University of Pecs, Doctoral School of Earth Sciences

Ph.D. Thesis Booklet

A FULLY DISTRIBUTED INTEGRATED HYDROLOGIC MODEL FOR INTEGRATED WATER RESOURCES MANAGEMENT IN A HIGHLY REGULATED RIVER FLOODPLAIN

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1. INTRODUCTION

Growing awareness about the benefits of more sustainable management and allocation of water resources has highlighted the need to manage surface water and groundwater systems as a single integrated system. Hydrological models are a simplified representation of hydrological processes and can be applied for water and environment resources management to provide an overall view of the status of Integrated Water Resources Management (IWRM). Incessant human interventions alter, at an increasing rate, the hydrological process and, consequently, reduce the availability of water in floodplains. Moreover, a growing global population exposed to climate change, pollution, and insufficient groundwater recharge result in dropping groundwater levels. A better understanding of the spatial and temporal distributions of water balance components, especially groundwater recharge, becomes essential for successful management of water resources and modeling subsurface fluid and contaminant transport (Arefaine et al., 2012), especially now where these resources become the primary source for drinking water.

The water resources are under serious pressure because of population growth, climate change, and industrialization, which make these resources more vulnerable (Heo et al., 2015). They can influence sustainable development and ecosystem services as well as socio-economic processes. Moreover, land-use/land-cover (LULC) changes are among the major factors altering regional hydrological processes of river basins (Yang et al., 2019). Without accurate estimation, the effects of LULC changes on hydrologic components may be misinterpreted, underrated or exaggerated. There are further research questions as to how concurrent changes in several LULC classes, and modified proportions of the individual LULC classes influence changes in each hydrological component. The answers to these questions will improve the predictability of hydrological consequences of LULC changes and, thus, are crucial and urgent for efficient water resources management, ecological restoration (Tang et al., 2005), and sustainable development.

Channel/floodplain connectivity is a decisive factor of water supply to oxbow lakes and, thus, a main ecological requirement for floodplain restoration (Wren et al., 2008). The sedimentological sequences along the lower sections of rivers have been created by the alluviation of meandering rivers in historical times. For the rehabilitation measures to enhance ecosystem services, the detailed hydrogeological study of alluvial deposits and soils is indispensable. The multi-layered sediments are of crucial importance as geological background to subsurface water dynamics. The exchange between the alluvial aquifer system and surface water will be affected by the degree of subsurface heterogeneity (Woessner, 2000). Although many studies address the interaction between groundwater and surface water, the degree of subsurface aquifer heterogeneity has been rarely investigated.

International examples show that the integrated (conjunctive) use of surface water and groundwater within a proper management system increases the efficiency of water utilization (Cheng et al., 2009), provides sufficient irrigation water for agriculture (Seo et al., 2018), and improves the environmental conditions of irrigated lands (Liu et al., 2013). The management of a sustainable river basin requires a better understanding of water resources systems and their relationships and types (e.g. groundwater, surface water, quantity and quality, upstream, downstream interactions, and biotic components). Computer models are widely available when it comes to applications in water resources and hydrological analyses. A surface water model is responsible for the surface water hydrology, while a groundwater model covers all processes associated with groundwater, including saturated flow and groundwater discharge into rivers. Coupling the surface water and groundwater models eliminates the limitations inherent in each model to yield a solution that is more in line with real-world hydro(geo)logy. Integrated models in IWRM have gradually gained significance as the problem of IWRM becomes more and more complex requiring more detailed, refined, and dynamic solutions in more challenging situations.

2. Problem Statement

The understanding and effective management of drought and flood issues within catchments are critical to the sustainability of these systems and the environments they support. The holistic consideration of surface water and groundwater systems in catchment hydrology requires the quantification of both surface and subsurface flow processes and their interactions. Whilst there has been a significant contribution to the knowledge and understanding of hydrogeological research of surface water-groundwater interactions in the past few decades, there are still specific knowledge gaps on how different types of systems (i.e., connected gaining and losing, and losing disconnected) function and interact at different spatial and temporal scales and in different hydrogeological environments. Consequently, a need has arisen for fully integrated surface-subsurface flow models to serve as an essential tool in understanding and quantifying these interactions/processes. This body of research addresses some of the complexities of surface water-groundwater interactions in highly regulated river basins, at different spatial and temporal scales, and investigates a number of the dominant controls (e.g. sediment sequences and LULC changes) that influence the exchange processes and dynamics between surface water and groundwater.

Over the last centuries, half of the European wetlands and more than 95% of riverine floodplains were converted to agricultural and urban lands (Gumiero et al., 2013). Human interventions have fundamentally altered the water availability of floodplain landscapes. Changes in the water regimes of rivers are predicted to be damaging to these ecosystems under extensive human pressure, resources exploitation, and pollution. Abandoned channels and oxbow lakes, the most common landforms of floodplains, are regarded particularly sensitive to such pressures. They are highly sensitive to human activities. Recently, the Hungarian Drava floodplain was influenced by large-scale landscape degradation. Global climate change, on one hand, and human interventions, on the other hand, substantially alter and disturb the ecological regime and balanced water budget of floodplains. River channelization and widespread agricultural utilization induced gradual desiccation in the Drava floodplain, loss of wetlands and reduced landscape diversity. In response to specific regional influences, droughts tend to occur with a frequency equal to that of floods. The previously satisfactory water availability in the Drava floodplain, disconnected from the river channel, was replaced by the alternation of flood and drought periods – occasionally even within a single year. With groundwater tables dropping by 1.5 to 2.5 m, the entrenchment of the river leads to intensified drought hazards and water stress in the floodplain. Increasing drought hazard is recognized as a key factor contributing to the loss of ecosystem services, including biodiversity and agricultural productivity, in the floodplain. Water shortages particularly manifested in decreased river discharge and wetlands desiccation, are aggravated by the acidification trend induced by global climate change. Therefore, the ecological functioning of the natural systems and physical habitats have deteriorated.

Moreover, water shortages have adverse effects on agricultural productivity, related socio-economic conditions, and the life quality of the local population. The optimal design of the groundwater table in the floodplain is a complex task because of the conflicts between agriculture, forestry, flood control, and natural conservation demands. The conditions for agriculture, the main source of subsistence for the population, became critical. Recently, competition between water users represented a serious issue in the Drava floodplain (Bonacci and Oskoruš, 2019) and it is predicted to radically aggravate in the next few years. Water resources are limited and any shortage in them threatens the sustainable development of different sectors (e.g., industry, agriculture, municipal, and tourism) in the Drava basin. Protecting groundwater resources in the Drava basin is especially important for the provision of ecosystem services, landscape management, nature conservation, and economic development through improving agricultural productivity. Therefore, it is required to investigate and manage alternative water resources.

3. Motivation and Objectives

IWRM is a complex process and requires integration at a different level. It is crucial to study hydrological and groundwater flow models and all processes which influence this model to assess the availability of water and investigate the LULC change effects on water resources. This study aims to present a comparative analysis of the use of an Integrated Surface Water-Groundwater Hydrologic Modelling to capture hydrologic responses and to integrate water resources management for the highly regulated river basin. Most studies focused only on one or two aspects of modeling for water resources management where a systematic approach is required:

- To assess the interactions between groundwater and surface water at a critical part of this system: between a protected oxbow (which is fed by water according to the Old Drava Programme, ODP) and the main river (Drava).
- To assess groundwater potential, and long-term spatial distribution of monthly, seasonal, and annual components of the water budget in the Drava basin.
- To assess the potential effects of LULC change on the total water budget and average groundwater level of the Drava floodplain.
- To recommend suitable management strategies for restoration of the surface and groundwater resources under the water replenishment scenarios through natural reservoirs.

The specific objectives are:

- To assess the effect of sedimentological sequences along the lower sections of rivers on surface water –groundwater interaction,
- To analyze the exchange of water fluxes between an oxbow lake and aquifers and the changes in groundwater levels under each scenario of oxbow lake(s) replenishment,
- To evaluate the feasibility of water replenishment through natural reservoirs under different management scenarios,
- To quantify the water budget and water retention, under different management scenarios in the lower parts of the floodplain.

One of the ambitions of this thesis is to support the Government in their decision-making by providing access to improved (processed) data and to provide planners with tools to assess the effects of LULC changes on ecosystem services and explore the hydrological feasibility of alternative water management, i.e., the restoration of natural reservoirs (abandoned paleochannels) to mitigate water shortage problems. One of the challenges for the study is to feed their knowledge into regional and national planning systems to manage the Drava River basin now and in the future. The outcome of this study may serve as a contribution to planning, by providing a deeper understanding of the special and temporal distributions of water balance components, the spatial extent and variation of groundwater levels, the effects of LULC change on hydrology, and the dynamic interactions between groundwater and surface water within the Drava River basin, especially water balance between the lake and groundwater. The research was also contrived to underpin the applicability of WetSpass–MODFLOW as a planning tool to predict the effect of natural and anthropogenic influences on the floodplain.

4. New scientific results

A hydrological model for a highly regulated river floodplain, the Drava River basin in Hungary, was developed using the WetSpass-M model to assess groundwater potential, and the long-term spatial distribution of monthly, seasonal, and annual components of the water budget in the Drava basin. The model was thoroughly validated against the calculated groundwater recharge of the water table fluctuation method. A 3-D groundwater model for this oxbow of the Drava floodplain is developed using MODFLOW-NWT to assess the effect of sedimentological sequences along the lower sections of rivers on surface water –groundwater interaction and to gain a better understanding of the water budget of the whole system under the normal situation and for different lake replenishment scenarios. The model was thoroughly calibrated against measured lake stages and groundwater levels from 18 observation wells.

Additionally, an integrated surface water (WetSpass-M) and groundwater model (MODFLOW-NWT) is developed and calibrated with an eight-year data series to improve the long-term stressor simulation of WetSpass standalone in the study area. The integrated model is applied to examine the human interventions within natural hydrological systems, assess the potential effects of LULC change on the total water budget, and groundwater hydrology, and evaluate the feasibility of water replenishment through natural reservoirs under different management scenarios. The main results of my work are summarized in the following theses.

4.1. 1 st Thesis:

The first stage is simulating long-term mean spatial patterns of actual evapotranspiration, surface runoff, and groundwater recharge of a highly regulated river system, the Drava River basin. A WetSpass-M model is utilized to estimate the spatial groundwater recharge on monthly, seasonal, and annual scales. The analysis of simulation results shows that the WetSpass-M model works properly to simulate hydrological water budget components in the Drava basin. The total components of the water balance of the vegetated, bare soil, open-water, and impervious fraction per raster cell are calculated. The basic input data of the WetSpass–M model include meteorological data (precipitation, air temperature, wind speed, and potential evapotranspiration), distributed groundwater depth, LAI, soil types, topography (DEM and slope), and land use/land cover of the investigated area. Such input data are prepared as grid maps using Geographic Information Systems (ArcGIS) collected for the period from 2000 to 2018. The cell size of the raster is 100 m × 100 m. The spatial variability of groundwater recharge relies on climate conditions, groundwater depth, distributed land cover, soil texture, topography, and slope. Land cover and soil textures are dominated by agricultural areas and loam in the Drava basin. Water balance components under different land use and soil textures were evaluated. The water-table fluctuation method (WTF) is used to validate the performance of the WetSpass-M.

The WetSpass-M model estimates the annually actual evapotranspiration of the basin, for the period from 2000 to 2018, to be 127 mm and 263 mm as a minimum and maximum values respectively. This represents 27% of the annual average precipitation. 83% of total evapotranspiration occurs in the wet season, while the remaining 17% occurs during dry seasons. Around 29% (199 mm yr^{-1}) of the average annual rainfall feeds surface runoff with minimum and maximum average values of 77 mm yr^{-1} and 418 mm yr^{-1}, respectively. Annually simulated groundwater recharge ranges from 175 mm yr^{-1} to 412 mm yr^{-1} with an average of 307 mm yr^{-1}, which correspond to 44% of mean annual rainfall. Moreover, a better understanding of the simulated long-term average spatial distribution of water balance components is required for managing and planning the available water resources in the Drava basin. Moreover, a better understanding of the simulated long-term average spatial distribution of water balance components is useful for managing and planning the available water resources in the Drava basin.

4.2. 2 nd Thesis:

The second stage is developing a 3-D steady-state and transient groundwater model using the finite difference code MODFLOW-2005 for the period from 1 January 2010 to 20 September 2018. Calibrated results of the transient groundwater flow model showed a good match between observed and simulated groundwater heads, with R^2 = 0.98. The mean error was −0.08 m, and the root mean square error was 0.4 m. The first three hydrological years from which data were available, i.e., from 1 January 2010 until 31 December 2012, were used as a warm-up period, after which the model was run (calibrated) throughout the following six hydrological years from 1 January 2013 to 20 September 2018 with a daily time step. The calibration process was carried out using measured lake stages and a time series of daily groundwater levels from 18 observation wells. The sensitivity analysis was achieved using UCODE-2005 with the help of ModelMate. The interaction between the Cún-Szaporca oxbow lakes and groundwater is simulated using MODFLOW-NWT under the ModelMuse environment, considering the interaction between surface water and groundwater by activating the Lake Package (LAK7), River Package (RIV), the Stream Flow Routing Package (SFR7), Recharge Package (RCH) and Evapotranspiration Package (ET). The sedimentological sequences were investigated using satellite images, GPR profiles, boreholes for revealing layering, and in situ studies of hydraulics of seepage. The origin and extension of layers were identified through geomorphological interpretation (distinguishing between point bar, dune, and other deposits). However, from the viewpoint of hydraulic modeling, a random spatial pattern of such deposits was reconstructed. Their hydrological properties show a wide range (k = 10^{-4}–10^{-7}). Different fluvial sediment structures scenarios were investigated to assess the interactions between groundwater and surface water at a critical part of this system: between a protected oxbow (which is fed by water according to the Old Drava Programme (ODP)) and the main river (Drava). Moreover, the model is applied to analyze two scenarios for the replenishment of the Cún-Szaporca oxbow lakes. The theory for creating our modeling space is that the generated (sub) structures that are characterized by different hydraulic properties and formed during the sedimentation are analogous to fluvial features such as point bars, traces of lateral migration of river channels, and other features of lateral accretion. The running of scenarios related to extended continuous layering in the whole model space was shown to be unsuccessful. The application of a multilayered structure provided the most realistic result.

Additionally, the calibration of lake stages showed a good agreement between simulated and observed stages with a correlation coefficient of 0.90, a mean error of −0.07 m, mean absolute error of 0.15 m, and root mean square error of 0.2 m. The parameters of the groundwater recharge (RCH), hydraulic conductivity (HKZ1), and evapotranspiration (EVT) had the highest composite scaled sensitivity values and were therefore the most sensitive parameters. accretion.

4.3. 3 rd Thesis:

The third stage is the coupling of the WetSpass model with MODFLOW to improve the simulation of impacts of long-term stressors, as this variable concerns the decision-makers for water resources. Land-use/land-cover (LULC) change is considered to be a key human factor influencing groundwater recharge in floodplains. Changes in built-up areas have a positive influence on surface runoff. The expansion of artificial (sealed) surfaces between 2012 and 2018 was detected as the main contributor to the increase of surface runoff by 9 mm yr^{-1} in the Drava basin. Changes of arable lands, forest, mudflat, and willow shrubs were observed as having a negative effect on groundwater recharge and a positive impact on actual evapotranspiration. The integrated hydrologic modeling framework is applied to assess the impacts of LULC changes from 1990 to 2018 on the hydrology of the Drava floodplain, where human interference has led to a critical environmental situation. Five different runs, for which, each run corresponds to one LULC map from the years 1990, 2000, 2006, 2012, and 2018, respectively were conducted. To isolate, and yet capture, the effect of LULC changes, other input parameters such as meteorological data, topography (DEM and slope), distributed groundwater depth, and soil types were kept constant among all the five runs. Each run simulated the long-term average water balance components. Impacts of impervious cover changes on water balance components were assessed. Moreover, the integrated model is applied to evaluate the effects of LULC changes on water budget and groundwater level.

The replacement of arable and meadowlands by forest, and mudflat, with expanding willow shrub areas was identified as the strongest contributor to the major increase in evapotranspiration by 9 mm yr^{-1} and a decrease in groundwater recharge by 7 mm yr^{-1} between LULC in 2012 and 2018. These changes in LULC have resulted in a decline in groundwater recharge over an area of 5.3×10^7 m^3 amounting to a 0.1 m drop in groundwater level regarding the whole floodplain between 2012 and 2018. A decrease in groundwater recharge would directly reduce recharge for both deep and shallow aquifers and it increased the environmental threat in the floodplain. As a consequence, the conditions of agriculture that represent the primary source of subsistence for the local population became critical. The results also show that LULC changes have a direct effect on groundwater recharge and the provision of floodplain ecosystem services. The coupled model proved to be a valuable assessment tool for the effective and sustainable implementation of floodplain rehabilitation plans. Finally, as a result of human intervention, available water resources in the Drava floodplain are rapidly diminishing, and effective integrated watershed management is required to address water availability. The approach tested in this study allows temporal and spatial estimation of hydrological components under the changes of LULC, providing quantitative information for decision-makers to implement sustainable management of water resources in the Drava floodplain.

4.4. 4 th Thesis:

The fourth stage of research covers the hydrological feasibility of alternative water management, i.e., the restoration of natural reservoirs (abandoned paleochannels) to mitigate water shortage problems was explored within the Drava Basin. The consequences of constructing a natural reservoir in augmenting surface water storage are investigated under variable management scenarios of recharging or feeding the reservoir. Natural reservoirs can be regarded as an economically feasible management practice of water retention and can help protect ecological values, the restoration of wetlands, and enhance agriculture productivity in the Hungarian section of the Drava floodplain

A digital elevation model, GPR section, satellite images and hydraulic soil properties revealed by auger samples were used to identify possible allocations of a natural reservoir. The model space covered two subareas: 1, the Korcsina oxbow system; and 2, the Okor–Fekete-víz back swamps for two natural reservoirs were simulated using the integrated surface water-groundwater model with filling rates ranging from 0.5 m^3s^{-1} to 1.5 m^3s^{-1}. Different management scenarios for the selected subareas were simulated as natural reservoirs with filling and discharge conditions based on +2 m vertical water depth increasing theoretically with different stream discharges of 0.5, 0.75, 1, and 1.5 m^3s^{-1}.

For both reservoirs, around 60 days and 25 days of stream feeding of 0.5 and 0.75 m^3s^{-1}, respectively, are required to achieve the target water depth for the reservoir (+2 m), the optimal and economical scenario of filling the reservoirs is with a stream discharge of 1 m^3s^{-1} for 14 days, based on the capacity of the feeding stream. Feeding at a rate of 1.5 m^3s^{-1} would need around just six days, but this is not an economic scenario as it necessitates impoundment and dam construction. With feeding at 1 m^3s^{-1}, the filling would be repeated twice per year, as the reservoir lasts for 180 days. The effect of the reservoir on the groundwater table in the adjacent area depends on the reservoir stage, leakage, and the distribution of the groundwater head using the reservoir resulting in raising the groundwater table by 0.8 m at the end of the filling period. Moreover, the findings of this research can be utilized in planning rehabilitation measures in lowlands with water shortages. The simulated water balance shows that reservoir-groundwater interactions are mainly governed by the inflow into and outflow from the reservoir. Such an integrated management scheme is applicable for floodplain rehabilitation in other regions with similar hydromorphological conditions and hazards, too. The modeling workflows developed here can be used to apply new GW–SW interaction scenarios with a multitude of both natural and anthropogenic influences. The use of this model can help scientists track water resources more accurately and can inform political decision-makers.

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6. List of publications

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