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Advancing in hydraulic analysis: Integration of optimisation methods and renewable energy sources

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ABSTRACT

Many freely available software programs for hydraulic analysis often fail to deliver adequate optimization outputs for topology design or may not be available at all. The novel software currently in development presents several innovative features compared to commercial programs. It integrates conventional distribution network elements alongside new components that aim to maximize the use of renewable energy. The components under review consist of a multifunctional water tower designed to utilize a wind turbine together with a ball reverse screw and a piston pump. This configuration ensures the full utilization of wind energy for pumping water to the upper reservoir of the tower. Another component is the irrigation zone, where the goal was to simplify modelling from the user's perspective. Additionally, the PV zone supplies users with data regarding energy generation for a specified area and the configuration of PV panels. These elements are mathematically integrated with the hydraulic analysis. The results indicate pressure values at nodes, flow through pipes, user recommendations, and data on specific areas like solar and wind power generation. After the calculations, users receive options for optimizing the distribution network. These options entail selecting the appropriate pipe diameter related to cost, as well as the optimal placement of tanks and water towers, ensuring suitable pressure at nodes (to prevent cavitation or excessive pressures), minimizing hydraulic losses, and reducing irrigation water costs (the application primarily focuses on irrigation in urban and natural landscapes). This paper further explored the selected options for optimizing the distribution network and the associated elements.

Keywords: optimization, irrigation, water cost, wind power, solar power, hydraulic analysis, renewable energy, urban smart irrigation.

INTRODUCTION

In today's context of climate instability, water scarcity, and growing demands for sustainable development, the optimization of water distribution systems (particularly irrigation) is critical. These systems play a fundamental role in both urban and agricultural settings, yet they are often plagued by inefficiencies, excessive operational costs, and a lack of integration with renewable energy sources (Mandal *et al*., 2019; Minhas *et al.,* 2019).

Various software tools have been created to help with hydraulic analysis. One of the most popular is Epanet 2.0, a free program for simulating the hydraulic and water quality behaviour of pressurized pipe networks (Rossman, 2000). It allows modelling of components such as pipes, tanks, reservoirs, pumps, and valves. Pipe2020 builds on these features with additional modules for control elements and dual hydraulic calculation methods, supporting pressure zone analysis and emergency scenarios (KY Pipe, 2019). Software tools such as AutoPEN and SiteFlow are utilised in the Czech Republic to design water networks and size pipes by hydraulic and regulatory standards (AutoPEN, 2022; AQUION, 2013). The integration of these tools into urban planning remains limited, and most are designed for engineers with advanced technical skills.

Despite advances, significant gaps persist in software. Most programs are limited to static hydraulic simulations and do not support optimisation based on economic or energy performance criteria. They often lack integration with renewable energy models such as photovoltaic or wind systems (Appelbaum, 2016; Mathew, 2006) and are disconnected from real-world conditions like crop-specific water demands, variable pricing of different water sources, or dynamic climate data. In addition, the ability to handle pressure or velocity constraints during system design remains limited, as does native support for irrigation-specific components such as emitters, sectors, or automatic zone control (Azenkot, 2004; Amer and Gomma, 2003). Calculation of pressure losses is often handled through approximations, although comparative studies have demonstrated the importance of selecting accurate head-loss models (Jamil, 2019). The limitations of existing software solutions can be summarised as follows:

- absence of cost- or energy-based optimisation capabilities,
- limited support for integrating renewable energy resources,
- poor adaptability to crop-specific or zone-based irrigation logic,
- weak or no connection to climate datasets or real-time weather parameters,
- a lack of intuitive graphical user interfaces for rapid configuration and simulation feedback.

To address these limitations, a new modular software application was developed in MATLAB App Designer. It enables both hydraulic modelling and parametric optimisation of irrigation systems under varying input conditions. The core of the optimisation is based on a genetic algorithm, a method proven effective for solving network optimization problems in prior research (Heydari et al., 2020). Unlike traditional tools, the application allows integration of different renewable energy sources, including photovoltaic panels and vertical wind turbines, as well as user-specified climate parameters. Resistance coefficients and hydraulic losses are derived based on empirical data from authoritative sources (Idelchik, 2008).

This tool is designed not only for researchers and engineers, but also for practitioners, such as municipal planners and agricultural technicians. The user-friendly, interactive graphical interface visualises key parameters, enabling users to adjust network designs iteratively, while monitoring system pressures, flow rates, and economic indicators. Considering the global shift towards smart infrastructure and renewable energy integration, the proposed tool supports data-driven decision-making in both rural and urban areas, thereby contributing to sustainable water management strategies.

This paper aimed to present the structure, methodology, and features of the developed software, and to validate its functionality through two contrasting case studies: one in the Špitálka district of Brno, an urban environment, and the other in an agricultural environment. The results demonstrate the flexibility and potential of this solution for optimising irrigation networks with minimal environmental and financial impact.

Furthermore, incorporating photovoltaic panels or wind turbines enables these systems to be powered by renewable energy, demonstrating a commitment to reducing the carbon footprint associated with conventional water management (Naderipour *et al.,* 2021). As communities and industries strive to adopt environmentally responsible practices, this application plays a pivotal role in achieving sustainable development goals, improving irrigation performance, and conserving water resources.

MATERIALS AND METHODS

This section presents the software background, the components of the distribution network, the input data used for modelling, the applied equations, and constraints relevant to the optimisation process. The software was developed in MATLAB App Designer and integrates various hydraulic and renewable energy elements for smart irrigation purposes.

Software environment

The application was developed using the MATLAB App Designer environment. It features a graphical user interface (GUI) with a coordinate system where users can create the distribution topology, place elements such as nodes, pipes, tanks, or renewable energy sources, and adjust input parameters like temperature or accuracy. The outputs are saved in.*xls* format and displayed visually within the application interface.

Components of the distribution network

The application allows modelling of a wide range of hydraulic and renewable energy components:

- basic hydraulic elements: pipes, nodes, reservoirs, water towers, tanks, pumps, turbines;
- renewable energy elements: photovoltaic fields (standalone or combined with irrigation), multifunctional water towers with integrated wind turbines;
- irrigation components: irrigation areas with emitter-based or sprinkler-based systems, automated calculation of diameter and pressure, and modelling of controlled irrigation in zones.

Each element has adjustable parameters. For example, the multifunctional water tower (Pochylý *et al.,* 2020, the patent), combines water storage with a renewable energy-powered piston pump based on a ball screw mechanism, photovoltaic areas, irrigated areas, and an element for dividing the network into irrigated circuits for separate scenario calculations are available. In the future, an axial pump element suitable for long-distance transport, known as the Smart Pump (Dobrovolný 2024), will be possible to implement.

Multifunctional water tower

The algorithm for the calculation of the multifunctional water tower (see Figure 1) component is based on the thesis of the author Švestka (2018). The reference to the patent can be found in (Pochylý *et. al.,* 2020, the patent). The output of the calculation is the required pump power, which is used for further calculations for the motor design.

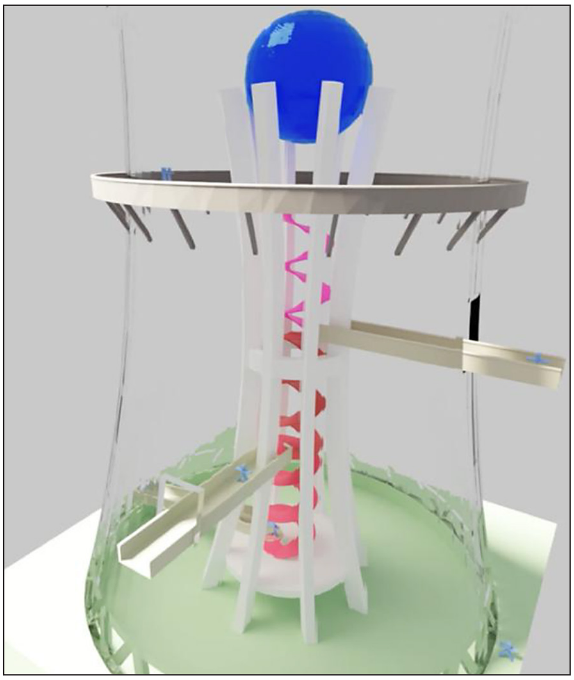

Figure 1. Spherical tank (Pírková *et al.,* 2024)

The P-Q characteristics of the pump for various required pressures in chamber p_1 and a graphical representation of the dependence of the axial force, which loads ball screws (Machát, 2010), on the flow rate for pressure p_1 are also generated. The input parameters are predefined, but their values can be changed. The information is taken from (Švestka, 2013; Mathew *et al.,* 2006; Dočekal, 2016, Jandourek *et al*., 2021; Pírková *et al*., 2024; Rychetník *et al.,* 1997). A piston pump with an inverted ball screw is integrated into the multifunctional water tank. Švestka (2013) used the following equation to calculate the pump performance:

$$\boldsymbol{P_p\ [W] = \rho \cdot a \cdot x_{max} \cdot Q \pm p_{S1} \cdot}$$

$$\boldsymbol{\cdot Q - \frac{Q^3}{2 \cdot S_1^2}\left(\rho \cdot \lambda \cdot \frac{x_{max}}{d_1} - 4 \cdot \rho \cdot \xi\right) + \Delta p \cdot Q_z} \quad (1)$$

where: ρ is the density [kg/m^3], a is the piston acceleration [m^2/s], x_{max} is the stroke [m], p_{s1} is the pressure difference between the discharge and suction, S is the piston area [m^2], λ is the friction coefficient [-], ξ is the local loss coefficient on the pump valves [-], the term $\Delta p \cdot Q_z = P_z$ is the power loss in the cylindrical gap between the piston and the chamber.

The settings allow for a renewable energy design in the form of a wind turbine to be used. The menu contains predefined wind turbines from ©LuvSide and Energy123 (2018). It contains the specified parameters such as rotor working area A, rotor diameter D, nominal power P_{nom}, nominal wind speed v_{nom}, wind speed at start-up $v_{cut\text{-}in}$, and at shut-down $v_{cut\text{-}out}$, and power at start-up $P_{cut\text{-}in}$. On the basis of these parameters, Equation 1 was developed and used by Mathew (2006) to calculate the wind power curve of a piston pump using a ball reverse screw as a function of wind speed and flow supplied by the pump. It also considers the conversion efficiency between the energy extracted from the wind and the energy delivered to the pump. The application also provides a recalculation of the wind speed at the rotor installation site.

Irrigated area

Another element of the distribution network is the irrigation area. Drip irrigation is considered, where emitters (drip emitters) are placed at the outlets of the pipes, but sprinklers can also be considered. Information taken from publications

(Amer *et al.*, 2003; Tiwari *et al.,* 2009*;* Azenkot, 2004, Keller, 1974).

The algorithm is based on sub-steps:

1) The user selects the desired sprinkler/washer with the values of the required pressure p_s, flow q_s and spacing s_l between the emitters.
2) The program calculates the number of sprinklers n along the sidewall for a given length and width of area and determines the length of the sidewall L according to the selected watering area distribution. One can choose to have the distribution pipe in the centre of the sidewalls or to have the sidewalls to the left or right of the distribution pipe.
3) The required flow rate through a side wall is determined by the relationship:

$$Q_u = n \cdot q_s \tag{2}$$

4) The lateral diameter D is designed to achieve a maximum loss along the pipe of 20%.
5) The loss height along the side wall is calculated as follows:
   - the side tube is smooth (no outlets); and
   - the result is multiplied by the factor F, see Equation 3, which can be obtained from the table by Christiansen (1942), a simplified procedure validated by Sadeghi *et al.* (2011).

$$\Delta H_f = \mathrm{F} \cdot \Delta H \tag{3}$$

Photovoltaic area

The program allows the user to add an element called Photovoltaic area. There are two main options to choose from, the first is an area with PV panels only and the second is an area with panels and an irrigation system. The calculation works with the online web application PVGIS (or Photovoltaic Geographical Information System; PVGIS.com, 2025), which provides information on solar radiation and PV system performance for any location in the world, excluding data from the North and South Poles. On this web application, the user selects the exact location and downloads the necessary data, which is then uploaded to the application. The user then processes and analyses this data. The program works with three main configurations from TSE (TSE, 2024) and Next2Sun (NEXT2SUN, 2024 – Figure 2), with the option to add more. The system developed by TSE, which also offers a range of other products, is very beneficial for crop production. These are agricultural canopies which, in addition to generating solar energy, also protect from adverse weather conditions (frost, hail, heavy rain, strong sunshine). Agricultural canopies cover a minimum of ground area, and the individual poles are spaced 27 m apart (specifically for agricultural machinery).

Another way of placing PV panels is perpendicular to the ground. Next2Sun uses so-called bifacial solar fences (see Figure 2). These fences are double-sided and face east and west. This allows the morning and evening sunlight to be used to generate electricity (Appelbaum *et al.,* 2016).

Input data and assumptions

The model requires a variety of input data from the user. These inputs reflect both technical specifications and environmental conditions:

- Climatic data: temperature, wind speed, and solar radiation are taken from the Czech Hydrometeorological Institute (CHMI) and the PVGIS system. These datasets are imported directly by the user based on the location and irrigation period.
- Irrigation configuration: area geometry, crop type (e.g., grass, trees, potatoes), irrigation

Figure 2. Next2Sun fences (NEXT2SUN, 2024)

months, and emitter/sprinkler details (pressure, spacing, flow).
- Network topology data: pipe lengths, diameters, elevations, and node connections are defined manually in the drawing interface.
- Renewable energy sources: wind turbine parameters (rotor area, start-up speed, nominal power) and PV panel configurations (agricultural canopy or bifacial fence layout).
- Water source costs: the application evaluates and compares different supply options (groundwater, surface water, roof runoff, mains water), prioritising by price per m³.

Default operational assumptions include:
- flow velocity: 0.5–2.0 m/s (can be customized),
- node pressure: min based on cavitation avoidance; max set to 2 MPa,
- water losses: maximum allowable irrigation lateral pipe loss set to 20%.

The user can modify all input parameters, allowing flexibility for both simple and complex network designs.

Hydraulic calculation model

Several methods for calculating head losses in a pipeline system include the Darcy-Weisbach equation, the Hazen-Williams equation, and the Manning formula (Jamil, 2019). The application utilises the Darcy-Weisbach equation because

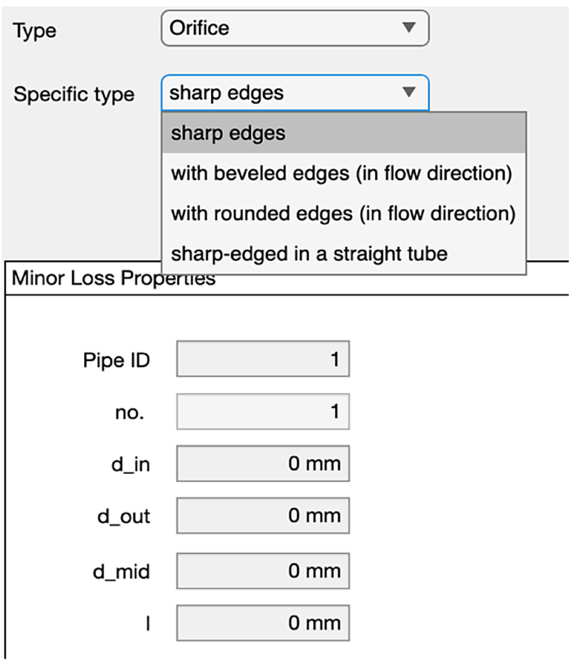

Figure 3. Library Orifice – minor losses

it provides more accurate results for determining length loss in the pipeline compared to other methods (Yogaraja *et al.,* 2021). This approach considers the nature of the flow and the pipe material properties (Valiantzas, 2008). The pressure and flow within the network are calculated using the Darcy-Weisbach equation:

$$h_f = \lambda \frac{L}{D} \frac{v^2}{2g} \quad (4)$$

where: h_f head loss [m], λ friction factor [-], L pipe length [m], D pipe diameter [m], v flow velocity [m/s], g gravitational acceleration [m/s²].

The λ is the friction coefficient, determined using the Colebrook-White equation for turbulent flow (Re > 4000). The program automatically selects the appropriate regime based on Reynolds number. For minor losses, the programme calculates the dimensionless local resistance coefficient, ζ, based on the shape of the component and flow conditions. A custom-built library enables users to input features such as sharp edges or rounded geometries (see Figures 3 and 4, for example).

Existing apparatuses employ fixed values of local resistances, whereas the application is based on calculating the local resistance coefficient, which depends on the resistance geometry and the Reynolds number. The model emphasises precise frictional loss modelling (based on Idelchik, 2008) and supports adjustable pipe geometry and material properties.

Optimisation methods

The optimisation component of the developed application enables users to refine the configuration of irrigation distribution networks concerning various design objectives. Although the software environment supports a range of optimisation methods, the current implementation and case studies presented in this paper utilize genetic algorithms (GA) due to their robustness for multi-objective, nonlinear problems.

Overview of available optimization techniques

Theoretical foundations for several optimisation strategies were reviewed and considered during the software design:
- linear programming (LP): LP formulations were evaluated for simple cost-minimisation

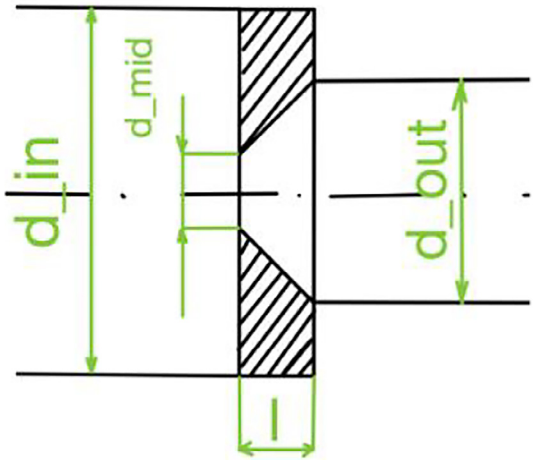

Figure 4. Orifice sharp edges

problems, using MATLAB's `linprog` function. However, their application was limited due to the nonlinear nature of hydraulic behaviour and constraints in the studied systems.
- nonlinear programming (NLP): MATLAB's `fmincon` and `fminunc` functions allow the solution of constrained and unconstrained nonlinear optimisation problems. These methods are useful for smooth objective functions with available gradients, but they may converge to local optima and require accurate initial guesses.
- evolutionary algorithms as genetic algorithms (GA): These methods imitate natural selection processes to explore a wide solution space and are effective in solving complex, non-convex, and multi-modal optimisation tasks without requiring derivative information.

A detailed comparison of the above techniques was conducted based on their theoretical suitability for water distribution systems optimisation, as described in Sarbu et al. (2020), Heydari et al. (2020), and MATLAB documentation (The MathWorks Help Centre, 2025).

Genetic algorithm implementation

Genetic algorithms were chosen as the primary optimisation method due to their flexibility and reliability when dealing with the following tasks. The application incorporates five types of parametric optimisation routines to improve system performance:
1. Pipe diameter optimisation (cost-based, velocity-constrained).
2. Minimisation of hydraulic losses.
3. Pressure optimisation at nodes (to avoid cavitation or excessive pressure).
4. Tank and water tower elevation optimisation.
5. Water consumption optimisation (based on crop type, irrigation period, and water source cost).

The GA was implemented using MATLAB's `ga` function with user-defined fitness functions tailored to each objective. The algorithm follows standard GA procedures:
1. Chromosome representation: each chromosome encodes variables such as pipe diameter, node elevation, or pressure limits.
2. Population initialization: a set of random feasible solutions is generated.
3. Fitness evaluation: based on cost, pressure deviation, or hydraulic efficiency.
4. Selection, crossover, and mutation: classical GA operators evolve the population toward optimal solutions.
5. Constraint handling: penalisation functions are used to discourage infeasible solutions (e.g., violating pressure or velocity limits).

By using the Genetic Algorithm Toolbox in MATLAB, one can focus on defining the problem and constraints and evaluating the optimisation results without having to implement the core genetic algorithm operations from scratch. By adjusting parameters such as population size, crossover rates, and mutation rates, one can effectively tailor the genetic algorithm to meet the water distribution system optimisation needs.

Optimization objectives in the application

The application currently supports the following optimization targets:
- pipe diameter minimisation – reduce total construction cost while maintaining acceptable velocity range (default 0.5–2.0 m/s).
- hydraulic loss minimisation – identify diameter combinations that result in the lowest total head loss.
- pressure optimisation at nodes – ensure that pressure stays within desired bounds (above cavitation threshold, below 2 MPa). Simultaneous variation of pipe diameters and tank elevations is supported.
- tank and water tower placement – determine optimal elevation to ensure sufficient pressure while minimising construction requirements.
- water source optimisation – allocate water from the most economical sources (e.g., roof

runoff, groundwater) depending on availability and volume constraints.

Each of these optimisation types can be activated separately in the user interface. The results of the optimisation are exported into tables for further review, including optimised pipe sizes, pressure distributions, hydraulic losses, and cost estimates.

Constraints and limitations

The optimisation and hydraulic simulations are subject to physical, operational, and economic constraints that affect the results and convergence of the model. These include:

- velocity constraints: the default acceptable water velocity range in pipelines is 0.5–2.0 m/s. In some simulations, this range was extended to 0.3–3.0 m/s to allow convergence, although high velocities may result in noise, and low velocities result in particle settlement.
- pressure constraints: the minimum allowable pressure is calculated using the saturation vapour pressure at the given water temperature to avoid cavitation. The maximum allowable pressure is set to 2 MPa but can be changed by the user.
- elevation constraints: water tower and tank elevations are optimised to minimise construction costs and hydraulic losses while maintaining sufficient pressure throughout the network.
- flow constraints: in irrigation zones, lateral pipe losses are limited to a maximum of 20%, and emitter placement is optimised for area coverage and uniformity.
- source prioritisation: water sources are ranked by cost, and the model attempts to fulfil irrigation demands using the most cost-effective combination, such as rainwater, groundwater, and surface water, before using mains water.
- convergence issues: if the optimisation fails to converge, it is often necessary to adjust initial guesses, extend permissible limits (e.g., velocities), or simplify the network topology.

A calculation may not yield valid results if all constraints are too strict relative to the system's size and configuration. These limitations reflect the inherent trade-offs between model flexibility, technical feasibility, and computational efficiency.

Computational workflow

The entire calculation and optimisation process in the application follows a structured workflow:

1. Topology creation – the user draws the distribution network in the graphical user interface, placing elements such as pipes, nodes, tanks, photovoltaic or wind energy zones, and irrigation areas.
2. Input configuration – climatic data, energy device parameters, water source details, crop information, and system constraints are specified by the user. Default values are provided for standard conditions.
3. Hydraulic analysis – the program calculates water velocity, pressure at nodes, head losses, and identifies areas with insufficient performance using the Darcy–Weisbach equation and minor loss coefficients.
4. Optimisation module – on the basis of the selected objective (e.g., minimise diameter or losses), the appropriate optimisation algorithm (typically GA) is executed under predefined constraints.
5. Result visualisation and export – the final optimised network is visualised within the application. Results are stored in.*xls* format, including optimized diameters, pressure distribution, loss coefficients, energy performance, and water cost estimates.

This workflow enables users to iteratively adjust designs based on the output data and supports both preliminary studies and refined design development.

The computational workflow of the application is illustrated in Figure 5. The diagram was created by the author using the Cardanit platform. It begins with defining input data and drawing the network topology, followed by the configuration of irrigation and energy parameters. Hydraulic calculations are then executed, after which the user selects an optimisation objective. The genetic algorithm iterates through possible solutions under defined constraints (e.g., pressure, velocity). If these constraints are not met, the design is adjusted and recalculated. Valid results are then visualised and exported as tables and graphical outputs.

Although no explicit statistical analysis was performed, the simulation-based approach of the application enables sensitivity testing by varying parameters such as emitter pressure, pipe

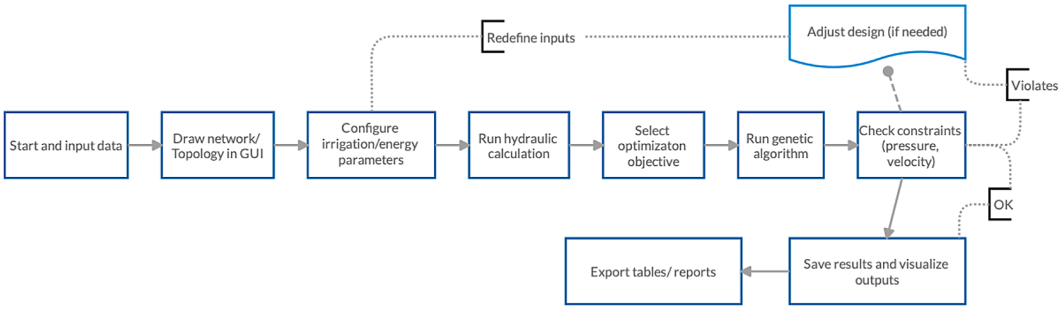

Figure 5. Computational workflow

diameter, tank elevation, and source cost. This allows users to evaluate the resilience of the irrigation design in different environmental and operational scenarios.

Case studies

Two case studies were used to validate the functionality and flexibility of the proposed optimisation and modelling tool. Each study presents a different context. The first was urban redevelopment, and the second was agricultural irrigation, allowing comparison of network structures and renewable integration.

Urban case study – Špitálka district (Brno, CZ)

For the validation of the optimization, the Špitálka irrigation model was selected from the work of Pírková *et al.* (2024) (see Figure 6). The area of interest is in the Czech Republic, in the city of Brno. The subject of this case 1 is the old, built-up, depopulated areas of the Brno heating plants. Within the RUGGEDISED project, a new ultra-modern innovative project is being developed in the Špitálka district to implement solutions for renewable energy production in cities, using new smart ways in the urban ecosystem (Re: ŠPITÁLKA, 2019; RUGGEDISED: Designing smart, resilient cities for all, 2020; Neumannová, 2022). Experimental measurements also confirmed the validity of the model. Table 1 below shows the pipes, their description, and the results of the hydraulic analysis. Figure 7 shows the results of the hydraulic analysis performed by the software.

Agricultural case study – demonstration model

The second case study is a conceptual irrigation system designed to demonstrate the flexibility and support of the tool for various network topologies. The system covers a 100 × 100 m² agricultural field, supplied via a looped (closed) network, unlike the branched configuration in the urban case. This setup allowed the evaluation of hydraulic performance under different topologies.

The layout was generated synthetically using design recommendations for emitter spacing and lateral distribution. The system does not simulate crop-specific water demand or real climate data, as its primary goal is to demonstrate the ability of the optimisation module to calculate irrigation water costs based on different supply sources and pressure zones.

Despite the simplification, the model allows evaluation of energy-free operation (no pumping) based on elevation gradients alone. The tool is suitable for later extension, where local weather, crop parameters, and pumping constraints are defined.

Input parameters and optimisation setup

The developed application includes several optimisation modes, each targeting specific parameters within the irrigation network model. The input data required for simulation and optimisation are collected through a user-friendly interface and are based on geometrical, hydraulic, climatic, and economic conditions. These inputs are used to define the boundaries and objective functions for the optimisation algorithms. For the agricultural case study, the following values were defined:

- irrigated area: 100 × 100 m²,
- emitter discharge rate: 2 L/h,
- emitter operating pressure: 1 bar,
- spacing between emitters: 4 m,
- spacing between laterals: 2.5 m,
- lateral length: 10 m,
- manifold length: 10 m,
- field slope elevation: 10 m,
- water temperature: 20 °C,
- no pumps were used in this simulation.

All pipes are assumed to have a circular cross-section, and initial diameter estimates are derived from the pipe cross-sectional area. The boundary conditions constrain flow velocities to remain within a realistic and safe interval (0.5–2.0 m/s) during all optimisation procedures.

Five independent optimisation modes were implemented, each corresponding to a unique objective function:

1. Pipe diameter optimisation.
Objective: minimize head losses in the system. Input: initial diameters based on pipe area. Optimisation is solved using a genetic algorithm with constraints on flow velocity.

2. Loss-based optimisation
Objective: minimise total energy losses (head losses and local losses). Includes both frictional and local components calculated from geometric inputs.

3. Tank elevation optimisation
Objective: maximize gravitational potential energy by adjusting tank and water tower elevations. This variant does not require pumps and focuses on passive water transport.

4. Pressure optimisation
Objective: maintain all node pressures within defined bounds based on temperature-dependent water vapour pressure and system constraints. This ensures safe operating conditions across different network sections.

5. Water cost optimisation
Objective: minimise total yearly water costs by selecting between multiple sources (e.g., surface, groundwater, rainwater, or public supply).

The algorithm assigns optimal water sources based on availability, cost per m³, and storage capacities of reservoirs and tanks.

All optimisation tasks were solved using a Genetic Algorithm (ga function in MATLAB), configured with population-based search and custom nonlinear constraints. The resulting configurations included pipe diameters, tank elevations, flow velocities, and water source allocations tailored to user-defined irrigation demands.

RESULTS

This section presents the outcomes of simulations and optimisation routines applied to two distinct irrigation models: one urban (Špitálka District) and one agricultural (demonstration looped network). The results validate the ability of the tool to model and optimise diverse irrigation networks, including renewable energy integration and multiple design objectives.

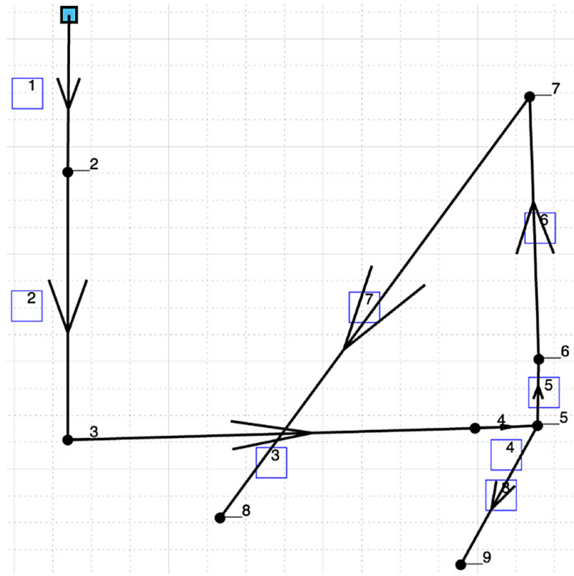

Figure 6. Topology of the Špitálka network

Urban case study – Špitálka district (Brno, CZ)

The proposed system was designed based on the planned redevelopment of the Špitálka district, a former heating plant complex undergoing smart city transformation. The hydraulic network follows a branched topology (Figure 6), consisting of 9 nodes and 8 pipe segments, and is supported by a multifunctional water tower equipped with a piston pump and renewable energy integration. Table 1 below shows the pipes, their description, and the results of the hydraulic analysis. Figure 7 shows the results of the hydraulic analysis performed by the software.

Diameter optimisation gave similar results to the topology diameter. According to the velocity results, the topology achieved a velocity of 0.5–0.9 m/s, which is also at the lower end of the velocity range for diameter optimisation, which is given as 0.5–2 m/s. Pipe loss optimisation includes another diameter size, which is shown in Table 2 below. The velocity constraint is the same as the previous optimisation: 0.5–2 m/s.

The topology consists of one tank. During optimisation, the minimal tank elevation remained at 1.6 m (velocity constraint is modified to 0.5–1 m/s). The results are shown in Table 3.

Table 1. Hydraulic analysis of the Špitálka area

Pipe no.	Length [m]	Diameter [mm]	Minor losses [-]	Velocity [m/s]	Hydraulic losses [-]
1	0.2	10	1	1.10	0.0324
2	4	10	3.2	1.10	0.0324
3	1.8	10	0.5	1.10	0.0324
4	0.1	10	0.5	1.10	0.0324
5	0.1	8	2	0.67	0.0388
6	1.4	8	2	0.67	0.0388
7	6	8	3	0.67	0.0388
8	2	8	3.5	1.05	0.0349

Note: Tables 1, 2, 5, 7, and 8 uses dimensionless coefficients to represent local and frictional hydraulic losses. Minor losses are expressed as K-values, indicating local head losses due to fittings such as elbows, valves, and junctions. Hydraulic losses refer to friction factors (f) derived from the Darcy-Weisbach equation using the flow rate (Q), head loss (H), and pipe characteristics.

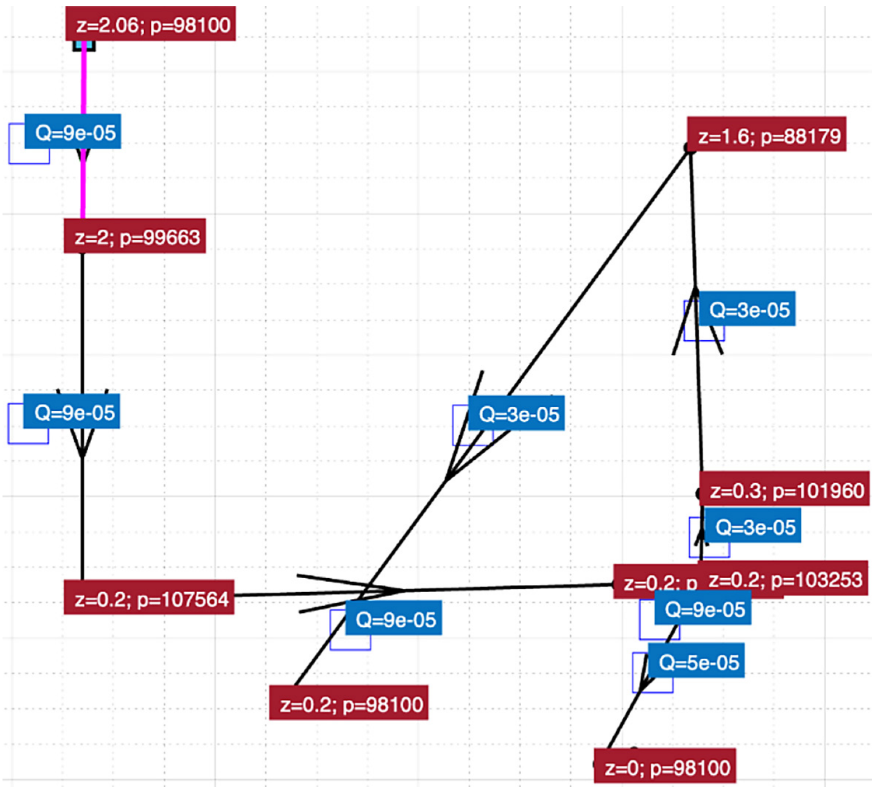

Figure 7. Steady-state results of the Case 1

Table 2. Pipe loss optimization

Pipe no.	Optimized diameter [mm]	Hydraulic losses [-]	Velocity [m/s]
1	166	0.0284	1.0804
2	219	0.0297	0.6337
3	148	0.0279	1.3592
4	153	0.0280	1.2830
5	81	0.0306	2.0009
6	156	0.0337	0.5380
7	81	0.0306	2.0009
8	92	0.0296	1.9978

Table 3. Water tower/tank elevation optimization (0.5–1 m/s)

Pipe no.	Velocity [m/s]
1	0.9998
2	0.9998
3	0.9998
4	0.9998
5	0.6322
6	0.6322
7	0.6322
8	0.9301

Agricultural case study – demonstration model

Case 2 refers to a conceptual looped network designed for irrigation purposes. This case study aims to evaluate the flexibility of the software in modelling irrigation systems with closed-loop topology, and to demonstrate the implementation of multiple optimisation routines under simplified yet representative conditions.

The irrigated area is defined as a 100 × 100 m² square field with a uniform slope of 10 m. Drip irrigation is considered, and an Irrigated Area point is established with predefined parameters, including emitter discharge rate of 2 L/h, operating pressure of 1 bar, spacing between emitters of 4 m, spacing between laterals of 2.5 m, and lateral and manifold length of 10 m each. Water temperature is set at 20 °C. No pumping system was used; the entire distribution is gravity-driven based on elevation gradients. At Point 2 in the network (green flower symbol), the required discharge is 0.005 m³/s. The corresponding configuration consists of 40 lateral lines, each with 25 emitters. Further details can be found in Table 4. The topology (Figure 8) consists of two tanks and two end nodes to atmospheric pressure (it can be the tank node or the groundwater source node). The results of the steady state calculation are shown in Figure 8 and Table 5. The diameter optimisation did not produce results for velocity in the range of 0.5–2 m/s. In the second step of the pipe diameter optimisation, the range was changed to 0.3–3 m/s, but there is a risk of settling and noisy operation in this velocity range. The result for this range is in Table 6. Pipe loss optimization includes another diameter size of pipes, listed in Tables 7 and 8. The velocity constraint is: 0.5–3 m/s and 0.5–2.5 m/s.

During the first elevation optimisation, the minimal tank elevation remained at 33.1 m (from 40 m) and 11.8 m (from 30 m), the velocity constraint is default as 0.5–2 m/s. In the second elevation optimisation, the minimal tank elevation remained at 36.2 m (from 40 m) and 23.4 m (from 30 m), the velocity constraint is defaulted as 0.7–2 m/s. The results are listed in Tables 9 and 10.

Irrigation water source evaluation – scenario-based results

An additional functional module of the application enables the estimation of water consumption and source allocation for irrigation under varying climatic and design conditions. While this module does not directly optimise hydraulic parameters, it allows users to simulate the distribution of irrigation demand among multiple water sources and assess the associated

Table 4. The irrigation area data

Area [m²]	H_{in} [m]	Q_{dem} [m³/s]	$D_{manifold}$ [mm]	$D_{lateralis}$ [mm]
100 × 100	16.9	0.00027	21	14

Table 5. Hydraulic analysis of the irrigation area

Pipe no.	Length [m]	Diameter [mm]	Minor losses [-]	Velocity [m/s]	Hydraulic losses [-]
1	20	200	4	1.58	0.0150
2	1000	100	4	1.75	0.0171
3	2000	100	6	0.88	0.0192
4	1500	150	4	2.03	0.0154
5	1000	100	4	1.10	0.0184
6	3000	100	6	0.81	0.0194
7	150	50	2	0.94	0.0221

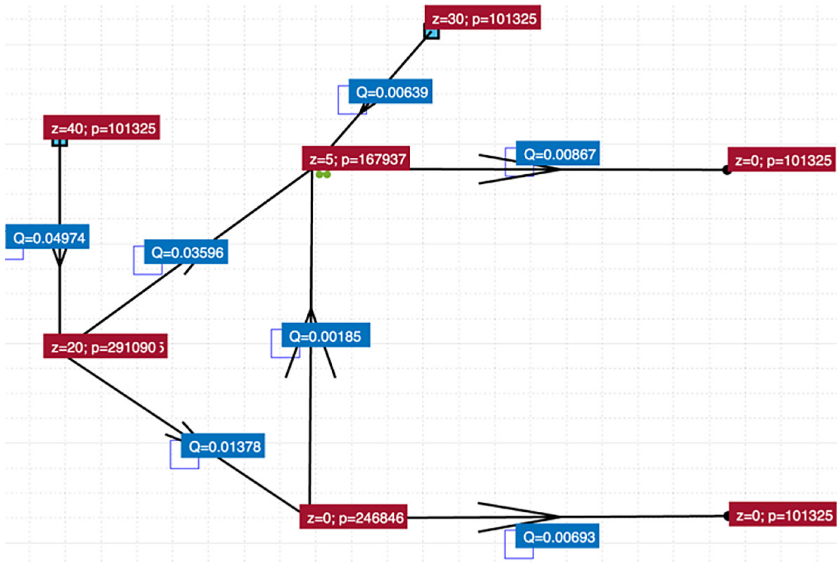

Figure 8. Topology and steady-state results of the agriculture irrigation network

Table 6. Pipe diameter optimisation (0.3–3 m/s)

Pipe no.	Optimized diameter [mm]	Velocity [m/s]
1	36	2.9687
2	42.6	1.5938
3	36	0.3190
4	36	0.7385
5	36.2	0.6723
6	36	0.5913
7	36	3.0007

costs. In the tested scenario, the user defines parameters such as:

- climate data (initial data from CHMI stations in the Czech Republic),
- climatic zone (eg., arid, humid),
- irrigated area size,
- crop or vegetation type,
- irrigation period (months of the year),
- availability of surface, groundwater, rainwater harvested, and public supply.

Table 7. Pipe loss optimisation (0.5–3 m/s)

Pipe no.	Optimized diameter [mm]	Hydraulic losses [-]	Velocity [m/s]
1	267	0.0148	1.5942
2	158	0.0145	3.0000
3	576	0.0116	2.5593
4	6	0.0414	0.5278
5	338	0.0126	2.9496
6	589	0.0114	2.9388
7	740	0.0120	1.4238

Table 8. Pipe loss optimization (0.5–2.5 m/s)

Pipe no.	Optimized diameter [mm]	Hydraulic losses [-]	Velocity [m/s]
1	360	0.0160	0.5536
2	6	0.0423	0.5475
3	5	0.0342	0.5050
4	174	0.0146	2.3652
5	280	0.0133	2.4892
6	390	0.0128	2.0511
7	100	0.0204	0.6513

Table 9. Tank elevation optimisation (0.5–2 m/s)

Pipe no.	Velocity [m/s]
1	1.3244
2	1.5651
3	0.8035
4	1.6588
5	1.1038
6	0.5000
7	0.5000

Table 10. Tank elevation optimisation (0.7–2 m/s)

Pipe no.	Velocity [m/s]
1	1.4415
2	1.6507
3	0.8391
4	1.8289
5	1.1038
6	0.7001
7	0.7001

The model then evaluates all connected water sources within the network topology (e.g., reservoirs, tanks, towers) and allocates flow based on source availability and cost per cubic meter. In cases of insufficient supply from primary sources, secondary sources are selected automatically. The user can define fallback strategies based on percentage allocation. This simulation highlights the flexibility of the tool in balancing ecological and economic objectives. In a scenario where the tank volume was limited and irrigation demand was high during the summer months, the model prioritized using rainwater and surface water sources, reducing reliance on the more expensive public supply. Such results support informed planning decisions and demonstrate the potential for long-term cost reductions in water-scarce regions.

Calculation limitation

Depending on the constraints, optimisation may not always yield results. It is necessary to modify the limitations and adjust the scope of the solution being sought. The first constraint lies within the initial estimate of the optimisation. Although it is not essential to begin the initial model with results within the constraints (such as diameter, pressure, or velocity), doing so is recommended for achieving better or faster convergence of the results.

Comparative discussion

The results from both case studies demonstrate the adaptability and effectiveness of the developed optimisation tool in two different network contexts, urban and agricultural. The urban network, characterised by a branched topology and the integration of renewable energy systems (e.g., multifunctional water tower), required pressure management to ensure efficient distribution under intermittent supply. In contrast, the agricultural looped network allowed for passive, gravity-driven irrigation without pumping, highlighting the benefits of elevation-based optimisation. Despite differing topologies and constraints, both models achieved:

- reduced hydraulic losses through diameter and elevation optimisation,
- economical design solutions, with up to 20% reduction in construction cost in the agricultural scenario,
- node pressure control within safe operational limits,
- functional integration of renewable sources for energy-efficient operation.

The comparative analysis confirms that the application can support robust design decisions for both existing urban infrastructure and new rural developments, with full adaptability to user-defined boundary conditions.

Summary of results

The simulation outcomes demonstrate that the developed tool effectively supports the design and optimization of irrigation networks of varying complexity, topology, and renewable energy integration. By allowing users to define their input parameters and offering multiple optimisation objectives, the system provides customisable solutions that are suitable for urban redevelopment and agricultural applications. The tool promotes efficiency, cost-effectiveness, and adaptability in different environmental and economic scenarios.

Sensitivity and scenario analysis

This study is based on simulation-driven optimisation and deterministic hydraulic modelling, which does not involve random sampling or variability typically required for standard statistical tests. Therefore, no classical statistical methods were applied.

Instead, the developed framework enables parametric sensitivity analysis by systematically varying key input parameters such as emitter pressure, pipe diameter and length, tank elevation, as well as water source cost and volume. Many parameters can be changed. This functionality allows users to test how changes in environmental or operational settings impact system performance, providing insights into the robustness and stability of the design.

For instance, altering the elevation difference in gravity-fed networks may affect the need for pump integration, while changes in crop type or irrigation period impact total water demand and cost-effective source allocation. These scenario-based simulations support decision-making under uncertain or changing boundary conditions, which is particularly valuable in sustainable urban or agricultural planning.

DISCUSSION

This study highlights the capabilities of the software tool developed to support multi-objective optimisation of irrigation systems by integrating hydraulic modelling, renewable energy planning, and economic evaluation. The tool was tested through two contrasting case studies: an urban study of the Špitálka district and an agricultural study. Each case demonstrated the tool's adaptability to different technical constraints and operational contexts.

In the urban Špitálka case study, the focus was on optimising pressure control and gravitational transport within a predefined infrastructure setting to reflect real-world redevelopment challenges. Including a multifunctional water tower equipped with renewable energy systems, such as photovoltaic panels or wind turbines, demonstrated the potential for autonomous operation, independent of conventional grid infrastructure. Optimizing pipe diameters minimised hydraulic losses while ensuring nodal pressures remained within prescribed safety margins. These findings are consistent with existing research that supports the development of energy-efficient urban irrigation networks with integrated renewable solutions (e.g., Appelbaum, 2016; Naderipour *et al.,* 2021).

In the agricultural case study, a looped topology enabled passive, gravity-driven irrigation, eliminating the need for active pumping. Although simplified, this model validated emitter distribution recommendations and demonstrated the impact of slope and water source selection on performance and cost. Scenario-based simulations revealed savings of up to 20% in construction costs through optimal sizing and source prioritisation, corroborating earlier findings on the economic impact of source configuration (Amer and Gomma, 2003).

Compared with conventional tools such as EPANET or Pipe2020, the software presented here offers a wider range of features, including pressure and velocity constraints, integration of multiple renewable energy sources, and dynamic response simulation based on seasonal or location-specific climate data. While these capabilities extend functionality beyond static hydraulic simulation, further validation against published optimisation outcomes is necessary to quantify improvements.

Some limitations must be acknowledged. Currently, the software assumes steady-state conditions and lacks support for transient analysis or real-time sensor input. Additionally, while the genetic algorithm is robust, it can be computationally intensive, particularly in complex or large networks. The agricultural case study excluded crop-specific or real-time climate parameters, which limits its generalisability.

Overall, this tool successfully bridges the gap between theoretical hydraulic optimisation research and practical irrigation network design. Further comparative analysis with literature benchmarks and deployment in real-world scenarios would strengthen its relevance and applicability in smart water management.

CONCLUSIONS

The developed software tool presents a new method for irrigation system design by combining hydraulic analysis, economic assessment, and renewable energy planning into one easy-to-use application. It allows for customisable, multi-objective optimisation with genetic algorithms and supports various setups for both urban and agricultural environments. Key findings include:

- Hydraulic losses were significantly reduced through optimised pipe sizing and elevation planning.

- Node pressures remained within safe operational thresholds under varying input conditions.
- Water supply costs were minimised by selecting optimal sources and prioritising low-cost alternatives.
- Renewable energy integration (e.g., photovoltaic or wind) was successfully incorporated to support autonomous operation.
- Both branched and looped topologies were effectively modelled and optimised.
- The main contributions of the tool include:
- broader usability for engineers, planners, and practitioners through a user-friendly interface
- enhanced flexibility compared to conventional tools in handling real-time climate data, energy integration, and scenario testing
- support for sustainability and resilience goals in water resource planning.

Despite its advantages, limitations include the absence of transient flow modelling, simplified climatic assumptions in some modules, and high computational demands in complex systems.

The relevance of the tool extends beyond academic exploration to practical applications in municipal water planning, smart agriculture, and climate-adaptive infrastructure development. As sustainable water use becomes an increasingly critical concern, this software provides a timely and versatile solution to modern irrigation design challenges.

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