

Management of large drainage systems - Pančevački Rit case study

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Abstract: Large drainage systems management usually lacks an integrated approach, while facing governance and institutional constraints, and is flawed by weak participatory planning and nonaligned private sector role. Improving the management of large drainage systems is even more important in the face of climate change, with pronounced drought and flooding events. The objective of this paper is to present the application of systematic analyses to ascertain better groundwater management of existing large drainage systems: detailed review of the drainage system design documentation, assessment of environmental conditions, evaluation of land use changes and investigation of user requirements. Application of mathematical modelling, followed by proposal of drainage system modernization through (re)construction of infrastructure, automatization, monitoring and accompanying data management system are then used to improve system effectiveness and efficiency. Paper presents case study of Pančevački Rit area which is particularly suitable since it consists of agricultural and urban zones and has a long history regarding protection from excess water. The numerical simulation model of Pančevački Rit, used to examine current drainage strategy, has shown that existing canal network, with density of 25 m/ha, and 7 pumping stations with the installed capacity 35.8 m³/s are not sufficient to protect total area of approximately 33,000 ha, mostly due to inefficient management. The results of mathematical model were then used to select acceptable groundwater engineering solutions, which will satisfy the protection criteria in the investigated area. Furthermore, introduction of advanced monitoring and data management system with corresponding computational tools would provide a significant step toward integrated water management and achieving the sustainability of the complex drainage system in future exploitation.

INTRODUCTION

The World Bank and the International Commission on Irrigation and Drainage (ICID) suggest a new universal definition of drainage that wraps all activities for soil and water management by implementation of control of groundwater and/or excess surface water, to meet optimal economic and sociological effects, and to preserve main ecological functions [1].

Reasonable drainage management strategy can improve overall quality of the environment, particularly when considering the land that is usually subject to flooding and/or high groundwater levels, thus complex water conditions. Drainage increases value of drained land, whether it is agricultural, forest or urban land. Right drainage management strategy becomes even more important owing to more often extreme climate events (severe drought and heavy precipitation followed by flooding), as foreseen by the Intergovernmental Panel on Climate Change [2]. It is confirmed that there is a clear tendency towards more extreme precipitation events that cause flooding [3], which will especially affect areas that already have problems with excess water. On a larger scale, such as river basin scale, flood control is also an essential aspect of drainage.

In general, the main challenges facing drainage are lack of an integrated approach, threats to drainage system sustainability, governance and institutional constraints, weak participatory planning and private sector role, policy and legal constraints, and so forth [1]. For instance, the single-sector approach centered on raising agricultural productivity neglects the growing complexity of water control systems and the interdependence of drainage with other sectors, such as the environment or rural infrastructure, i.e., ignores the interests of non-agricultural stakeholders.

In agricultural areas, high groundwater table in addition to flat topography and soils of low permeability increase risk of water logging and salinization, which affects soil quality and agricultural production. The prime development objectives of the agricultural drainage projects are to increase crop productivity, sustain land resources, and enhance rural development. In some lowland areas urban and agricultural zones overlap, but their drainage needs, and criteria

are different. Nevertheless, in such areas the stricter criteria should be met, which could be done through building additional structures in drainage system and/or through drainage management. Accordingly, in areas characterized with more complex conditions, an integrated approach is needed.

The effectiveness of drainage system depends on existing (designed) infrastructure, but also operational practices [4]. In many cases, the organization of planning, designing, and constructing of a drainage system is not going to be the same as the one for operating, managing, and maintaining the system [5]. Drainage systems require careful management to be successful, which ideally should be managed for optimal agricultural production and/or housing and maximum environmental protection [6].

To meet all needs, it is necessary to use large data sources in conjunction with advanced numerical tools to help operators adopt the right management practices at the right rates, times, and places, with the goal of achieving both economic and environmental targets [7]. Therefore, an integrated approach to drainage system management considers complex data management system that encompasses all required criteria regarding land protection, suitable models (hydrologic and hydraulic models of surface and groundwater flow), and adequate monitoring system [8].

The objective of this paper is to present the application of systematic analysis, which couples several modelling procedures with data management system to prioritize investment plans and to achieve the best management strategy for large drainage systems.

MANAGEMENT OF LARGE DRAINAGE SYSTEMS

Large drainage systems, of which systems for removal of excess groundwater from the soil are the subject of this paper, spread over areas greater than several thousand hectares and provide their services to more than one user. Land usage within the drainage system area can be uniform, such as urban, industrial, agricultural, natural habitat zones etc., or mixed between these uses. Open channels, underground perforated plastic pipes, or a combination of these two types of drainage infrastructure can be used for collection and removal of excess water within the boundaries of a system. The choice for the type of drainage infrastructure is made in the course of the design phase in relation to the land use, soil characteristics, slope of the terrain, etc. Also, according to the method of water evacuation, drainage systems can be divided into systems in which water flows only by gravity (if topography allows it) and into systems in which pumping is necessary to drain off the collected water into recipient.

During the ordinary utilization of the drainage system circumstances may occur different than those that were considered during the initial analysis of the needs for the drainage system and its design. Usually these are only events that cause temporary undesirable conditions in parts of drainage system, but bigger problems within larger area can arise if these variations are persistent during time. Changes can be diverse: changes in the environment, changes in the land use, changes from one type of drainage infrastructure to another (open channels or pipelines), changes in the characteristics of drainage facilities due to inadequate maintenance, changes in the drainage criteria, changes in the crop rotation on agricultural land, development of irrigation within the area of drainage system, etc.

A monitoring practice to observe the operation of drainage system is necessary in order to collect relevant data for the assessment of the criteria fulfilment and the assessment of the individual elements or the whole system work efficiency. Some of the changes mentioned in the previous paragraph can be documented in a timely manner only if there is data on the groundwater level observations. Contrary to that, problems caused by inadequate system management can be amended only if the operation of the drainage system infrastructure is monitored at the same time.

Based on numerous study and design experiences aimed at establishing an appropriate groundwater regime (including spatial distribution, amount, seasonal variation, etc.), the following five steps have been recognized in solving the problems in existing large drainage systems.

Requirements (criteria) of users at the area

Drainage systems serve the users occupying the command area of the system. The "user" in this context is a party whose property lies within the boundaries of system, which can be an urbanized area with public or private assets (houses, apartment buildings, schools, hospitals, parks, etc.), private land subjected to any possible use or other system which provides different kind of service in the same area. Each user has its own drainage criteria the designer should have studied and implemented, and according to which the drainage system should have been constructed.

As mentioned, there are cases in which different systems intertwine within the drainage area, each having its own objectives and criteria, regulations, requirements for proper operation, and management decisions that are used to

accomplish optimal system operation in terms of cost, security, durability, etc. This complexity refers to public systems that serve a larger number of users, especially in suburban zones (such as water supply systems, wastewater systems and stormwater system) that can overlap with drainage systems of nearby agricultural land.

Sometimes the requirements (criteria) of a single user will prove to be dominant, for example due to their significance or the influence they exert with their size. An example of such a user would be a large agricultural farm, factory, chemical plant, etc.

Identifying problems in the present water management

When criteria are recognized throughout the considered area the next step is to determine the issues in present water management. Problems related to the work of drainage systems can be different in causes and characteristics, such as:

- Raising groundwater level to depths that exceed the established criteria for a certain land use (urban environment, industrial zone, agricultural land, etc.); in extreme cases, groundwater can even appear on the surface of the terrain and in other occasions, excessive soil saturation can occur.
- Changes in groundwater regime as a result of change in natural conditions compared to those at the time when the project was developed and the system started working, e.g., frequency of intense storms or higher total amounts of precipitation, higher levels in rivers that affect the level groundwater, etc.
- Inadequate working schedule for drainage system facilities such as insufficient operation hours of pumps in pumping stations that remove excess water from drainage area, or their untimely operation (i.e., starting pumps after high water level exceeded).
- Inadequate maintenance of channel network and other facilities within drainage system.
- Negative influence of other users in the area (i.e., spilling sewage directly into the soil or into the canal network).
- Adverse influence of other users which are not located in the immediate vicinity. For example, the amount of the electricity produced by the Iron Gate I Hydroelectric Power Station ("Đerdap I") is in proportion to the levels in the Danube River, whose watercourse serves as the reservoir since the dam was built. Maintaining higher levels in the reservoir influences not only the surface water regime but also the groundwater regime in the areas as far as few hundred kilometres away.

All these problems must be properly identified, together with the wide variety of initiating circumstances, to find the most suitable approach for their solution. This implies that all the necessary data related to identified problems must be collected, such as groundwater level observations, meteorological and hydrological data, operation hours and maintenance records for the drainage system facilities, etc.

Establishing a balance between the users and the systems in the area

In this step, the drainage requirements of all the users and the systems present in the area should be evaluated. The goal is to compare their needs usually by answering the questions: "Where, When, How long and How much? ", in order to recognize their distinctions which could influence the work of drainage system.

It is also necessary to simultaneously consider different land uses if they are present, and different other resources if their utilization affects the water regime. In this way, it is possible to analyse and adopt harmonized solutions that not only relate to water and land, but also to the environment and socio-economic characteristics of an area.

Important outcome of this step is the understanding, validation, and short-term and long-term prioritization of individual user's needs in drainage area.

Finally, improved development and management of surface and groundwater, water quantity and quality, and leads to establishment of integrated water management in the basin and its environment.

Applying numerical models and groundwater engineering

Numerical modelling of groundwater regime presents an unavoidable method in modern water management. Models, when analyses are focused on the existing drainage systems, are used as an interpretative tool which enables:

- Detailed insight into complex natural conditions usually very closely combined with water and land use.
- Review of the modelling scenarios that contain the proposed solutions for various drainage system problems.
- Timely analysis of hypothetical scenarios for sensitivity and uncertainty evaluation for risk-based decision-making in real system.

- Design and operation optimization for economic efficiency of drainage system.
- Visualization of inputs and outputs and better communication of aquifer responses and performance of a system, which can be analysed in elements, parts or as a complete technological system.

Groundwater flow modelling in constructed drainage systems could be based on completely new model or on the existing model. In the first case, developing conceptual model should be the first step during which aquifer geometry and model domain, boundary conditions, aquifer parameters (hydraulic conductivity, porosity, storativity, etc.), initial conditions and water balance are to be defined or estimated. In second case, the existing model should be amended to suit the calculation according to new scenarios which may include change in model parameters or construction of new facilities, i.e., addition of new impermeable surfaces due to the change in land use, increase in pumping station capacity, addition of new canals, etc.

The calibration step is necessary so that initial estimates of the model parameters could be adjusted, making sure that the calculation results are close enough to the field measurements. This task is conducted as a trial-and-error procedure but in recent years automated calibration is used as a method to speed up the process. No matter which approach is used, the adequate agreement correlation between computed and observed groundwater heads must be achieved, which may ask for fine-tuning of the model parameters.

Calibrated models are then fit for making the desired predictions, which may ask for a change in model configuration, mainly the boundary conditions. For example, influence of practical engineering solutions is examined with scenarios that include even the most complicated changes of drainage system infrastructure. Modelling scenarios can quickly give answers to following or similar questions:

- What are the consequences of a change in characteristics of the existing infrastructure?
- What if new the facilities are constructed?
- Which management practice brings the most benefit?
- How often must maintenance be carried out for the drainage system to operate as planned?

Decision support system

Complex monitoring system is necessary to ensure reliable work of a drainage system servicing a larger area. Key issues in this regard are:

- Proper observation of groundwater levels resulting in accurate and regular field data is a prerequisite for any kind of action.
- Monitoring system must be able to observe other quantities that may influence the water balance or water quality. Other quantities may not be in direct relation with groundwater.
- Extent of the monitoring system may even be larger than the area under the drainage to obtain enough necessary information.
- Monitoring may have to be directed toward activities of all users in the area.
- Some monitoring results should be disseminated between interested parties to achieve transparency and better communication of required measures.

CASE STUDY - PANČEVAČKI RIT

All five steps listed in previous chapter, necessary for the improvement of drainage system, will be elaborated on the example of Pančevački Rit drainage system in the next chapter.

Study area

Pančevački Rit area (PRA) covers alluvial plain of the Danube and the Tamis River, whose size is around 33,400 ha. From south to north, elevations rise from 69.5 m+msl (mean sea level) to 76.0 m+msl. Most of the area are agricultural plots, then forests (and other land use) and settlements (Figure 1).

The southern part of PRA is densely populated and characterized by large industrial zone. The settlements in the southern part of PRA were built on unfavourable terrain with a high level of groundwater, incomplete infrastructural equipment, and an underdeveloped network of central and supporting facilities. The northern and central part of PRA is a predominantly agricultural area, with settlements of a suburban and rural character, and forest areas. Nevertheless, the major land use in PRA is agriculture, specifically the land under intensive temporary agricultural crop production.

The total size of agricultural area is 28,700 ha (around 85 % of total area), of which the greater part is used by the large agricultural corporation Al Dahra.

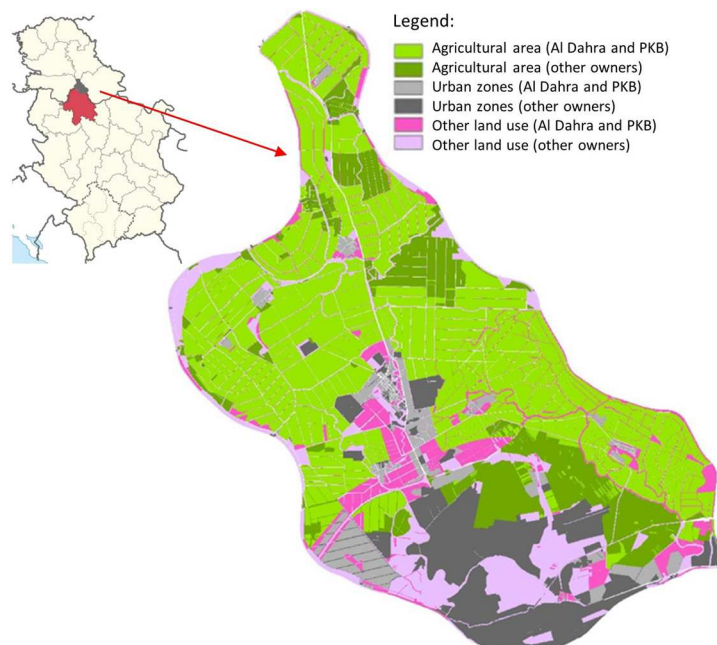


Figure 1. Location of Pančevački Rit (left) and the usage of land (right)

Favourable soil characteristics and suitability for agricultural production stipulated actions for flood protection of this area, back in 1913. With ending of construction of defence embankments, canal network, pumping stations and accompanying objects in 1935, the area of PRA was enclosed in unique "container". In that period the southern part was more intensively populated, roads and railways were built, and the area took on the spatial organization it still has today. Further construction and reconstruction of drainage system of PRA was done in the framework of protection from raised surface water levels and groundwater levels, which was necessary due to the construction of "Đerdap 1" plant.

Today, protection system of PRA consists of:

- Embankments that surround PRA, constructed along the rivers Danube, Tamiš and Karašac, with total length of 90 km. Embankments are designed to protect area from 100-year floods and were reconstructed in the past to provide protection against additional increase in Danube levels.
- Hydro system "Donji Tamiš" (HS "Donji Tamiš") that consists of large sluices (Opovo and Čenta) and hydro-structure "Pančevo" (pumping station, sluice, and lock), with the aim to protect the lowland area along the Tamiš River from the backwater impact (Figure 2, right).
- Drainage system that consists of earthen canal network (816 km long, with the density of the canal network of around 25 m/ha), pumping stations (7), and subsurface horizontal drainage (6.160 ha). This system is mainly intended to serve agricultural land and in accordance with that purpose its operating parameters were determined. On the other hand, numerous canals pass through the urbanized area draining groundwater but also collecting stormwater discharge from the impervious areas.

Along the borderline of the area (in parallel with the embankments), deep canals that make the so-called "1st drainage line" were constructed during the 1980s. However, these canals are not continuous around the whole perimeter of the area as some parts are missing (Figure 2, left). For example, this type of protection is missing in the southern part of PRA because in the period before 1980s land was occupied by buildings and facilities of the industrial zone, preventing the construction of 1st drainage line.

The concept of PRA protection is based on separating the area into 7 subsystems (drainage basins; Figure 3). The subsystems are divided according to topography, existing drainage structures and pumping stations that control water levels. Total installed capacity of pumping stations is 35.8 m³/s, but their average yearly engagement in the previous 30 years was only 10-15 % of installed capacity.

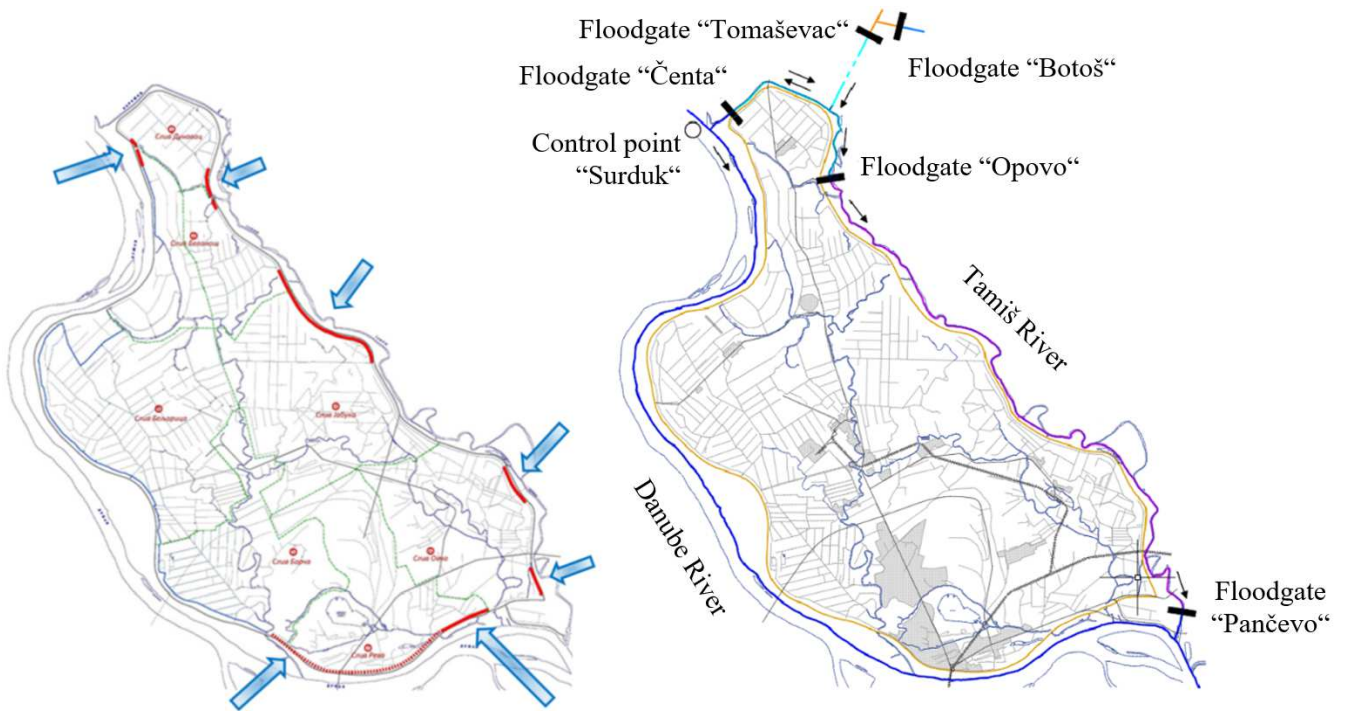


Figure 2. Canal network and missing parts of the I drainage line (left) and structures of the HS "Donji Tamiš" (right)

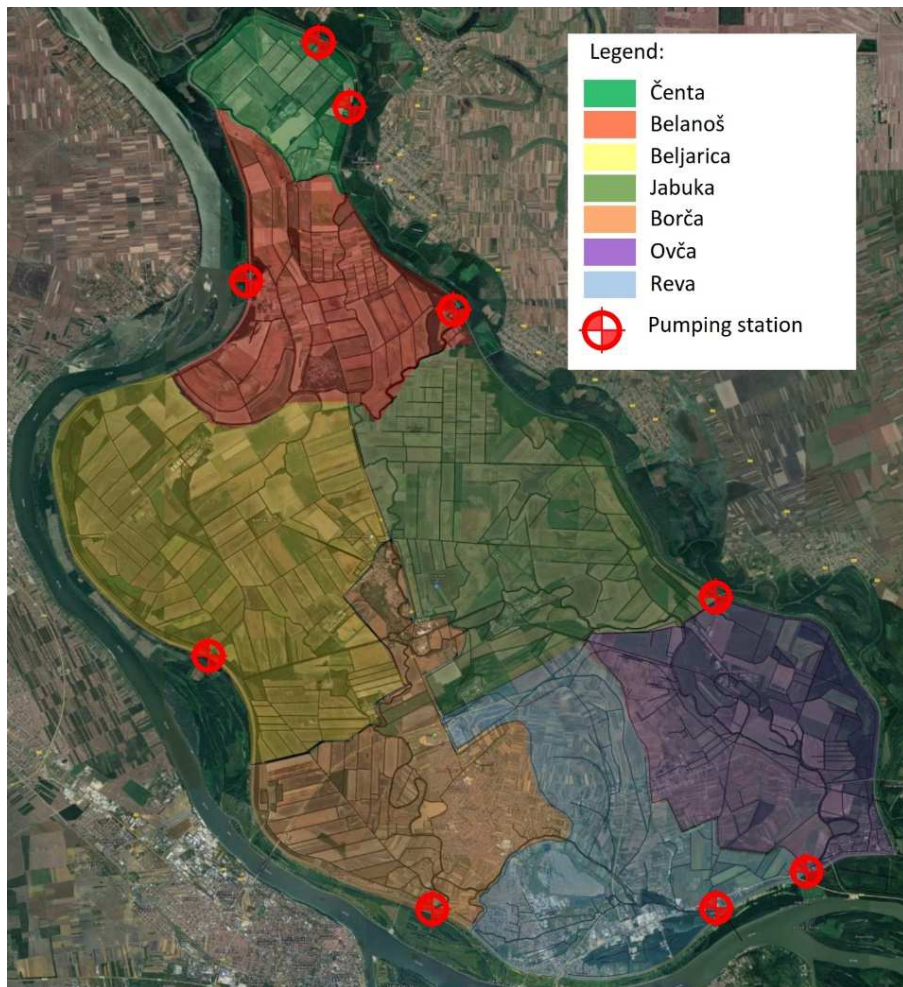


Figure 3. Drainage basins and pumping stations in Pančevački Rit

Research focus

The current system of protection against excess water in PRA was designed and built as agricultural drainage system. However, the basic purpose of the system, which is collection and transport of drained water from the agricultural land to the recipient, expanded due to urbanization. In the meantime, the system acquired additional roles, the collection and transport of stormwater and (partly) urban wastewater, which overburdened the existing system. The water budget of urban zones is enlarged by water delivered for water supply purposes (on average 250-300 l/s, i.e., about 8-9 million m³ of water annually) and which "remains" (as wastewater) in PRA. Besides expanded water budget, there are other issues with the operation of the existing drainage system. Although there was an intention to separate it into 7 subsystems, as previously described, the drainage system works as one, so the pumping stations are not equally burdened, and the general result is unsatisfactory level of protection. Additionally, inadequate maintenance and management and certain technical shortcomings of the drainage system contribute to its inefficiency.

The goal of this research is to propose a water management solution in PRA, which should enable favourable living and working conditions in the area and meet the necessary requirements to:

- provide required levels of protection from flooding, considering both surrounding rivers (the Danube and Tamiš) and inland waters,
- provide satisfactory conditions for agricultural production,
- integrate existing and planned infrastructure (urban wastewater and storm water sewage),
- provide for modern monitoring and integrated water management,
- provide for appropriate environmental protection measures,
- be economically acceptable, and
- enable an adequate division of responsibilities between all subjects (public companies, local authority, private sector, etc.).

Modelling concept – integrated model development

The integrated model of PRA connects the vertical water balance model and the groundwater model in order to couple the water balance and flow dynamics (Figure 4). Since only one part of the output of the vertical water balance model is the input for the groundwater model (the base runoff that recharges groundwater, Q_{base}), it is necessary to have models that will adequately take into account other components of the surface water model (components of surface runoff). The integrated model is implemented as a central program, in the form of a shell script developed for the Linux platform, whose role is to manage each of the previously mentioned models as well as the model of canals that conduct water to pumping stations, and to control communication and file exchange between them. This modelling concept developed in this way can be easily incorporated together with contemporary monitoring into the data management system.

The surface water model is based on a hydrological model that makes the transformations of the components of the vertical balance, considering the characteristics of the calculation elements, HRU (Hydrologic Response Unit), obtained by the spatial decomposition of the modelled area. For the purposes of the model, 4 different HRUs were identified in the area (two for agricultural land, two for urbanized area). The input quantities, such as precipitation and temperature, are transformed through the land use (vegetation cover) and soil characteristics into runoff that ends up in the canal network (Q_{chn}), a runoff that ends up in horizontal subsurface drainage (Q_{drain} , on agricultural land) or a runoff that ends up in the sewage system (Q_{sew} , in urbanized area), and the amount that infiltrates in the soil and recharges groundwater (Q_{base}). The first three components of the runoff reach the canal network, while the last component recharges groundwater (Figure 4). The related calculations were done using a Python script, which implements the equations for the transformation of precipitation into the runoff for a series of daily input data in the period January 1987 – December 2016.

Groundwater models are generally represented by a system of equations to be solved by one of the numerical methods, boundary, and initial conditions, as well as parameters of the aquifer (geometry, filtration characteristics). The physical properties and processes that determine groundwater flow are highly heterogeneous; therefore, many groundwater management problems require complex, fully distributed models that can accommodate fields for the hydraulic properties and boundary conditions that vary in time and space [9]. The most widely used program for simulating groundwater flow is MODFLOW, the modular finite-difference groundwater flow model developed by McDonald and

Harbaugh with the support of U.S. Geological Survey [10, 11]. Software numerically solves the three-dimensional groundwater flow equation for a porous medium by using a finite-difference method [12]. The analyses of groundwater regime in this case study were done using MODFLOW. Data input and interpretation of the results were done using graphic user interface Groundwater Vistas, version 8 (Environmental Simulations, Inc.).

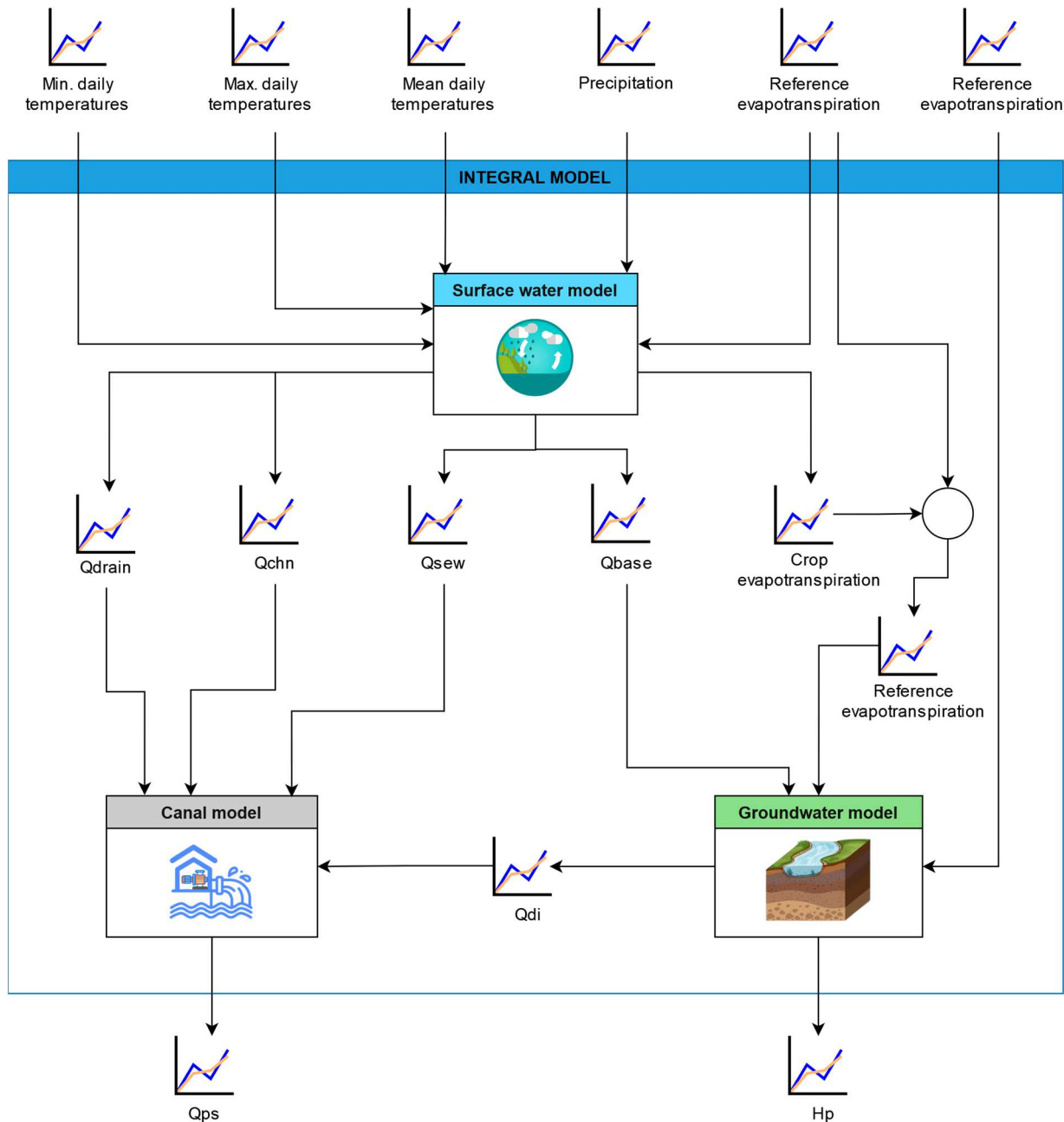


Figure 4. Integrated model - calculation algorithm

Input Data

Data sets from various data sources and providers were compiled. The data sets included:

- Digital Elevation Model (DEM) based on LiDAR
- Soil data: Soil maps of Republic of Serbia (scale 1:50.000)
- The land use and vegetation types: Corina land use map and cadastral data.
- Climate and hydrologic data: Republic Hydrometeorological Service of Serbia
- Data that represent water regime (surface water and groundwater levels, operation of pumping stations, etc.) were obtained from available studies and previous research.

Protection requirements for different land uses

Protection requirements or requested criteria for a depth to groundwater table is different for urban and rural zones. In rural zones, it is sufficient if the groundwater table is at depth of 1 m or more. In fact, the depth of groundwater table for agricultural fields could be less than proposed 1 m, but since the fields overlap with smaller farms and households, 1 m is adopted as criterion. In agricultural area, exceeding the criteria in 5 consecutive days is allowed during the first half of the growing season (March - June), while during the rest of the year it could last longer, 10 consecutive days (Table 1).

Table 1. Requested criteria for agricultural land

| Description | D_{gwl} [m] | K_l [day] | | K_l [day] | K_p [-] | K_g [-] |
|--|------------------|----------------------|-------------------------|----------------|--------------|--------------|
| | | 1 March to 1 July | the rest of the year | | | |
| Agricultural areas (fields) | 1 | 5 | 10 | 0.95 | 0.95 | 0.20 |
| Rural settlements within agricultural area | 1 | 5 | 10 | 0.95 | 0.95 | 0.20 |

Requested criteria for urban zones are stricter and consistent throughout the year (Table 2). The criteria must be provided on 95% of the territory, within 95% of the time analysed in the model, for both zones, with the minor exception of urban zones outside the area covered by spatial plans (90% of the territory).

Table 2. Requested criteria for urban zones

| Description | D_{gwl} [m] | K_l [day] | K_v [-] | K_p [-] |
|---|---------------|-------------|-----------|-----------|
| Urban zones covered by spatial plans | 2 | 15 | 0.95 | 0.95 |
| Urban zones outside the area covered by spatial plans | 2 | 15 | 0.95 | 0.90 |

Protection requirement criteria defined above were used for the assessment of drainage system efficiency in current conditions and predictive scenarios.

Modelling results: current conditions

The first step is the assessment of groundwater management in current conditions. This step assumes model calibration in existing conditions, considering natural conditions, and operating mode of drainage system. The analysis of available data, studies, reports, and results of other research conducted for PRA area confirmed that the groundwater flows in the medium that consists of two layers, which was essential for model discretization. Lower layer is water-bearing sandy layer, where the horizontal flow is predominant, while the groundwater table is in the upper layer.

Calculations were done for unsteady flow with the time step of 1 month, for the period of 360 months (January 1987-December 2016). This period is characterized by recorded minimum and maximum water levels of surrounding rivers, as well as periods with extreme precipitation. The groundwater modelling domain for MODFLOW was vertically separated in two layers, which were discretized into cells of 25×25 m each (1.5 million of active cells in each layer).

Several groups of parameters of the integrated model were included in the calibration process, in order to achieve the optimal values that reflect the conditions in the modelled area. First group of parameters characterize hydraulic connection of rivers with groundwater (different for the Danube and other rivers), second characterize hydraulic connection of canals with groundwater and the third group represents parameters for kriging (for spatial interpolation of parameters). The model calibration represents a complex nonlinear multi-criteria optimization problem, which requested the application of NSGAI genetic algorithm. NSGAI is one of the most widely applied and the most popular multi objective optimization algorithms that is characterized by fast non-dominated sorting approach, fast crowded distance estimation procedure and simple crowded comparison operator [13]. Through selection, mutation and crossover processes, this algorithm evolves a population of possible solutions (individuals) in order to find solutions that minimize errors according to the specified criteria. An integral part of the algorithm is the evaluation of the quality of all individuals in the population, which in this case requires the complete simulation on the integrated model and the comparison of the calculation results with the observed values. The parallel NSGA-II algorithm was implemented on a distributed computer platform with 7 clusters of 100 computers in total [14]. The calibration process resulted in

representative parameters of the aquifer (filtration coefficients of defined layers). Moreover, the values of certain components of the groundwater balance were obtained as part of the model calibration process.

Calibration of the hydrodynamic model was done using 43 observation points (piezometers), distributed across the agricultural area of PRA, as well as measured discharge of pumping stations, until satisfactory match was achieved. General trend of changes in water levels was successfully achieved; some differences between the observed data and calculated values are considered acceptable. Model verification was done comparing calculated and measured quantities of discharged water.

The modelling results show that defined protection criteria (Tables 1 and 2) are violated in most of the area (both agricultural and urban) in average year. In some parts that violation is quite small (just few centimetres), but in some parts, such as topographic depressions, even the water logging occurs, as shown in Figure 5 (urban area violation represented in blue, agricultural area in red). On average, 2,310 ha in the growing season and 900 ha in the dormant period did not meet the protection criterion on agricultural land, while in urban zone protection criterion was violated on 550 ha. Modelling results imply that current drainage system with other protective structures cannot fulfil completely requested criteria and is not sufficient to adequately protect PRA. Calibrated model was further used for evaluation of various proposed technical measures and other activities impacting water regime.

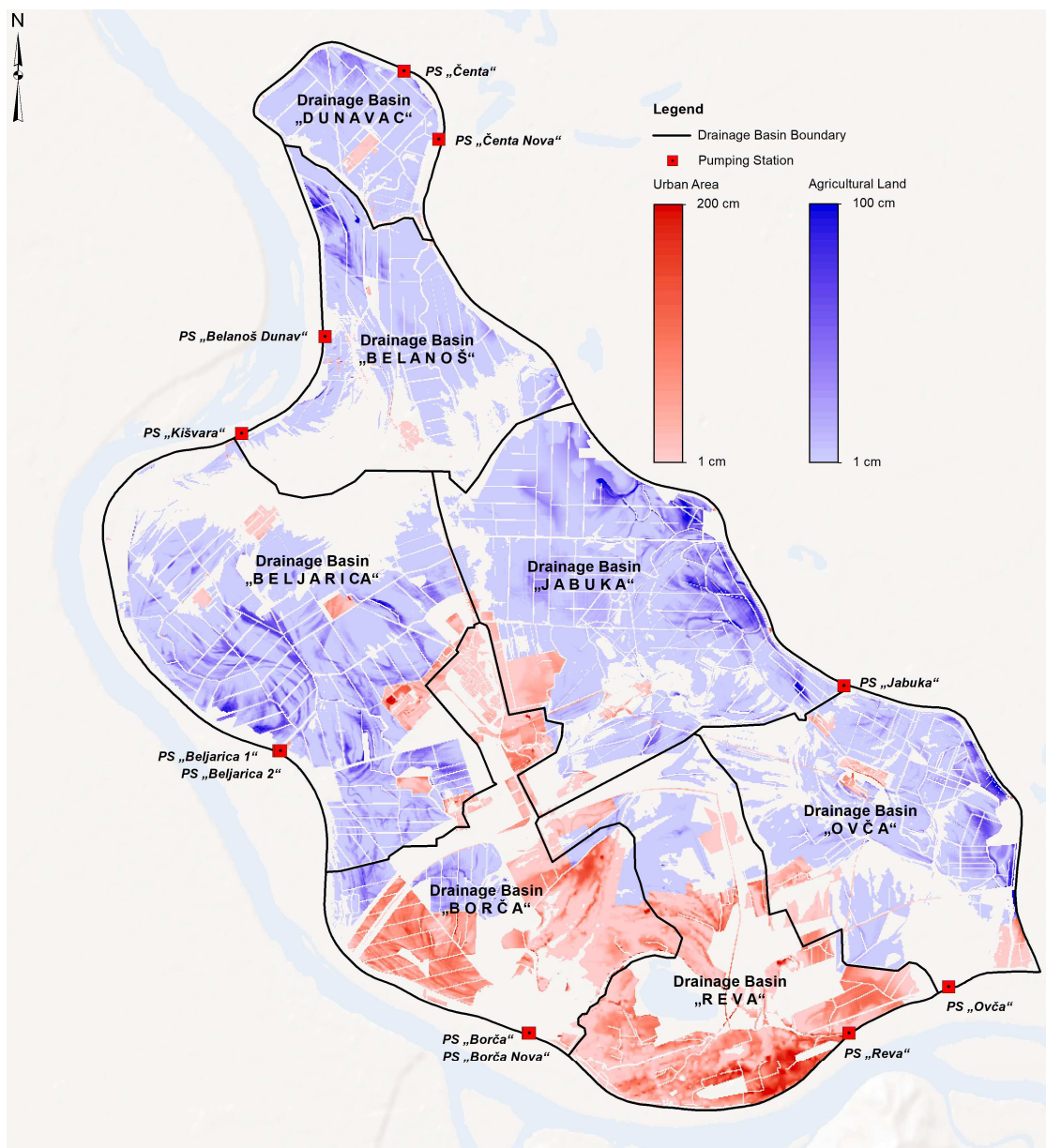


Figure 5. Fulfilment of the criteria on agricultural land and in the urban zones in current conditions

Modelling results: predictive scenarios

This step considers addition of different technical measures that would assure efficient work of drainage system. Technical measures are divided in two groups, i.e., necessary technical measures and additional (optional) technical measures. Necessary technical measures for the revitalization and modernization of the existing protection system are:

- Reconstruction of the existing canal network.
- Reconstruction and modernization of drainage pumping stations.
- Reconstruction and modernization of monitoring system and establishing operating centre with accompanying telecommunication and IT infrastructure.

Additional or optional technical measures that can improve drainage system efficiency are:

- Catchment separation – actual separation of 7 drainage basins in PRA through reconstruction, modernization, and activation of existing and construction of new sluices.
- Regular maintenance of the entire system for protection against the harmful effects of water - maintenance of canals and pumping stations.
- Operating of HS "Donji Tamiš" according to rulebook – operation of sluices so that the water levels of the Tamiš are lower (as proposed by the current rulebook) than those achieved in current practice.
- Construction of the remaining I drainage line which will decrease the influence of surrounding watercourses on groundwater regime.

Nine scenarios that encompass different sets of technical measures were suggested. Namely, a scenario represents the simultaneous application of one or more technical measures, whose effects are monitored through model simulations lasting 30 years (Table 3).

Table 3. Analyzed scenarios for assessing the effectiveness of different technical measures

| Scenario | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|--|---------|---|---|---|---|---|---|---|---|
| Catchment separation | × | × | × | × | × | × | × | × | × |
| Regular maintenance | × | × | × | × | × | × | × | × | × |
| HS "Donji Tamiš" according to rulebook | | × | × | | | × | | | |
| 1 st drainage line | Danube | | | × | × | | × | × | |
| | Krnjača | | | × | × | × | × | | |
| | Tamiš | | | | × | | | | × |

The common measures in all nine scenarios are catchment separation, which considers work of all pumping stations, and regular maintenance, which keeps continuous water flow in canal network to the pumping stations and rapid evacuation of excess water. Other proposed technical solutions mainly have local impact, so modelling results for all scenarios are quite similar. The average water discharge from the PRA in predictive scenarios is 3.40 m³/s, which is considerably higher than water discharge in current conditions, which amounts 1.63 m³/s. Likewise, the differences between additional amount of water (Q_Δ) that had to be evacuated from the part of the agricultural land and the part of the urbanized area are relatively small (Table 4).

Table 4. Predictive scenarios: calculation results

| Scenario | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
|-------------------------------|------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| \bar{Q} [m ³ /s] | 3.410 | 3.176 | 3.275 | 3.547 | 3.504 | 3.271 | 3.511 | 3.409 | 3.384 | |
| Agricultural land | Q _Δ [m ³ /s] | 0.013 | 0.007 | 0.009 | 0.014 | 0.014 | 0.008 | 0.015 | 0.014 | 0.014 |
| | Area [%] | 0.660 | 0.560 | 0.574 | 0.645 | 0.680 | 0.568 | 0.683 | 0.674 | 0.637 |
| Urban zone | Q _Δ [m ³ /s] | 0.135 | 0.126 | 0.074 | 0.081 | 0.082 | 0.073 | 0.082 | 0.135 | 0.134 |
| | Area [%] | 3.136 | 3.036 | 2.114 | 2.201 | 2.210 | 2.104 | 2.216 | 3.137 | 3.125 |

Construction of drainage line along the Danube and the settlement Krnjača in the south, together with setting the operation of HS "Donji Tamiš" according the Rulebook (Figure 6, right) make a small difference in general protection of the area in comparison to scenario 1 (Figure 6, left), although it makes somewhat better protection of the urban zone. Construction of drainage line along the Tamiš makes a better protection of agricultural land in the east part of the study area (Figure 7, right) in comparison to other scenarios. When considering protection criteria in predictive scenarios, endangered agricultural land covered between 185 and 223 ha, on average 205 ha in the growing season and between 80 and 109 ha, on average 95 ha in dormant period. Protection criteria in urban zones was violated at area that varies from 128 to 195 ha, depending on setting of the scenario, on average 158 ha. Such minor differences, namely the small increase of protected area does not justify large investments and operational costs. Some basic changes in operation of the system depicted in scenario 1 can significantly improve the efficiency of the whole drainage system.

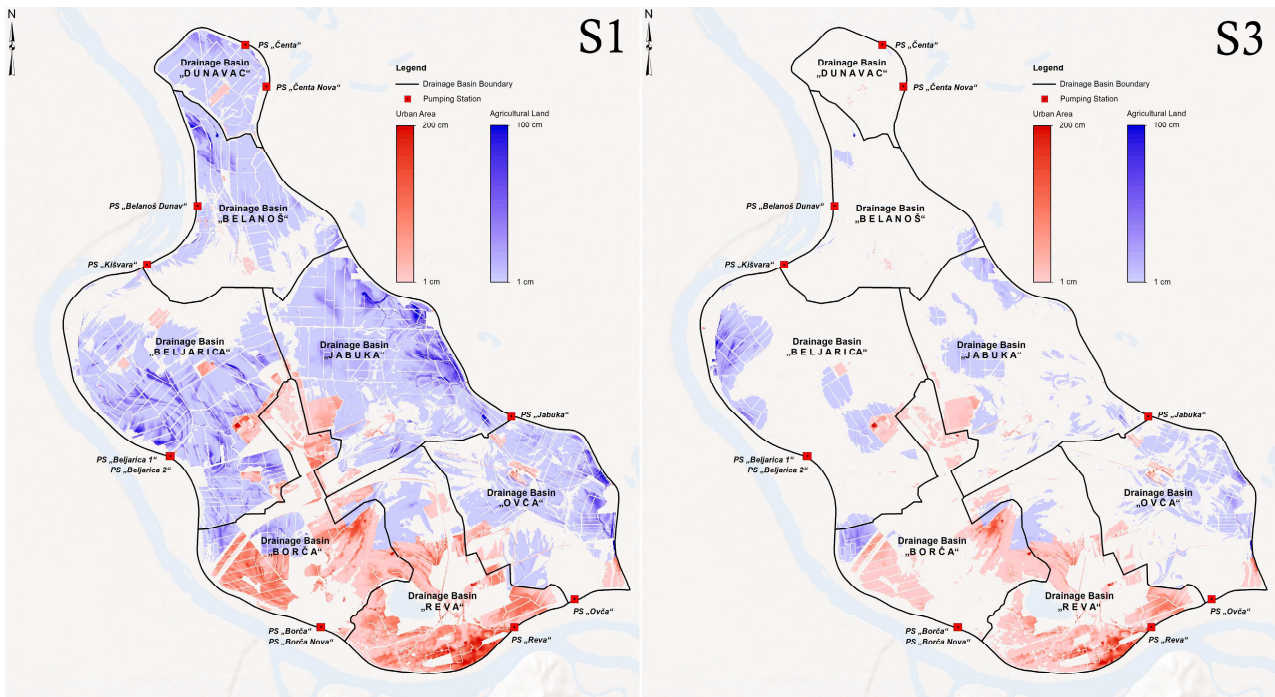


Figure 6. Modelling results: fulfilment of the criteria on agricultural land and in the urban zones in scenarios 1 and 3

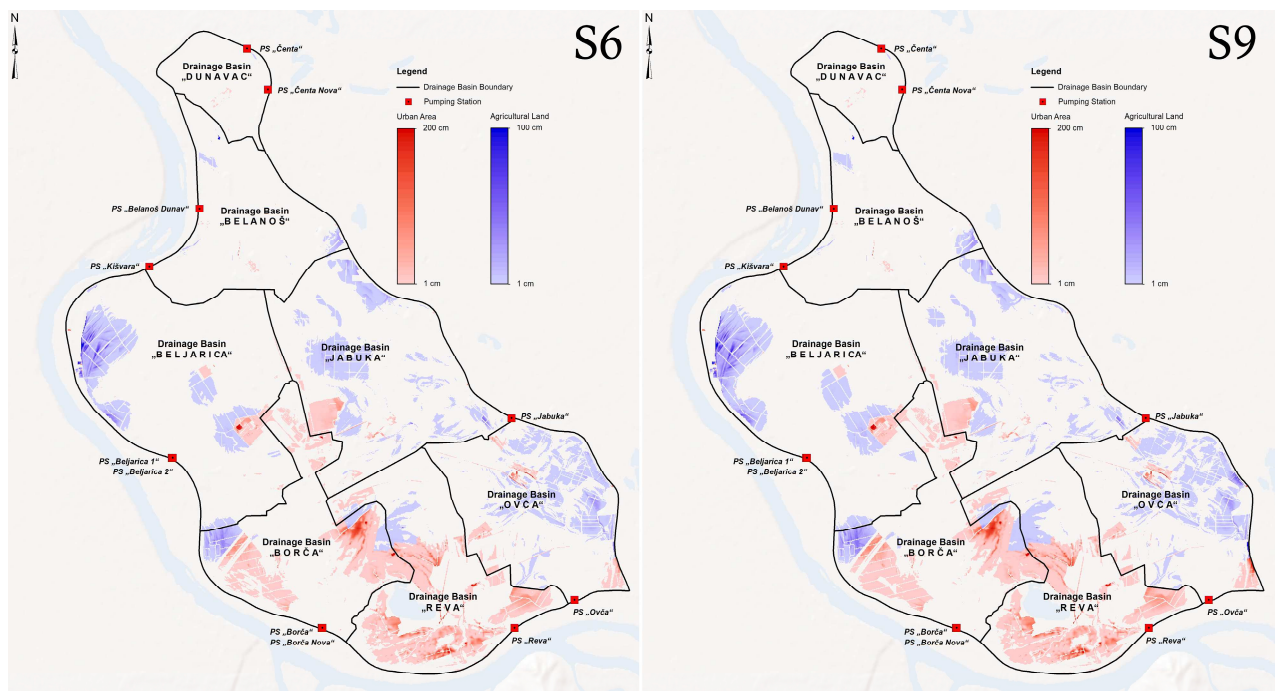


Figure 7. Modelling results: fulfilment of the criteria on agricultural land and in the urban zones in scenarios 6 and 9

The economic benefit of the revitalization and modernization of the drainage system and accompanying protective structures (scenario 1) can be achieved through a significant reduction in damage when comparing to the previous period. Efficient drainage has direct impact on enabling and stabilizing agricultural production, through the improvement of environmental conditions (satisfactory soil water regime for growing) and enabling timely tillage and other cultivation activities. It is assessed that the reduction of damage on agricultural land amounts to EUR 3,921,000 (annual average). The effects of stormwater drainage and other structures for protection from shallow groundwater can increase the value of real estate in an urban area. The reduction of damages calculated as the increase of the price of residential and commercial space amounts to EUR 37,162,000 (one-time).

Monitoring, control, and management

To achieve optimal water management in PRA, accompanied by tolerable investments and risk minimization, it is necessary to ensure a high-level monitoring and data management. Also, it is necessary to modernize and expand the existing monitoring system and establish SCADA system, to implement a decision support system, and to form a control centre for optimal use of the aforementioned systems. The conceptual design of monitoring system and control centre is shown in Fig. 8.

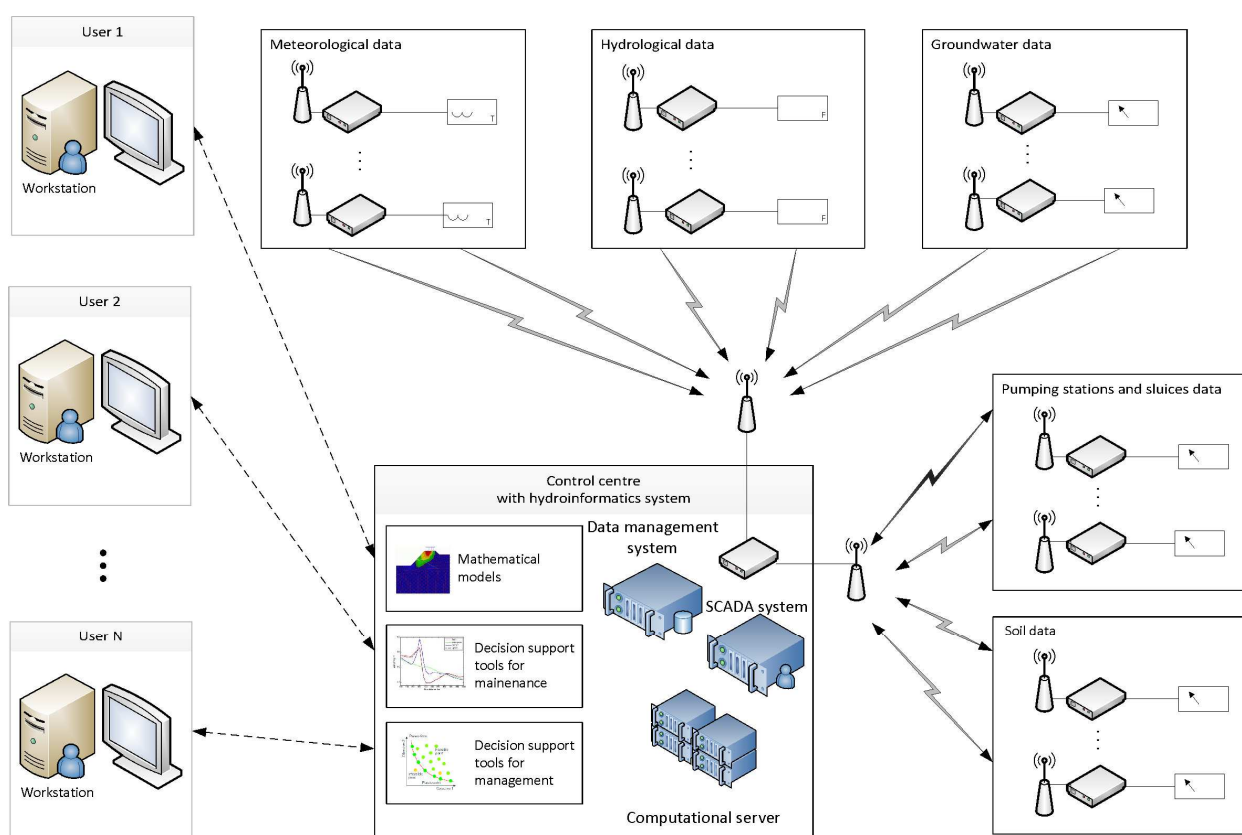


Figure 8. The concept of monitoring system and control centre for Pančevački Rit area

The study and simulation of groundwater regime require an extensive and high-quality fund of field data, which are provided through field investigations and regular monitoring. Basic observations primarily refer to the measurement of groundwater levels at piezometers adequately distributed across the area in regular time intervals. Reliable monitoring data are essential for a development of groundwater model, but they are even more important for automatic management of drainage system. Therefore, the current monitoring must be improved so that the observed data can meet the operating requirements of the facilities within the drainage system. It is necessary to modernize and expand the monitoring system in PRA so that it includes observations and/or measurements of the parameters of operation of pumping stations and the sluices, groundwater levels, meteorological parameters, water levels, flow and quality in the canal network, deposited sediment, and relevant soil parameters. It is necessary to establish a unique system for monitoring and data management in the area, which can be upgraded and developed over time, in accordance with future requirements.

The monitoring system provides data for forecasting future conditions (e.g., before and after the construction of new structures or changes of the performances of the existing structures). Consequently, monitoring and modelling are

inextricably linked, and for their use a suitable software system is assumed, whose ultimate role is to contribute to decision-making for the purposeful control of the groundwater regime. This can be achieved through establishing a modern support system for water management in PRA, i.e., a hydroinformatics system that will provide several important functions. First of all, an efficient data management function provides data archiving, quality control and access to data. The other important function is providing optimal operational decisions based on observed, estimated, and forecasted system conditions. Also, providing optimal strategic decisions based on the historical and hypothetical system operation is an important function of water management system. Furthermore, the function of providing reliable analyses and reconstructions of conditions and processes (e.g., for quantification of the impact of subjects on the water regime for the purposes of compensation or similar) is also necessary. Finally, providing optimal system maintenance by evaluating certain maintenance activity to achieve the required safety and functionality of facilities while minimizing investment is also a vital function of the management system. The use of reliable data for simulations and optimizations with mathematical models of relevant processes in PRA should be attained through implementation of hydroinformatics system, which incorporates all the required functions that are accessed through specialized software tools.

The control centre should be equipped with a SCADA system for managing pumping stations and sluices. SCADA issues executive commands to the water structures through its RTU modules, which are located on mentioned structures. In addition to the implementation of management decisions, the SCADA system will share necessary information (position of the sluices, pump power, etc.) with the management support system via defined data exchange protocol.

All the software/hardware components of the decision support system and the SCADA control system are placed in a control centre. Data and information of wider interest can be exchanged with other users in the area through control centre. Besides that, a control centre can have a role in issuing recommendations and warnings on upcoming situations that may cause direct or indirect damage to subjects in the area. The control centre should be formed as "smart room" with suitable ICT and presentation equipment (communication equipment, servers, video wall, etc.).

CONCLUSION

The analysis of the operation of drainage systems can be effectively carried out using a modern approach based on mathematical models for the simulation of various aspects of the water regime in different natural, socio-economic, and ecological conditions. The approach applied to the Pančevački Rit area described in this paper is regularly used in the Jaroslav Černi Water Institute. Providing reliable data for simulations and optimizations is necessary for analysis and definition of improvement strategies in operation of large drainage systems. Combining these elements in a comprehensible decision support system is strategic orientation at Jaroslav Černi Water Institute when dealing with improvements of management in complex drainage systems.

The main conclusions of the assessment of drainage system in PRA is that there is an absence of integrated water management, protection criteria are periodically not satisfied in some parts of the area and that the existing monitoring doesn't provide sufficient quality data on water regime. The requested criteria can be met by improving the maintenance and operation of drainage system and accompanying water structures. Improvement of operation of pumping stations, sluices and other structures of the drainage system can enhance work results and optimize the costs necessary for work and maintenance. Contemporary data management system that includes collection, storage, processing and distribution of data and information from many sources would facilitate regular or strategic decision making and enable high-level management and maintenance of this large drainage system.

The knowledge and understanding gained from Pančevački Rit case study could also be used as a guideline for the design and construction of new drainage systems or for the area increase of the existing systems. This could especially prove useful in areas where the working conditions are subordinated to the requirements of multiple parties or where changes in the land use within drainage area are expected to take place in foreseeable future. Also, multidisciplinary approach to management of data, models, simulations and optimizations, together with design of decision support tools should provide operators with more information for operations planning and maintenance.

REFERENCES

- [1] World Bank. (2004). *The Integrated Solutions to Drainage in Land and Water Management*.
- [2] IPCC. (2007). *Climate Change 2007 - The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC*.

- [3] Grum, M., Jorgensen, A.T., Johansen, R.M., Linde, J.J. (2006). The effect of climate change on urban drainage: an evaluation based on regional climate model simulations. *Water Science and Technology*, 54(6-7), 9-15.
- [4] Vlotman, W.F., Jansen H.C. (2003). Controlled drainage for integrated water management. Proceedings of the 9th International Drainage Workshop, Utrecht, The Netherlands.
- [5] Vlotman, W., Smedema, L., Rycroft, D. (2004). Modern Land Drainage: Planning, Design and Management of Agricultural Drainage Systems. *2nd edition*, Leiden: CRC Press.
- [6] Ballantine, D.J., Tanner, C.C. (2013). Controlled drainage systems to reduce contaminant losses and optimize productivity from New Zealand pastoral systems, New Zealand. *Journal of Agricultural Research*, 56(2), 171-185.
- [7] Khanal, S., Kushal, K.C., Fulton, J.P., Shearer, S., Ozkan, E. (2020). Remote Sensing in Agriculture - Accomplishments, Limitations, and Opportunities. *Remote Sensing*, 12, 3783.
- [8] Rudić, Ž., Lukić, V., Milošev, D., Stošić, E., Božić, M., Nikolić, G. (2022). Hydrotechnical aspects of sustainable land development in complex groundwater conditions. Proceedings of the Contemporary Water Management: Challenges and Research Directions, Belgrade, Serbia. (Accepted conference paper)
- [9] Asher, M.J., Croke, B.F.W., Jakeman, A.J., Peeters L.J.M. (2015). A review of surrogate models and their application to groundwater modeling. *Water Resources Research*, 51, 5957–5973.
- [10] U.S. Department of the Interior, U.S. Geological Survey. (5 September 2022). Retrieved from the USGS website: <https://ca.water.usgs.gov/projects/central-valley/groundwater-modeling.html>
- [11] McDonald, M.G., Harbaugh, A.W. (1984). A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 83– 875, 528 p.
- [12] U.S. Geological Survey. (2000). MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model - User Guide to Modularization Concepts and the Ground-Water Flow Process.
- [13] Yusoff, Y., Ngadiman, M.S., Zain, A.M. (2011). Overview of NSGA-II for Optimizing Machining Process Parameters. *Procedia Engineering*, 15, 3978 – 3983.
- [14] Milošev, D., Milivojević, N., Milivojević, V., Lukić, V. (2021). Parallel NSGA-II algorithm application in development of mathematical models for groundwater management. Proceedings of the 19th SDHI & SDH Conference, Belgrade, 436-447.
- [15] Heerish, B., Kavi, K., Virendra, P. (2017). PL-UDMS: A Wireless Sensor Network System for Monitoring of Urban Drainage in Mauritius. *Journal of Wireless Networking and Communications*, 7(1), 9-20.

Editors

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CONTEMPORARY WATER MANAGEMENT: CHALLENGES AND RESEARCH DIRECTIONS

Proceedings of the International Scientific Conference
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October 19-20, 2022, Belgrade, Serbia

EDITORS

Dejan Divac

Nikola Milivojević

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PREFACE

Institute of Hydrology was established in 1947 within the Serbian Academy of Sciences. The Hydraulics Laboratory was established that same year within the Federal Ministry of Electricity, a predecessor of the later Hydropower Institute created in 1950. These two institutions were soon merged under the auspices of the Serbian Academy of Sciences into the Hydrotechnical Institute Eng. Jaroslav Černi. This Institute merged with the Serbian Water Management Institute in 1959 to create today's Jaroslav Černi Water Institute.

Over the past decades, the Institute has been the backbone of scientific research in the field of water in Serbia and the former Yugoslavia. The international scientific conference Contemporary Water Management: Challenges and Research Directions is organized to celebrate 75 years of the Institute's long and successful history. The Scientific Board selected 26 papers to provide readers with the best view of the current research results, as well as the further scientific research directions and potential challenges in the future. Selected papers are classified into six conference topics according to the corresponding research field, although one should note that most of the presented works is multidisciplinary, which is after all a characteristic of a modern problem-solving approach in the field of water. Hence, the chosen conference topics and corresponding papers represent only one possible way of classification of the presented works.

We wish to express our gratitude to the International Scientific Board and the Organizing Committee of this international conference for their efforts in selecting the papers, reviewing, and organizing the conference. We also wish to express our gratitude to all the authors of selected papers for the time they spent presenting the results of their research in a way suitable for this conference, and for contributing to the celebration of 75 years since the establishment of the Jaroslav Černi Water Institute. Respecting the importance of jubilee and wishing to express gratitude to previous generations of scientific workers, the Honorary Committee was also formed.

Following the path of previous generations, the Institute's present and future staff remain privileged, and under duty and obligation to continue and improve the scientific and research work of the Institute in the years and decades to come.

Belgrade, October 2022

Editors

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