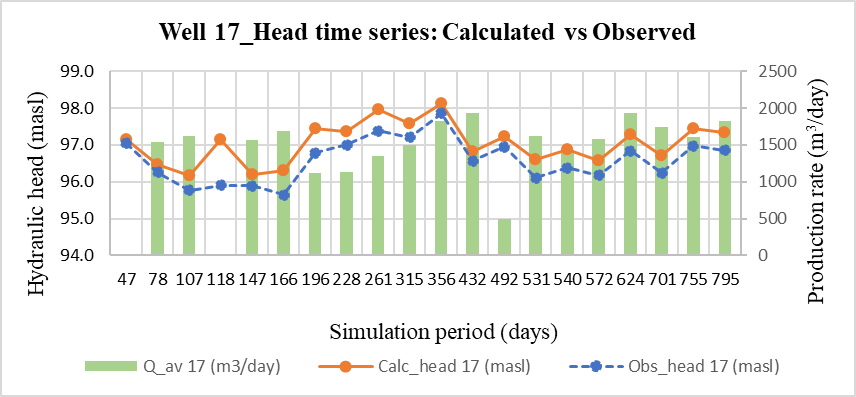
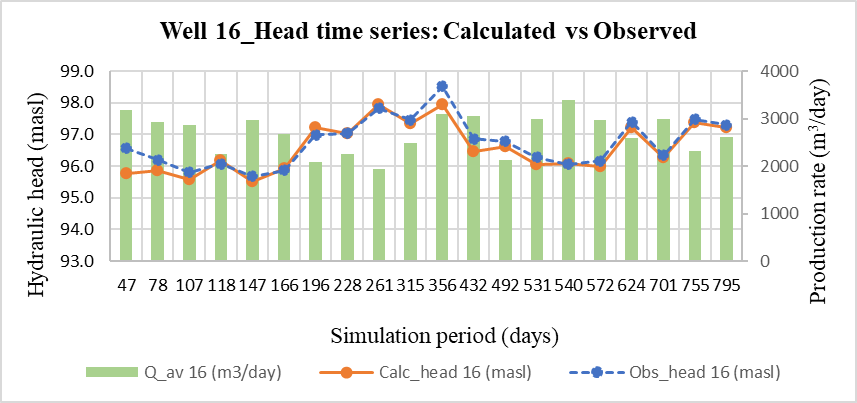
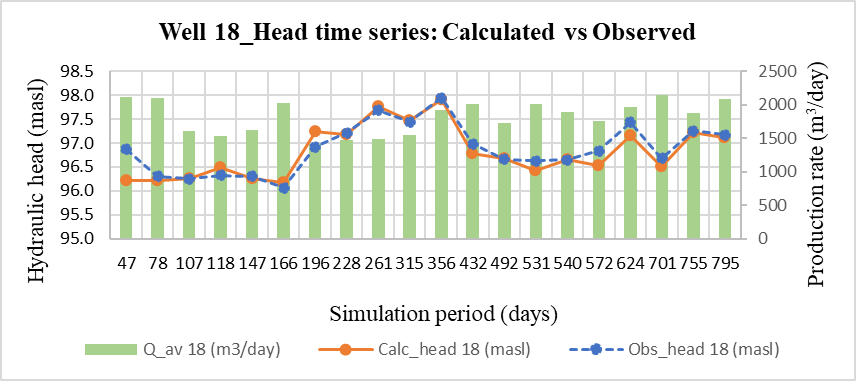
**Table 4.** Error between the calculated and observed hydraulic heads for the studied wells

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Well ID** | 1 | 2 | 3 | 11 | 12 | 13 | 16 | 17 | 18 |
| **Mean error [m]** | 0.12 | 0.22 | 0.19 | 0.39 | 0.36 | 0.23 | 0.21 | 0.45 | 0.14 |
| **Max error [m]** | 0.34 | 0.47 | 0.41 | 0.72 | 0.63 | 0.70 | 0.80 | 1.20 | 0.60 |
| **Min error [m]** | 0.00 | 0.01 | 0.01 | 0.06 | 0.00 | 0.01 | 0.01 | 0.11 | 0.00 |

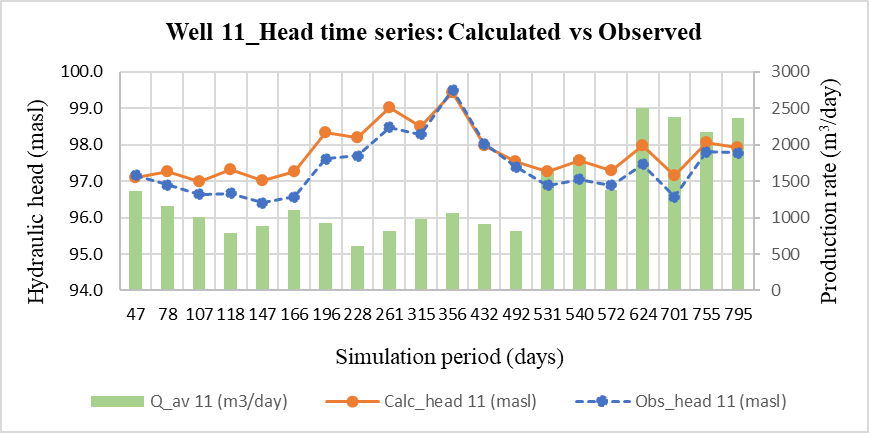
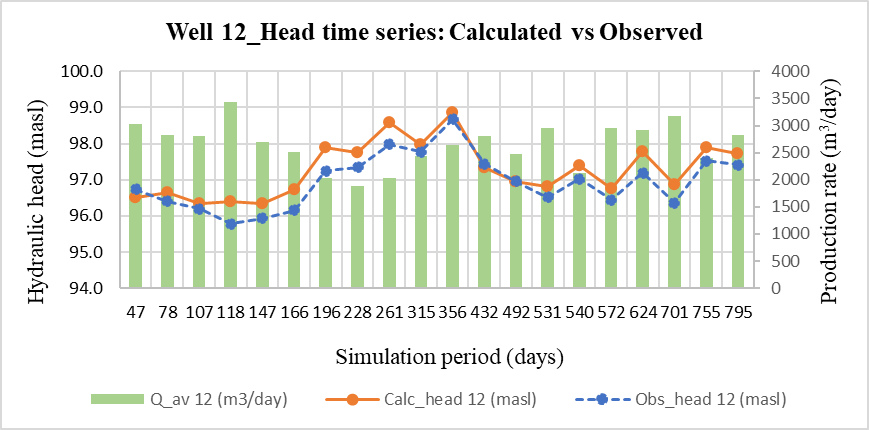
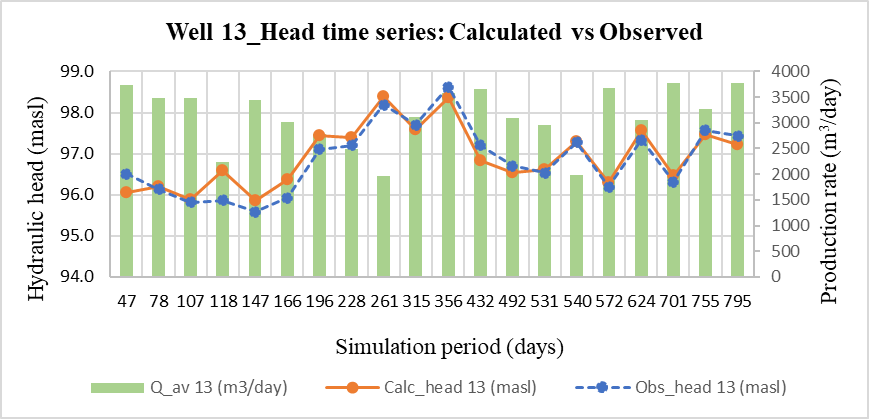


**Figure 5.** Most fitting curves of Calculated versus Observed heads for six sample wells.

The calculated versus the observed head-time curves were then generated for each of the wells using the calibrated model. The daily production rates were also combined as a chart in the combo graph so as to visualize the effect of pumping rates on the hydraulic heads for each well (**Figures 6, 7** and **8**).

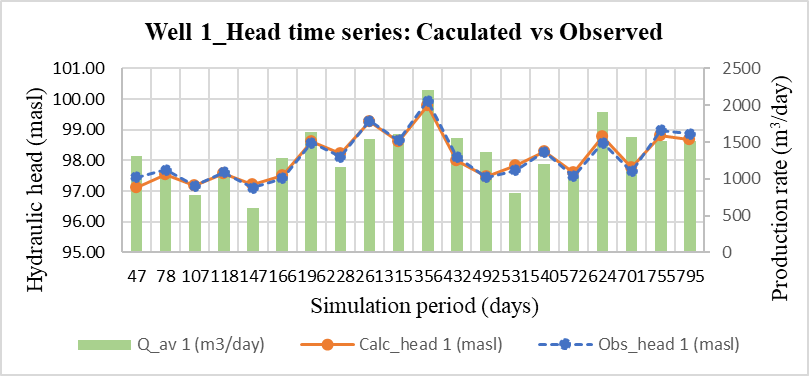
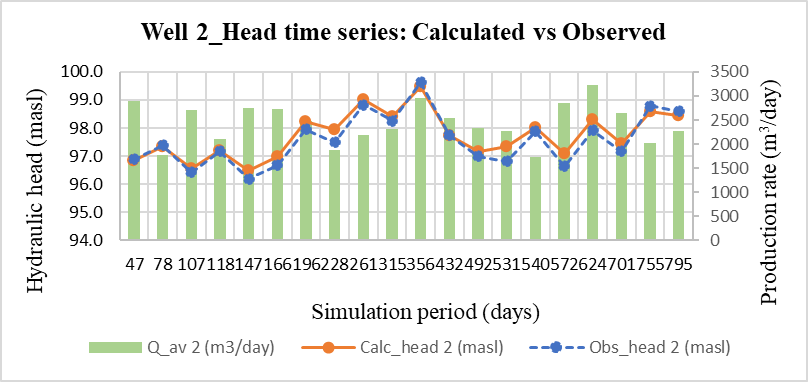
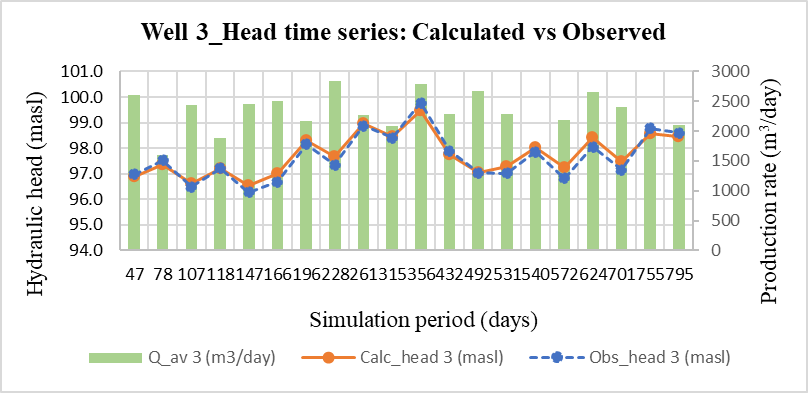


**Figure 6.** Head-time curves with production for wells 16, 17, and 18 from calibrated model



**Figure 7.** Head-time curves with production for wells 11, 12, and 13 from calibrated model

It was notable from the graphs that there was a significant reduction in the rate of pumping in well 11 for the simulation period 166 to 531 i.e. 2018/12/24 to 2019/12/24. From the reports obtained from the Budapest



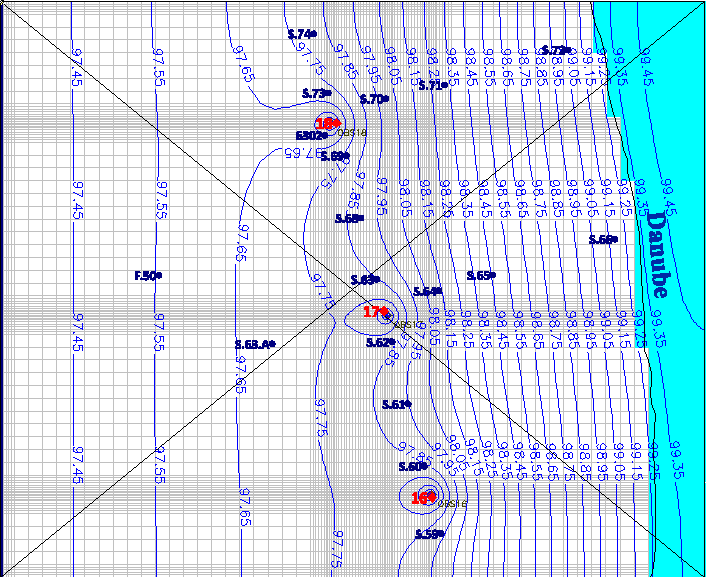
**Figure 8.** Head-time curves with Production for wells 1, 2, and 3 from the calibrated model

Waterworks company, the well pump was replaced with a smaller one since a reducing yield was noted from the well due to siltation over time. The company later flushed and cleaned the well and re-installed the original bigger pump.

The nine head-time series curves (Figures 6, 7 and 8) suggest that there is a direct influence of the daily production rate (Q m3/day) on the hydraulic head. The hydraulic heads are higher during the periods of lower daily production rates and lower when the production rates are higher. This observation can generally be made for all the wells. However, this effect is more pronounced in wells 11 to 16, which are farther away from the river. This is because the recovery due to recharge from the river is decreasing with an increase in the distance from the river. It is also observed that the highest points noted in all the curves are periods 261 and 356 which represent the period between 2019/02/25 and 2019/03/29 and the period from 2019/05/23 to 2019/07/02 which had the highest average river stage (flood) in the whole 3-year study period. This can be attributed to the high precipitation leading to flooding experienced during these periods.

### ***Head Distribution Contours***

After a successful run of the three models, head distribution contours were generated from the models that showed the changing piezometric surface between the Danube River and the shallow aquifer containing the production and observation wells (**Figures 9, 10** and **11**).

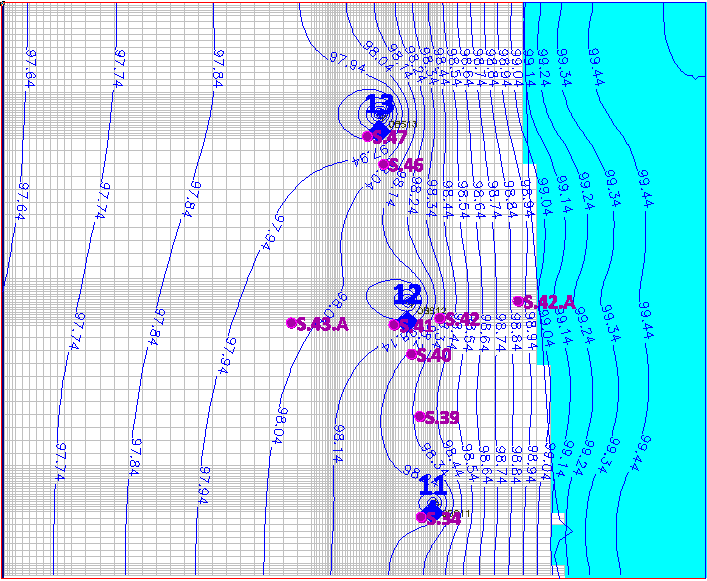


**18**

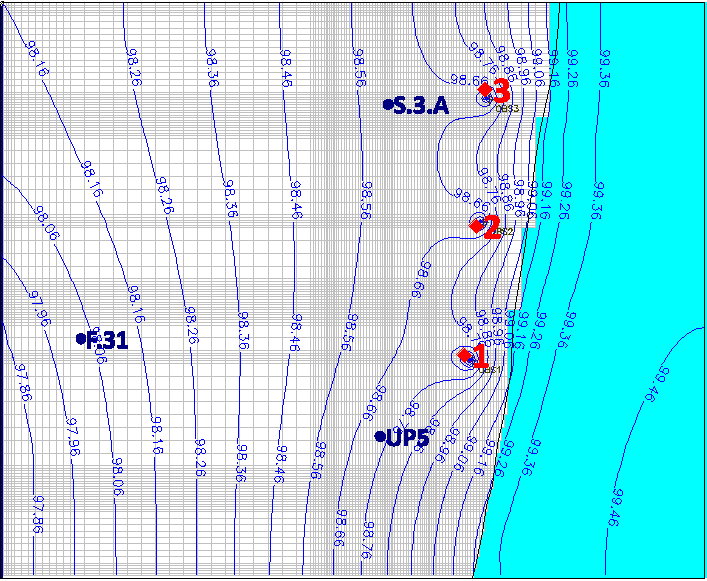
**16**

**17**

**Figure 9.** Head distribution in the aquifer for wells 16, 17, 18 at the end of the simulation period (period 20)



**Figure 10.** Head distribution in the aquifer for wells 11, 12, 13 at the end of the simulation period



**Figure 11.** Head distribution in the aquifer for wells 1, 2, 3 at the end of the simulation period

From the three snapshot figures of head distribution as derived from the models, it is noted that the piezometric surface was generally decreasing/dipping with distance away from the Danube River i.e. from 99m to 97m. The biggest depression is experienced around well number 18 which is the farthest from the river while the smallest depression occurs in wells 1 and 2 which are closer to the river. This means that the river provides a continuous recharge to the wells and due to the close proximity of wells 1 and 2 to the river, the wells only suffer a limited drawdown as a result of production pumping.

## **Calculation Of The Water Budget**

The three Processing MODFLOW models were used to calculate the water budget within the modelled areas. The purpose of the water budget calculation was to establish the extent of water contribution of the Danube River into the Surány aquifer. The water budget of the whole model domain for each of the three models covering the entire simulation period of 795 days (i.e. 12/07/2018 to 13/09/2020) was calculated (**Table 5**).

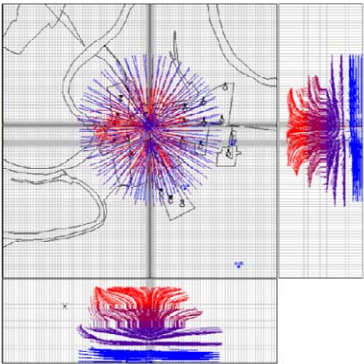
**Table 5.** The summarized water budget for the three models during the simulation period 12/07/2018 to 13/09/2020. “In” means water inflow into the modelled aquifers while “Out” means water outflow from the aquifers. For example, River Leakage (In) means a losing river condition where water seeps to the aquifer and recharges it (i.e. when river stage is higher than water table) while River Leakage (Out) is a gaining river condition where water flows from the aquifer to the river (when water table is higher than river stage). Constant Head represents flow either into or from the neighboring unconfined aquifer with known water table elevation.

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Aquifer around Wells 1, 2, 3** | **Aquifer around Wells 11, 12, 13** | **Aquifer around Wells 16, 17, 18** |
| Storage (In) [m3] | 18,280 | 18,978 | 13,574 |
| Constant Head (In) [m3] | 28,809 | 29,674 | 27,556 |
| Recharge (In) [m3] | 4,123 | 4,123 | 4,142 |
| River Leakage (In) [m3] | 158,199 | 168,966 | 119,670 |
| **Sum (In)** [m3] | **209,410** | **221,740** | **164,942** |
| Storage (Out) [m3] | 47,508 | 49,228 | 36,994 |
| Constant Head (Out) [m3] | 38,648 | 30,293 | 10,250 |
| Wells (Out) [m3] | 121,173 | 142,219 | 117,698 |
| River Leakage (Out) [m3] | 2080 | 0 | 0 |
| **Sum (Out)** [m3] | **209,410** | **221,740** | **164,942** |
| **Sum (In) – Sum (Out)** [m3] | **0** | **0** | **0** |
| % of river leakage to total Inflow | **75.5%** | **76.2%** | **72.6%** |

The important information deciphered from the water budget which is relevant to this investigation is about the contribution of river inflow to the water balance in the aquifer within the modelled areas. It can be seen that the proportion of river leakage (seepage) to the total inflow into the aquifer (i.e. contribution of the Danube River to the shallow aquifer) is above 72% for the three models. This means that river leakage is the biggest contributor of inflow into the aquifer. When the river stage rises to flooding levels, excess water is recharged to the aquifer. This important information further quantifies the direct connection between the river and the shallow aquifer.

## **Determination of Travel time of Bank Filtrate**

To further support the aim of examining the hydraulic and hydrogeologic connectivity between the Surány aquifer and the Danube River, particle tacking was performed in order to estimate the travel time of water particles (bank filtrate) to flow from the river bank to the production wells. This was achieved by use of the PMPATH package in-built in Processing MODFLOW to track the water particles flow path backwards from the wells to the riverbank. The particle tracking was performed under transient flow conditions.



**Figure 12.** The plan and cross-sectional views showing water particles travelling paths from a pumping well to the surface. The red ends show the particles arriving at the surface. In our case, the time was measured when the first particle reached the river bank. The average depth of the wells from where the particles originated from was 14.8m below ground level.

The flow path time was defined as the time taken by the first particle travelling underground through the subsurface from the far end of the well laterals to arrive at the river bank. This will give the reverse information about the time taken by a bank filtrate particle travelling from the riverbank to the wells. The well laterals were represented by cells with known lengths around the cell belonging to the central well. The depth of the wells was an average of 14.8m with an average aquifer thickness of 10.6m (Appendix 8.4). To present the results of the particle tracking, the stage-time series graph in **Figure 13** was used to select the stress periods to display based on the level of the Danube River stage. The extreme high and low flows were chosen so as to examine the effect of level of river stage on the particle travel time.

**Figure 13.** River stage-time series during the simulation period (20 stress periods)

**Table 6.** Particle travel times from the river bank to the studied collector wells

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Stress**  **period** | **Particle travel times (days)** | | | | | | | | |
| **Well 1** | **Well 2** | **Well 3** | **Well 11** | **Well 12** | **Well 13** | **Well 16** | **Well 17** | **Well 18** |
| 1 | 3 | 4 | 7 | 38 | 32 | 28 | 60 | 140 | 110 |
| 2 | 3 | 6 | 13 | 46 | 38 | 34 | 65 | 94 | 110 |
| 3 | 5 | 7 | 12 | 69 | 47 | 42 | 83 | 138 | 179 |
| 5 | 5 | 6 | 11 | 80 | 52 | 46 | 90 | 160 | 205 |
| 7 | 2 | 4 | 8 | 33 | 31 | 30 | 60 | 78 | 90 |
| 9 | 2 | 4 | 8 | 33 | 32 | 33 | 57 | 69 | 79 |
| 11 | 2 | 4 | 6 | 26 | 26 | 24 | 44 | 54 | 63 |
| 13 | 3 | 6 | 10 | 67 | 48 | 44 | 105 | 170 | 165 |
| 17 | 2 | 4 | 7 | 24 | 26 | 28 | 55 | 65 | 79 |
| 20 | 4 | 6 | 10 | 28 | 30 | 29 | 64 | 79 | 88 |
| **Average:** | **3** | **5** | **9** | **44** | **36** | **34** | **68** | **105** | **117** |
| **Minimum:** | **2** | **4** | **6** | **24** | **26** | **24** | **44** | **54** | **63** |
| **Maximum:** | **5** | **7** | **13** | **80** | **52** | **46** | **105** | **170** | **205** |
| **Mode:** | **2** | **4** | **7** | **33** | **32** | **28** | **60** | **-** | **110** |

**Table 6** shows that the travel times for wells 1, 2 and 3 ranged from 2 – 13 days, 24 -80 days for wells 11, 12 and 13, and 44 – 205 days for wells 16, 17 and 18. The results of the nine wells were taken to represent the rest of the wells since the three model areas were selected based on the distances of the wells from the river; the wells that were closest to the river i.e. 1, 2 and 3, those mid-way i.e. 11, 12, 13 and those relatively further way i.e. 16, 17 and 18. This was done in order to enable a more detailed, in-depth and concentrated investigation of the Surány aquifer, through representative smaller-scale areas. Another vital information obtained from Table 7 was that the level of river stage influenced the length of particle travel time; stress period 11 with the highest river stage yielded the shortest particle travel time across all the wells while stress periods 3 and 5 with the lowest river stages yielded the longest travel times. The big variances noted in the particle travel time ranges from well to well was attributed to the distances of the wells from the river, inhomogeneity within the aquifer and the differences in the amount of daily production rates.

The results of analysis of the bank filtrate travel times show that in the likely event that the Danube River gets polluted, it will take few days to few months for the pollution to reach the Surány production wells, depending on the distance the wells are from the river bank. This is beneficial because the information may guide in delineating protection zones of production wells, that is, zoning of protection areas based on the calculated time a polluting particle may take to travel from a surface water body to an aquifer.

Through the application of numerical modelling, this research showed that there was a strong hydraulic and hydrogeological connection between the Danube River and the shallow aquifer supplying the Surány waterworks. The results are well corroborated by past studies within the same groundwater field. Nyiri et al. (2023), using field measurements of stable isotopes, water levels, temperature, and electrical conductivity concluded that the Danube River played a significant role in the evolution of the production and monitoring wells’ levels located in Surány of Szentendre Island. Additionally, Kármán et al. (2014) applying the lumped-parameter “steady-state” dispersion model and observation of time-dependent stable isotopes (i.e. oxygen), established that 60% - 95% of the Danube River water were found in the collector wells and that means travel time of bank filtrate ranged between 6 –14 days depending on the Danube River water levels/stage. These results compared quite well with the results of our study which obtained an over 72% river contribution to the aquifer notwithstanding the unrefined nature of the models used.

# **5.0 CONCLUSION**

The overall aim of this study was to examine and quantify, through numerical modelling, the hydraulic groundwater-surface water connection between the river and adjoining shallow groundwater aquifer of Surány aquifer along the Danube River in Hungary. Numerical modelling revealed that there were bigger depressions due to pumping in production wells located farther away from the river as a result of decreasing recharge from the river. The water budget from the models showed that the river leakage (recharge) is the biggest contributor of inflow into the aquifer with over 70% contribution. The analysis of bank filtrate within the models demonstrated that the level of river stage influenced the length of particle travel time; higher river stages led to shorter particle travel times. For the wells closer to the Danube River, the calculated travel times were between 2 – 13 days while for those farthest away were between 80 and 205 days. The knowledge of the travel time of bank filtrate to the production wells may guide in delineating protection zones of wells, that is, zoning of protection areas based on the calculated time a polluting particle may take to travel from a surface water body to an aquifer. Additionally, the results of this study may help in the determination of suitable location and optimal pumping rates of RBF collector wells which ensure that a contamination plume does not reach an extraction well. The results may also have important implications for improving the understanding of the water supply, water quality risks, and floodplain ecosystem functioning for both the Danube River and the Surány aquifer. The investigation therefore was able to quantitatively achieve the objective of the study that numerical modelling can be applied to demonstrate a strong hydraulic and hydrogeological connection between a permanent river and an adjacent alluvial aquifer. In this study, the hydraulic and hydrogeological connection between Surány aquifer and the Danube River has been shown and quantified both empirically and numerically.

Further work is recommended in the conceptual model development especially mesh refinement and input parameters to ensure that it simulates the actual flow conditions between the aquifer and the river. Moreso, better specialized packages that include the Multi-Node Well package that accurately simulates the production wells may be applied to yield results that are closer to reality. It is also recommended for further research to be considered exploring the finite element method of numerical modelling in examining the GW-SW interactions and evaluating the differences with the current method of finite difference applied. The success of this investigation which was based mainly on monitoring data underscores the critical part played by continuous data collection and monitoring in tracking surface water-groundwater interaction especially in flooding environments and contaminant transport. The output of this work will directly contribute to the Danube River basin-wide water resources management and flood risk management plan developed in 2015 and the European Union Floods Directive. The results may as well be applied to examine similar aquifer-river relationships in the future, with a special focus on floodplains and SW to GW contamination.

# **ACKNOWLEDGMENT**

This paper was part of the first author’s master’s thesis research. The authors would like to extend sincere appreciation to the Faculty of Earth Sciences and Engineering, University of Miskolc - Hungary) where part of this work was carried out. The authors further acknowledge the Stipendium Hungaricum Scholarship for offering the first author an opportunity to advance his studies and research in Hungary. Finally, the authors do recognize Budapest Waterworks Company who provided and allowed the use of their data for the purpose of the research

# **REFERENCE**

1. Anderson, M.P., Woessner, W.W. and Hunt, R.J. (2015) *Applied Groundwater Modelling: Simulation of Flow and Advective Transport*. Second. San Diego, United States: Elsevier Inc.
2. Bailey, R. T., Jeong, J., Park, S., & Green, C. H. (2022). Simulating salinity transport in High-Desert landscapes using APEX-MODFLOW-Salt. Journal of Hydrology, 610, 127873.
3. Bara, M. K., Dulovičová, R., Velísková, Y., & Farkas, C. (2024). Impacts of riverbed aggradation on groundwater regime in a lowland area. Journal of Hydrology and Hydromechanics, 72(2), 185-198.
4. Boano, F. *et al.* (2006) ‘Sinuosity-driven hyporheic exchange in meandering rivers: HYPORHEIC EXCHANGE IN MEANDERING RIVERS’, *Geophysical Research Letters*, 33(18), p. n/a-n/a. doi:10.1029/2006GL027630.
5. Bonduà, S., Bortolotti, V., Macini, P., & Strpić, K. (2023). A toolset for handling unstructured voronoi grids for MODFLOW. Environmental Modelling & Software, 159, 105563.
6. Brunke, M. (1999) ‘Colmation and Depth Filtration within Streambeds: Retention of Particles in Hyporheic Interstices’, *International Review of Hydrobiology*, 84, pp. 99–117. doi:10.1002/iroh.199900014.
7. Budapest Water Works (2018) *Annual Report 2018*. Budapest. Available at: https://www.vizmuvek.hu/files/public/Fovarosi\_vizmuvek/tarsasagi\_informaciok/bw\_annual\_report\_2018.pdf.
8. Bui, Dieu Tien, Khabat Khosravi, Mahshid Karimi, Gianluigi Busico, Zohreh Sheikh Khozani, Hoang Nguyen, Micol Mastrocicco, Dario Tedesco, Emilio Cuoco, and Nerantzis Kazakis. "Enhancing nitrate and strontium concentration prediction in groundwater by using new data mining algorithm." Science of the Total Environment 715 (2020): 136836.
9. [Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks](http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32007L0060:EN:NOT)
10. Eleftheriadou, E., Giannopoulou, I., & Yannopoulos, S. (2015, June 10). *The European Flood Directive: Current Implementation and Technical Issues*.
11. Felfelani, F., Hughes, J., Chen, F., Dugger, A., Schneider, T., Gochis, D., ... & Essaid, H. (2024). Simulation of groundwater-flow dynamics in the US Northern High Plains driven by multi-model estimates of surficial aquifer recharge. *Journal of Hydrology*, *630*, 130703.
12. Nyiri, G., Andrea, K. T., Zsombor, F., Balázs, Z., & Péter, S. (2023). Examination of the effect of the river in riverbank filtrated system using field measurements. *Multidiszciplináris Tudományok*, *13*(4), Article 4. <https://doi.org/10.35925/j.multi.2023.4.11>
13. Gadadhara, F. and Krámer, T. (2021) ‘Surface Water-Groundwater Interactions and Bank Storage during Flooding: A Review’, *Periodica Polytechnica Civil Engineering,* (66(1)), pp. 149–163. doi:https://doi.org/10.3311/PPci.18594.
14. Grischek, T. *et al.* (2002) ‘Bank filtration in Europe — An overview of aquifer conditions and hydraulic controls’, in *Management of Aquifer Recharge for Sustainability*. 1st edn. CRC Press.
15. Grischek, T. and Ray, C. (2019) *Efficiency of Bank Filtration and Post-Treatment*. MDPI.
16. Guevara Ochoa, C., Medina Sierra, A., Vives, L., Zimmermann, E., & Bailey, R. (2020). Spatio‐temporal patterns of the interaction between groundwater and surface water in plains. Hydrological Processes, 34(6), 1371-1392.
17. Ferraz, G., & Krámer, T. (2022). Surface Water–Groundwater Interactions and Bank Storage during Flooding: A Review. *Periodica Polytechnica Civil Engineering*, *66*(1), Article 1. <https://doi.org/10.3311/PPci.18594>
18. Hiscock, K.M. and Bense, V.F. (2014) *Hydrogeology: Principles and Practice.* Second. Chichester, West Sussex, UK: John Wiley & Sons Ltd.
19. Hiscock, K.M. and Grischek, T. (2002) ‘Attenuation of groundwater pollution by bank filtration’, *Journal of Hydrology*, 266(3–4), pp. 139–144. doi:10.1016/S0022-1694(02)00158-0.
20. ICPDR. (2015). The Danube River Basin district management plan–update 2015.
21. Jafari, T., Kiem, A. S., Javadi, S., Nakamura, T., & Nishida, K. (2021). Fully integrated numerical simulation of surface water-groundwater interactions using SWAT-MODFLOW with an improved calibration tool. Journal of Hydrology: Regional Studies, 35, 100822.
22. Jaramillo, M. (2012) ‘Riverbank filtration: An efficient and economical drinking-water treatment technology’, *DYNA*, 79, pp. 148–157.
23. Kármán, K. *et al.* (2014) ‘Transit time determination for a riverbank filtration system using oxygen isotope data and the lumped-parameter model’, *Hydrological Sciences Journal*, 59(6), pp. 1109–1116. doi:10.1080/02626667.2013.808345.
24. Kolencsik-Tóth, A. and Kovács, B. (2015) ‘Calibration process for groundwater flow model of a river influenced shallow aquifer’, *Central European Geology*, 58(1–2), pp. 186–198. doi:10.1556/24.58.2015.1-2.12.
25. Kreft, S., & Güngöroglu, C. (2018). *Natura 2000 – An Overview* (pp. 1–16).
26. Lakshmanan, E. (2005). *Numerical simulation of groundwater flow and solute transport* (p. viii + 246).
27. M. M., Busico, G., Mastrocicco, M., & Kazakis, N. (2022). Modeling groundwater and surface water interaction: An overview of current status and future challenges. Science of the Total Environment, 846, 157355.
28. Nagy-Kovács, Z. *et al.* (2018) ‘Operational Strategies and Adaptation of RBF Well Construction to Cope with Climate Change Effects at Budapest, Hungary’, *Water*, 10(12), p. 1751. doi:10.3390/w10121751.
29. Nagy-Kovács, Z. *et al.* (2019) ‘Water Quality Changes during Riverbank Filtration in Budapest, Hungary’, *Water 2019*, 11(302). doi:doi:10.3390/w11020302.
30. Ritzema, H., Kselik, R.A.L. and Chanduvi, F. (1996) *Drainage of Irrigated Lands*. FAO.
31. Simcore Software (2012) ‘Processing Modflow: An Integrated Modeling Environment for the Simulation of Groundwater Flow, Transport and Reactive Processes’. Available at: https://www.simcore.com/files/pm/v8/pm8.pdf (Accessed: 3 May 2022).
32. Szabó A., Á.S. (2021) *Hydrogeological investigations of bank filtered aquifers including flow time and recharge ratio determination*. Thesis. University of Miskolc.
33. Szilágyi, J., Kovács, Á. and Józsa, J. (2012) ‘Remote-Sensing Based Groundwater Recharge Estimates in the Danube-Tisza Sand Plateau Region of Hungary’, *Journal of Hydrology and Hydromechanics*, 60(1), pp. 64–72. doi:10.2478/v10098-012-0006-3.
34. Tóth K. A, A.K. (2017) *Investigation of Interaction Between River and Shallow Groundwater*. Thesis. University of Miskolc.
35. Tóth, M., Bajor, Z., Bárány, A., G., F., Görföl, T., Halpern, B., Sz, L.-Ő., Mészáros, R., Péntek, A., Tóth, B., Tóth, Z., & Vörös, J. (2015). *Budapest* (pp. 22-73.). <https://doi.org/10.1007/978-1-4939-1698-6_2>
36. Velickovic, B. (2005) ‘Colmation as one of the processes in interaction between the groundwater and surface water’, *Facta universitatis - series: Architecture and Civil Engineering*, 3(2), pp. 165–172. doi:10.2298/FUACE0502165V.
37. Woessner, W.W. and Poeter, E.P. (2020) *Hydrogeologic Properties of Earth Materials and Principles of Groundwater Flow*. Canada: Groundwater Project. Available at: gw-project.org.
38. Zhang, L., Li, X., Han, J., Lin, J., Dai, Y., & Liu, P. (2024). Identification of surface water-groundwater nitrate governing factors in Jianghuai hilly area based on coupled SWAT-MODFLOW-RT3D modeling approach. Science of The Total Environment, 912, 168830.
39. Zhang, Z. Y., & Sato, M. (2024). Conjunctive surface water and groundwater management in a multiple user environment. Environmental Economics and Policy Studies, 1-39.

# **APPENDICES**

## Appendix 8.1: The basic data of the 20 RBF collector wells located in Surány

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Well ID** | **Installation year** | **Y coord (EOV)** | **X coord (EOV)** | **Diameter (mm)** | **Bottom of well (mBf)** | **Ground level (mBf)** | **Top of aquifer (mBf)** | **Bottom of aquifer (mBf)** | **Total Depth (m)** | **Aquifer Thickness (m)** |
| 1 | 1969 | 655623.70 | 263949.90 | 2200 | 93.79 | 104.27 | 101.77 | 94.17 | 10.48 | 7.60 |
| 2 | 1969 | 655641.85 | 264151.00 | 2200 | 88.59 | 104.97 | 101.77 | 88.96 | 16.38 | 12.81 |
| 3 | 1969 | 655656.75 | 264363.50 | 2200 | 89.70 | 103.79 | 100.88 | 89.88 | 14.09 | 11.00 |
| 4 | 1969 | 655682.35 | 264547.10 | 2200 | 89.34 | 103.52 | 100.42 | 90.12 | 14.18 | 10.30 |
| 5 | 1969 | 655697.15 | 264742.85 | 2200 | 87.10 | 103.31 | 100.36 | 88.01 | 16.21 | 12.35 |
| 6 | 1969 | 655718.90 | 264939.40 | 2200 | 87.79 | 102.98 | 99.97 | 88.37 | 15.19 | 11.60 |
| 7 | 1969 | 655787.90 | 265334.50 | 2200 | 88.19 | 103.60 | 98.59 | 89.56 | 15.41 | 9.03 |
| 8 | 1969 | 655855.75 | 265731.45 | 2200 | 88.38 | 104.00 | 100.09 | 88.59 | 15.62 | 11.50 |
| 9 | 1969 | 655889.30 | 265928.60 | 2200 | 88.24 | 104.23 | 99.92 | 88.62 | 15.99 | 11.30 |
| 10 | 1969 | 655923.00 | 266126.70 | 2200 | 89.21 | 104.24 | 101.56 | 88.26 | 15.03 | 13.30 |
| 11 | 1972 | 655972.55 | 266504.00 | 2200 | 88.93 | 104.82 | 102.62 | 90.12 | 15.89 | 12.50 |
| 12 | 1972 | 655932.90 | 266801.65 | 2200 | 88.88 | 105.04 | 102.13 | 89.13 | 16.16 | 13.00 |
| 13 | 1973 | 655889.75 | 267098.00 | 2200 | 87.21 | 103.81 | 101.21 | 88.76 | 16.60 | 12.45 |
| 14 | 1973 | 655838.30 | 267392.60 | 2200 | 88.06 | 104.31 | 99.50 | 89.71 | 16.25 | 9.79 |
| 15 | 1970 | 655746.65 | 267826.55 | 2200 | 91.28 | 104.44 | 100.33 | 89.33 | 13.16 | 11.00 |
| 16 | 1970 | 655673.05 | 268126.40 | 2200 | 88.92 | 104.23 | 100.13 | 89.93 | 15.31 | 10.20 |
| 17 | 1970 | 655598.60 | 268416.90 | 2200 | 90.81 | 103.67 | 98.72 | 91.37 | 12.86 | 7.35 |
| 18 | 1970 | 655524.80 | 268709.70 | 2200 | 90.15 | 104.23 | 101.13 | 90.03 | 14.08 | 11.10 |
| 19 | 1970 | 655450.40 | 268994.40 | 2200 | 90.66 | 104.56 | 99.56 | 90.36 | 13.90 | 9.20 |
| 20 | 1970 | 655374.40 | 269282.90 | 2200 | 91.67 | 104.99 | 96.59 | 91.99 | 13.32 | 4.60 |

## Appendix 8.2: Summary of the simulation period divided into 20 stress periods with the average river stage and production rates for wells 1, 2, 3, 11, 12, and 13 during the period.

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Stress Period** | **Simulation period** | | **Period length (days)** | | **River stage, Hd\_average (masl)** | **Average pumping rate, Q\_av (m3/day)** | | | | | |
| **Start** | **End** | **Well 1** | **Well 2** | **Well 3** | **Well 11** | **Well 12** | **Well 13** |
| 1 | 2018/07/12 | 2018/08/27 | | 47 | 98.01 | 1311 | 2890 | 2604 | 1362 | 3024 | 3729 |
| 2 | 2018/08/28 | 2018/09/27 | | 31 | 98.19 | 1044 | 1779 | 1593 | 1152 | 2824 | 3489 |
| 3 | 2018/09/28 | 2018/10/26 | | 29 | 97.60 | 785 | 2712 | 2429 | 1011 | 2815 | 3474 |
| 4 | 2018/10/27 | 2018/11/06 | | 11 | 98.31 | 1101 | 2106 | 1888 | 784 | 3429 | 2240 |
| 5 | 2018/11/07 | 2018/12/05 | | 29 | 97.55 | 599 | 2742 | 2458 | 883 | 2687 | 3450 |
| 6 | 2018/12/06 | 2018/12/24 | | 19 | 98.31 | 1285 | 2723 | 2501 | 1109 | 2520 | 3024 |
| 7 | 2018/12/25 | 2019/01/23 | | 30 | 99.65 | 1633 | 2477 | 2164 | 923 | 2034 | 2781 |
| 8 | 2019/01/24 | 2019/02/24 | | 32 | 98.92 | 1155 | 1868 | 2832 | 607 | 1887 | 2489 |
| 9 | 2019/02/25 | 2019/03/29 | | 33 | 100.36 | 1542 | 2197 | 2264 | 813 | 2030 | 1972 |
| 10 | 2019/03/30 | 2019/05/22 | | 54 | 99.53 | 1615 | 2315 | 2088 | 985 | 2445 | 3110 |
| 11 | 2019/05/23 | 2019/07/02 | | 41 | 101.12 | 2211 | 2962 | 2796 | 1069 | 2643 | 3583 |
| 12 | 2019/07/03 | 2019/09/16 | | 76 | 98.79 | 1553 | 2551 | 2291 | 908 | 2808 | 3653 |
| 13 | 2019/09/17 | 2019/11/15 | | 60 | 98.20 | 1370 | 2328 | 2678 | 810 | 2472 | 3096 |
| 14 | 2019/11/16 | 2019/12/24 | | 39 | 98.40 | 801 | 2264 | 2290 | 1636 | 2945 | 2964 |
| 15 | 2019/12/25 | 2020/01/02 | | 9 | 99.20 | 1204 | 1732 | 1575 | 1826 | 2128 | 1979 |
| 16 | 2020/01/03 | 2020/02/03 | | 32 | 98.19 | 1029 | 2848 | 2185 | 1376 | 2947 | 3671 |
| 17 | 2020/02/04 | 2020/03/26 | | 52 | 99.92 | 1909 | 3231 | 2655 | 2508 | 2925 | 3054 |
| 18 | 2020/03/27 | 2020/06/11 | | 77 | 98.59 | 1565 | 2649 | 2400 | 2385 | 3176 | 3773 |
| 19 | 2020/06/12 | 2020/08/04 | | 54 | 99.78 | 1517 | 2014 | 1973 | 2176 | 2407 | 3259 |
| 20 | 2020/08/05 | 2020/09/13 | | 40 | 99.60 | 1507 | 2278 | 2107 | 2361 | 2824 | 3775 |