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JalTantra: A System for the Design and Optimization of Rural Piped Water Networks

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Abstract. Government bodies responsible for drinking water distribution in India face the challenging task of designing schemes that provide a quality of service that is adequate to meet the needs of citizens at a cost below the strict government norms. Engineers at these government bodies must undertake the design process using tools that are not optimal and consider only pipe diameter selection, which is only one component of the entire scheme design. As such, much of the design process is undertaken in an ad hoc and heuristic manner, relying on the experience and intuition of the engineers. We developed JalTantra, a web system that aids these government engineers in sizing both pipe diameters and the various other water network components, such as tanks, pumps, and valves. We use an integer linear program model, which allows us to solve the problem optimally and quickly.

History: This paper was refereed.

Keywords: water distribution • optimization • integer linear program • pipe diameter selection • tank configuration selection

Multiple-village piped water schemes are projects designed to provide water to several villages from a common source of water. They consist of several components and thus require engineers to make many choices regarding sizing and service. These choices impact the cost of the scheme. Government guidelines lay out the per-capita limits on the capital cost of a scheme. Maharashtra Jeevan Pradhikaran (MJP) is the government body responsible for the planning, designing, and implementation of water supply schemes for the state of Maharashtra in India. It employs over 1,500 engineers and has designed more than 11,000 rural water supply schemes over the past several decades. In deciding to design and implement a scheme, MJP must adhere to these government cost guidelines. Thus, a scheme design must provide an adequate quality of service while minimizing costs.

The pipe networks for these rural schemes are typically gravity fed because the electricity supply is often unreliable. Acyclic (branched) networks are common because the redundancy that cyclic (looped) networks provide is an unaffordable luxury. Thus, our focus is on gravity-fed branched networks.

Cost optimization by selection of pipe diameters in piped water networks has been studied for more than 30 years. Several constrained optimization techniques from linear programming (Samani and Mottaghi 2006) to genetic algorithms (Savic and Walters 1997) to newer metaheuristics such as tabu search (Cunha and Ribeiro 2004) and the shuffled frog leaping algorithm (Eusuff and Lansey 2003) have been employed to solve various variations of the cost-optimization problem. The water networks considered are looped networks, which are harder to solve than branched networks. Therefore, heuristic techniques, which provide non-optimal results, are employed to solve these networks in a reasonable amount of time.

Government bodies such as the MJP use software such as BRANCH, EPANET, and WaterGEMS to aid their design of water networks (Lad et al. 2012, Choudhary et al. 2013, Hooda et al. 2013, Vyas et al. 2014). The World Bank developed an optimization tool, BRANCH (Modak and Dhoonia 1991), which attempts to minimize pipe cost for branched pipe networks with a single water source. It is the software of choice for MJP engineers when designing a rural water scheme. Alternatively, some engineers use WaterGEMS (Bentley Systems 2019), a commercial software package, to design and analyse water networks. Because it uses genetic algorithms, the cost optimization is heuristic and thus not optimal. Both BRANCH and WaterGEMS consider only the pipe diameter selection component of water network design. Other components are designed manually in an ad hoc manner. EPANET is a water network modelling software package that simulates the hydraulics of a water network over an extended period. It is used to analyse and verify the network once its components have been designed.

Solving the pipe diameter selection problem is difficult partly because each link can consist of multiple pipe diameter segments. Samani and Mottaghi (2006) propose an integer linear program (ILP) formulation for the special case of one pipe diameter per link. Hooda and Damani (2017a) present an improved formulation that solves the more general formulation while still maintaining optimality.

Rural water networks also consist of intermediate tanks known as elevated storage reservoirs (ESRs), which act as buffers between the incoming flow from the primary source and the outgoing flow to the demand nodes. The network from the primary source to the tanks is called the primary network, and the network from the tanks to the demand nodes is called the secondary network. During the design stage, the primary and secondary networks are optimized separately with the tanks acting as demand nodes for the primary network. The selection of tank locations, their elevations, and the set of demand nodes to be served by different tanks is currently made manually in an ad hoc fashion prior to optimization. Therefore, including this tank configuration selection in the cost-optimization process is desirable (Hooda and Damani 2017b).

Pipes and tanks are, however, not always sufficiently large to provide water to the entire network. In areas where the source of water is at a relatively low elevation, one cannot rely solely on gravity to provide water to all the nodes in the network. Even in networks where water can reach all nodes, the cost might be too great if the pipe diameters required are very large. The inclusion of pumps can help mitigate such problems. Pumps provide pressure to the network in excess of the natural pressure because of gravity. Pumps, however, require electricity to operate throughout the lifetime of the scheme. Therefore, being economical with the usage of pumps is important because their inclusion comes at the cost of both capital expenditure of the pumps and continual operational expenditure. Conversely, in networks where the source is at a significantly higher elevation than the other nodes, excess pressure in the network could cause pipes to burst. In such cases, reducing this excess pressure using pressure-reducing valves is desirable.

Because currently used software solutions cannot optimally solve the problem and are restricted to only pipe diameter optimization, we developed the JalTantra system, which includes both the cost optimization of pipes and tanks. In this present work, we extend JalTantra by including pumps and valves, which requires considering both the capital cost and the operational cost. Because we modelled it as an ILP, the optimization is optimal. We developed it with constant feedback from government engineers.

We structured the remainder of the paper as follows. In the Components of a Multiple-Village Piped Water Scheme section, we describe the building blocks of a multiple-village piped water scheme. In the Problem Formulation section, we formally describe the inputs, outputs, and objective for the problem. The Pipe Diameter Selection Problem and The Tank Configuration Selection Problem sections describe the cost impact and model details for the first two network components included in the model. We follow this with the Integrating Pumps and Valves in the Model section, where we describe an extension of the model to include operational cost in addition to the capital cost considered so far. In the JalTantra System Description section, we describe the implementation of the model in the freely available web system JalTantra. In the Performance Results section, we highlight the performance of the system. GIS Integration describes how designers can easily import details of a new network into JalTantra. In the Government Impact section, we detail our interactions with several government engineers. In the Future Work section, we provide some future directions for the JalTantra system. Finally, we provide details of the model in the appendix.

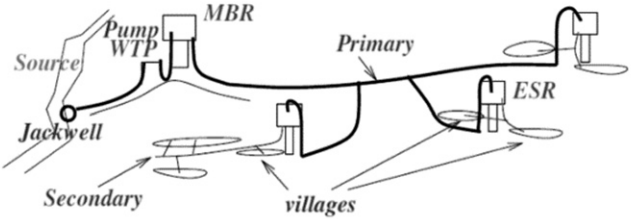
Components of a Multiple-Village Piped Water Scheme

The purpose of a multiple-village piped water scheme is to transport water from a water source to a group of villages. This is achieved by using several components, such as pipes, pumps, tanks, treatment plants, and valves. The choices made regarding these components contribute to the cost of the scheme as well as the quality of the service provided. The objective is to minimize cost while maintaining desired service quality. We briefly describe the components that compose a typical scheme (Hooda et al. 2013) and detail how each impacts the scheme cost and quality. The layout of a typical multiple-village scheme is depicted in Figure 1.

Source

The water source is the location from which the water is drawn and then distributed to the rest of the network. The source can be surface water (e.g., lakes, reservoirs, and rivers) or groundwater. Several sources might be available from which to select one or more

Figure 1. The Diagram Shows the Components of a Typical Rural Piped Water Scheme



Notes. Water is pumped from the source to the WTP and then to the MBR. The primary network then transports water from the MBR to the ESRs and then finally the secondary network connects the ESRs to individual villages (Sohoni 2016).

sources to service the scheme. The choice of source(s) depends on several factors, such as water head of the source, location in relation to the rest of the network, quality of water available, amount of water that can be drawn sustainably, and reliability in times of stress (e.g., summer months).

Water Treatment Plant

The water that is drawn from the source needs to be treated at a water treatment plant (WTP). WTPs vary both in the types of treatments that they can provide and in their capacities—that is, the amount of water that the WTP can process in a day. The factors influencing the choice of WTP are the supply of water that must be provided, the quality of the source water, and the task for which water will be consumed (e.g., drinking and irrigation).

Mass Balancing Reservoir

Water from the WTP is stored in the mass balancing reservoir (MBR) and then released into the rest of the network. Thus, it serves as a buffer in the supply of water to the rest of the network. It acts as an "effective" source of the network, and the water head it provides is a key component in shaping the rest of the network. The MBR choices that must be made are location, elevation, and sizing.

Elevated Storage Reservoirs

Elevated storage reservoirs (ESRs) are the reservoirs, also known as tanks, which are placed at various points of the network from which water is delivered to the villages. Water is supplied to these tanks from the MBR. Each ESR can serve one or more villages. The villages served are selected depending on their locations relative to the ESR, the amount of water demanded by the villages, and the capacity of the ESR. An important consideration is the elevation of the ESR because this impacts the choice of pipe diameters in the primary and secondary networks.

Pipes

Pipes are the backbone of the water distribution network. As water flows in a pipe, water loss occurs in the waterhead along the length of the pipe. This is caused by friction losses as a result of the movement of water in the pipe. This head loss depends on factors such as the diameter, length, and material of the pipe, as well as the amount of water flowing in the pipe. The choice of pipe depends on all these factors. In addition, pipes need to withstand the water pressure, which is applied constantly.

Pumps

Pumps are required to supply water where water cannot be supplied naturally (i.e., via gravity). The power of the pump required depends on the amount of water to be pumped and the waterhead that must be provided. Pumps are one of the primary sources of operational cost, and their usage should be on an as-needed basis.

Valves

At times, part of the network has excess water pressure because of large natural elevation differences. Therefore, the pipes chosen must be able to withstand such pressures; however, these pipes increase capital costs. If a lower head can suffice for the downstream network, pressure-reducing valves can be employed to reduce the pressure and thus allow the use of pipes with lower pressure ratings.

The job of the scheme designer is to choose all the above components such that adequate service quality is provided and the cost of the scheme is within government norms. Currently, only the pipe diameters are optimized, and the rest of the components are chosen manually. JalTantra incorporates the other network components (e.g., tanks, pumps, and valves) into the optimization model.

Problem Formulation

We formally describe the problem statement below and then provide brief details on how we implemented the model to solve the problem. Note that we consider only branched networks.

Input

- General: primary and secondary supply hours, minimum and maximum head loss per kilometer, maximum water speed
- Source node: head
- Node: elevation, water demand, minimum pressure requirement
- Link: start and end nodes, length
- Existing pipes: start and end nodes, length, diameter, roughness, parallel allowed
- Commercial pipe diameter: cost per unit length, roughness
- Tanks: maximum tank heights, tank capacity factor, nodes that must (must not) have tanks, capital-cost table
- Pumps: minimum pump size, efficiency, capital and energy cost, design lifetime, discount and interest rate, pipes that cannot have pumps
- Valves: location, pressure rating

Output

- Length and diameter of pipe segments
- Partitioning of set of links into primary and secondary networks
- Location, height, and size of tanks
- Set of nodes being served by each tank
- Location and power of pumps

Objective

- Minimize total capital cost (i.e., pipe, tank, pump) and total energy cost (pump)

Constraints

- Node pressure must exceed minimum pressure specified
- Water demand must be met at each node

Because we consider only branched networks, the flow through each link in the network is fixed. This allows us to employ linear models without making any approximations regarding the head loss due to the flow of water in pipes. However, with the inclusion of tanks and pumps, we need to use an ILP.

We now look at the three major water network components that constitute the model—that is, pipe diameters, tank configurations, and pumps and valves. The first iteration of the JalTantra model was based on the BRANCH functionality and thus only looked at the pipe diameter selection problem. Below, we describe why the problem is important to the design of a water supply network and give brief details of the implementation. Interacting with government engineers, and from their feedback, we extended JalTantra to include other network components. Although the tank configuration selection is a part of every scheme, it is done manually and heuristically. This approach is both time consuming and nonoptimal. We describe how different tank configurations impact the cost of the scheme and provide brief details on how we included their selection in the model. We then motivate the integration of pumps/valves to the JalTantra system. Because of the continuous operational cost involved, these components should be used sparingly; however, in cases in which the waterhead is too little or too much, their use is unavoidable. The variables and constraints that constitute the overall model are described in detail in the appendix.

The Pipe Diameter Selection Problem

The pipes that are laid out in the links between the nodes of the network are the backbone of a water network scheme. The primary choice to be made is the diameter of each pipe. As water flows through a pipe, the waterhead along the pipe length decreases because of friction losses experienced as the water flows in the pipe. This loss of pressure is called the head loss, and it depends on several factors, such as the type of pipe chosen, the length of the pipe, the water flow through it, its length, and its diameter.

The type of pipe chosen depends on where the scheme is being designed and its purpose. The length of the pipe is commonly fixed because the network topography is fixed along the existing road network. The water flow through a pipe is also effectively fixed in a branched network because the design demands at each node are precomputed using population forecasts and the desired demand per capita. Therefore, the pipe diameter is the lever that the designer has in changing and managing the head loss through the pipes.

A larger diameter results in a smaller head loss; thus, the service quality in terms of the waterhead provided at downstream nodes is better. Typically, there is a minimum waterhead requirement for each node in the network; larger diameters require costlier pipes. Therefore, the designer must choose pipe diameters such that the required head constraints are satisfied while costs are minimized.

The choice of pipe diameter is made from a discrete set of diameters because commercial pipes are available only in specific fixed diameter sizes. Typically, the designer can choose from between 10 and 20 pipe diameter sizes. Therefore, even for a relatively small network with 20 pipes and 10 diameter choices, the number of combinations for pipe diameter allocation is an astonishing 10^{20}. Clearly, enumerating and choosing the best solution from all possible combinations is not a feasible strategy.

The solution space is extended further if a single link in the network consists of multiple pipes with different pipe diameter sizes. Such configurations can arise because only discrete pipe diameter sizes are allowed. For example, the ideal pipe diameter size for a link in the network might be 70 mm; however, the only pipe diameters available are 50 mm and 100 mm. In this case, allocating a 50 mm diameter will result in violating the node head constraints; however, allocating a diameter of 100 mm will be costlier than necessary. The link can be split into two pipes, one with a 50 mm diameter and one with a 100 mm diameter, resulting in an effective diameter of 70 mm. A link can be chosen such that it can be broken up into as many pieces as there are pipe diameters available. However, Fujiwara and Dey (1987) show that in the optimal case, each link will have at most two adjacent diameters. Even with the restriction of two adjacent diameters, the possible combinations are infinite because the link can be broken up at any point. Thus, an enumeration strategy is not feasible when trying to optimize the cost of the pipes.

A common approach for designers in the developing world is to manually explore the search space using some heuristics and personal design experience. They then verify these manual designs using EPANET. For example, consider the following greedy algorithm that many engineers employ. Assign a single pipe with the largest diameter to every link. If this does not satisfy the head requirements at every node, then no solution is possible. Then, starting at the end nodes and going upward, decrease the diameter of the pipe until the head requirement is satisfied.

Do this iteratively for the entire network. At each step, we ensure that the head requirements are met, so the resulting solution is guaranteed to be feasible; however, it is not guaranteed to be optimal. The pipe diameter decisions are being made one by one in a greedy fashion; however, choosing a diameter that is larger than required downstream might result in more cost-efficient choice for an upstream pipe. The strategy provides even poorer results when we consider the split-pipe configurations.

Alternatively, some designers use tools that help optimize the capital cost of pipes. BRANCH is the tool used most commonly in India (Modak and Dhoonia 1991). Developed in 1991 as part of a World Bank initiative, it reports multiple pipe diameters per link as part of the solution; however, it can only solve networks of up to 125 nodes. Also, the solutions it provides are typically not optimal. Because the BRANCH software is not open source, extending the optimization parameters beyond pipe diameters is not possible; however, several network parameters, other than pipe diameters, impact the design of a water supply network. The JalTantra system was created to provide an optimal and scalable alternative. Hooda and Damani (2017a) present a model for the cost optimization of piped water networks that can be solved optimally in a short time.

They formulate the problem as a linear program (LP) model. The primary variable is l_{ij}, which represents the length of the jth pipe diameter component of the ith link in the network. Each link can consist of components corresponding to each pipe diameter size that is available. Although we know that the eventual optimal solution will consist of at most two pipe diameters (Fujiwara and Dey 1987), we formulate the model more generally. This allows the use of an LP model instead of an ILP model if the model had been restricted to have only two pipe diameters per link. This results in a much faster optimization, even in networks of more than 1,000 nodes, which take a few seconds.

After implementing the pipe diameter selection for water supply networks, we demonstrated JalTantra to several water network engineers from MJP, the government body in charge of providing drinking water in the state of Maharashtra, India. In talking with designers, a common point they brought up often was that when designing a scheme, the pipe diameter size is only part of a bigger picture. Other components, such as tanks, pumps, and valves, must also be designed. A trial-and-error process, which is both nonoptimal and time consuming, is used to manually design these components. Therefore, we extended the scope of JalTantra to also include these components.

The Tank Configuration Selection Problem

The purpose of ESRs or tanks is to serve as demand points for the secondary network. They act as a buffer of water supply between the primary and secondary networks. The primary network distributes the water from the source to the tanks. Each tank then distributes water in a secondary network to the set of demand nodes for which it is responsible. The tank configuration problem involves determining the tank locations, heights, and capacities, and the set of downstream nodes that each tank will service. Currently, these choices are made in an ad hoc manner, relying on the intuition and experience of the designer. Hooda and Damani (2017b) include tank configurations in the cost optimization formulation implemented in the JalTantra system.

The mapping of downstream nodes to tanks can be done in several ways. Each demand node can be mapped to a tank, a single tank can service all the nodes, or the configuration may be anywhere between the two extremes. A tank is sized about 33%–50% of the daily demand for which it is responsible.

With the introduction of tanks, the network is now split into the primary and secondary networks. The flow through the pipes depends on whether the pipe belongs to the primary or secondary network. The primary network runs for the entire day, whereas the secondary network runs for only for a few hours to manage the distribution of the limited amount of water supply. This means that in satisfying the same daily demand, a pipe in the primary network will have a lower flow rate (volume per second) than if the same pipe belonged to the secondary network. This occurs because although the total quantity of water being transported is the same, the number of transportation hours is fewer in the case of the secondary network. Therefore, for the same head loss across a pipe, higher diameters are required for secondary networks.

Therefore, total pipe cost is minimized when the entire network consists of a single primary network (i.e., a tank is installed at each demand node). The capital cost of the tanks depends on the sizes of the tanks to be built. The total tank capacity of the network is the same irrespective of the configuration because the total demand that needs to be served is the same. The cost for different configurations, however, will differ because an individual tank's cost rises nonlinearly as the tank's capacity increases; for example, doubling the size of the tank raises the cost to less than double the original cost. Therefore, the total tank cost is maximized when each demand node has its own tank.

Similarly, tank cost is minimized when a single tank serves the entire network. In such a configuration, the secondary network is the largest, and thus the pipe cost is maximized. The overall cost-optimum tank configuration depends on the network topology, node demands, and elevations, and it can lie anywhere in between these two extremes.

To implement the primary/secondary split of the network, we introduce a binary variable, f_i, which represents whether the ith link belongs to the primary or secondary network. This determines the flow in the link and in turn helps determine the head loss across the link. Binary variable s_{ij} represents a tank at the ith node that serves the demand for the jth node. Several constraints are also added to ensure that the network configuration chosen is appropriate. For example, one constraint ensures that each node can only be served by a single tank. The designer also has the option of fixing tank locations or of disallowing specific nodes from having tanks. This allows the designer to incorporate operational considerations that might be outside the scope of the model.

Integrating Pumps and Valves in the Model

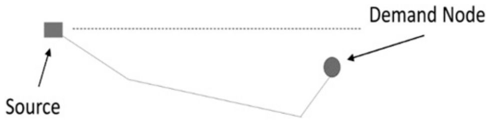
So far, we have considered only gravity-based networks. In many real-life scenarios, however, some parts of the distribution network may lie at elevations that are higher than the source. In such cases, no matter what pipe diameters we use, water cannot reach the higher elevations. Even if the source is at a higher elevation than every other node, having downstream nodes at relatively higher elevations might result in a significant increase in pipe costs. Consider the elevation profile shown in Figure 2. To provide water to the final demand node, there must be very little head loss in all the pipes from the source, even though the head is required only at the end. Therefore, using large pipe diameters is necessary, thus incurring higher costs.

Conversely, in some networks in which the source is at a very high elevation, excessive pressure in the entire network might result despite using the smallest pipe diameters. This excess pressure may lead to pipes bursting; to avoid this, higher resilience pipes must be employed, thus increasing the capital cost.

To address the problems of too little or too much head, network components such as pumps and valves can be employed. Pumps help provide additional head to the network. This can allow the network to (1) reach nodes that were otherwise impossible to reach or (2) use smaller pipe diameters for the majority of the network and therefore significantly reduce the overall pipe cost. We have considered only the capital cost of the scheme until now. The energy required to run the pump is a continuous cost that the scheme must reflect. Therefore, with the introduction of pumps, both the operational cost and the capital cost of the scheme must be considered.

To include pumps in the model, we introduce a continuous variable ph_i, which represents the pump head provided by a pump in link i of the network. If the value of a given pump head is 0, we know that no pump is installed for that link. We take several inputs, such as the pump capital cost per kilowatt (kW), energy cost per kilowatt-hour (kWh), pump efficiency, design lifetime, minimum pump size, inflation, and interest rates, from the user (i.e., the designer). These are used to translate the pump head required to the capital and operational cost of the pumps. The capital and energy pump costs, together with the previous pipe and tank costs, are then minimized. As with tanks, users of the JalTantra system have the option of fixing existing or predesigned pumps.

Figure 2. The Diagram Shows an Elevation Profile



Notes. Even though the source is at a higher elevation than the demand node, most of the head required is only at the tail end of the network. Thus, a pump may allow a designer to reduce upstream pipe diameters and reduce overall cost.

When pressure-reducing valves are introduced into the network, they reduce the downstream head along the pipe in which they are installed. Thus, they serve to reduce excess pressure in the network. Currently, the notion that excess pressure is negative is a concept that is purely external to the model. We decided not to strictly enforce any maximum pressure constraints because doing so might be unavoidable in some cases (e.g., hilly areas). Because no penalties or constraints are included to "punish" excess pressure, the model will never choose valves. Thus, to incorporate pressure-reducing valves, a manual option is included, allowing the user to introduce for any pipe i a valve with pressure-reducing setting VH_i.

JalTantra System Description

The ILP model for the cost optimization of a branched water supply network, which we describe above, has been implemented in the JalTantra system. We developed it over several iterations with feedback from government water supply engineers. Several features, such as the inclusion of other network components and geographic information system (GIS) integration, are a direct result of such feedback.

We developed JalTantra as a Java-based web application. For the ILP optimization we use the linear solver library CBC (Forrest and Lougee-Heimer 2014) and its Java interface by Google (Google OR Tools 2017). The online web system is freely available at https://www.cse.iitb.ac.in/jaltantra. It can also be downloaded and run as a local server, which requires Java 7 or above (Oracle 2014).

Data input to the software can be entered manually or via importing files in various formats, such as XML, Excel, and BRANCH files. Allowing BRANCH files as input allows legacy users of BRANCH software to easily test JalTantra using their existing files. The output of the optimization can be saved as an Excel File. The output network can also be saved as an EPANET (United States Environmental Protection Agency 2017) file to be used in further modelling and verification. Figure 3 shows a screenshot of the JalTantra System.

Performance Results

We compare the performance of JalTantra to BRANCH, the tool currently used by practitioners in India. We tested them across eight networks of sizes ranging from 10 nodes up to 200 nodes. Three of the networks are real-world networks, and the rest are artificially generated to test the scalability of the tools. The artificial networks are procedurally generated, starting at the source in a top-down manner. Because the networks we are looking at are branched/acyclic, the graph density is simply $1/n$, where n is the number of nodes in the network. The various node and link properties are randomly assigned from the following ranges:

- Number of children nodes: 1 to 5
- Elevation (in metres): 100 to 300
- Demand (in litres per second): 0.01 to 5
- Length of links (in metres): 500 to 5,000

In the first approach, all three network components (i.e., pipes, tanks, and pumps) are being optimized. Because BRANCH does not include an option to optimize tanks and pumps, we assume no pumps in the network and assume a single tank at the head of the network. We then also tested JalTantra with similar constraints to do a like-to-like comparison.

Table 1 displays the results of the three approaches over the eight networks. To compare overall cost for BRANCH and JalTantra (only pipes), we precomputed the cost of a single tank and added it to the pipe cost to determine the overall cost. Across all eight networks, the first approach performs the best in terms of overall cost. When the tank configuration is fixed, approach 2 (JalTantra) outperforms approach 3 (BRANCH) in terms of cost and time taken. In addition, BRANCH could not provide a solution in networks with 100 or more nodes.

GIS Integration

To describe the network, we need to provide elevation data for nodes and the lengths of the links connecting them. These values are measured using physical surveys to ensure accuracy before doing the final design. For earlier prototype designs, however, to gauge the feasibility of the design, GIS data were used. These data had to be looked up and then entered manually. This can be a very tedious process, especially for link distances because the link must be manually drawn along the road network.

As part of the web system, we integrated Google map-based GIS (Google Maps Platform 2017), which allows the user to add nodes on the map. Links between the nodes can be added simply by using the Google directions service without having to manually enter the entire path. The tool also allows a user to view the elevation profile of the paths generated. This is then used to add dummy nodes along the path at points of high elevation. Elevations and distances can then be extracted directly into the node/pipe

Figure 3. The Graphic Shows an Example of the General Network Properties Tab of the Online Interface of the JalTantra System

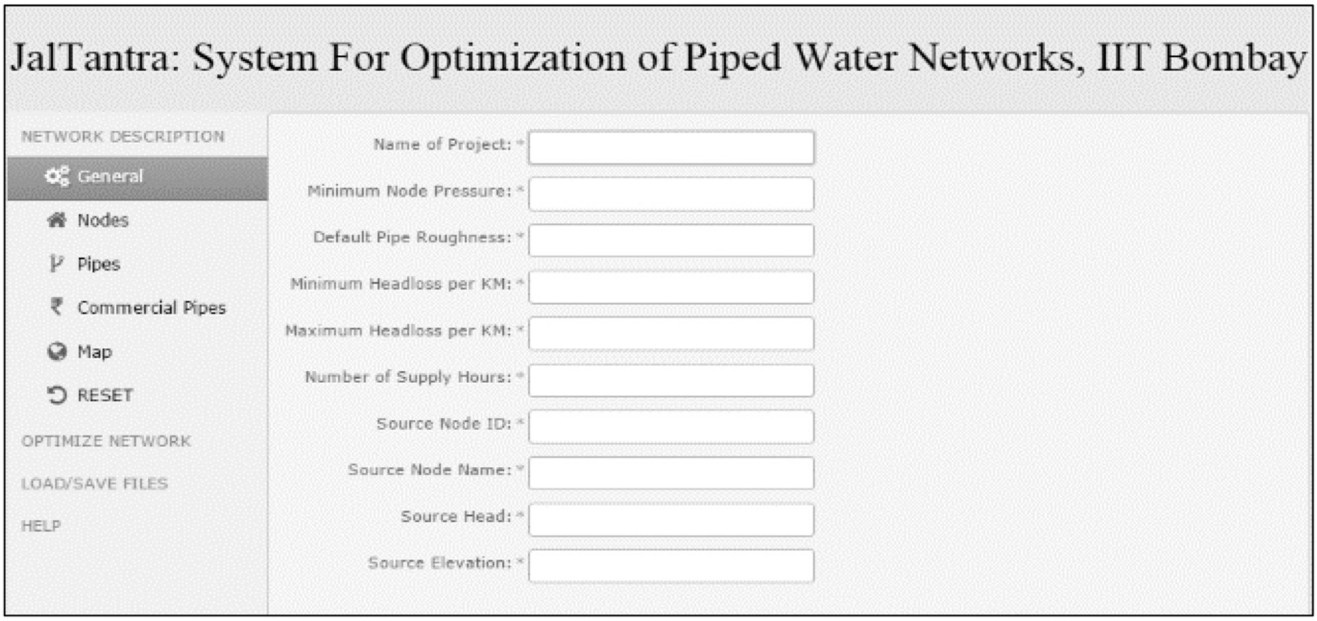


Table 1. The Table Shows the Cost Breakdown and Time Required for the Design of Eight Networks Using JalTantra and Branch

		Optimal						Single Tank						
		JalTantra							JalTantra			BRANCH		
				Cost (10^5 Rs)				Fixed		Cost (10^5 Rs)			Cost (10^5 Rs)	
Network	Nodes	Time (sec)	No. of tanks	Pipe	Tank	Pump	Total	Tank Cost (10^5 Rs)	Time (sec)	Pipe	Total	Time (sec)	Pipe	Total
gen_10	10	0.5	3	143	57	11	212	37	0.02	200	237	11.6	204	241
Khardi	11	0.4	3	247	201	0	448	184	0.03	422	605	9.1	424	607
Shahpur	21	1.3	12	286	165	2	454	76	0.04	812	888	63.5	820	896
Mokhada	37	2.4	13	279	213	0	492	93	0.04	676	769	183.1	679	772
gen_50	50	2.6	11	584	292	66	942	180	0.06	918	1,098	511.4	957	1,137
gen_100	100	7.7	43	1,431	773	125	2,329	694	0.11	2,533	3,228	—	—	—
gen_150	150	11.3	62	1,935	1,184	235	3,354	519	0.17	3,760	4,278	—	—	—
gen_200	200	787.3	66	2,825	1,441	160	4,427	724	0.22	4,864	5,588	—	—	—

Notes. BRANCH does not do tank or pump optimization; therefore, we also used JalTantra to do a pipe-only optimization to allow a like-to-like comparison with BRANCH. Rs refers to Indian rupees.

tables. Figure 4 shows a sample network created using the GIS tool.

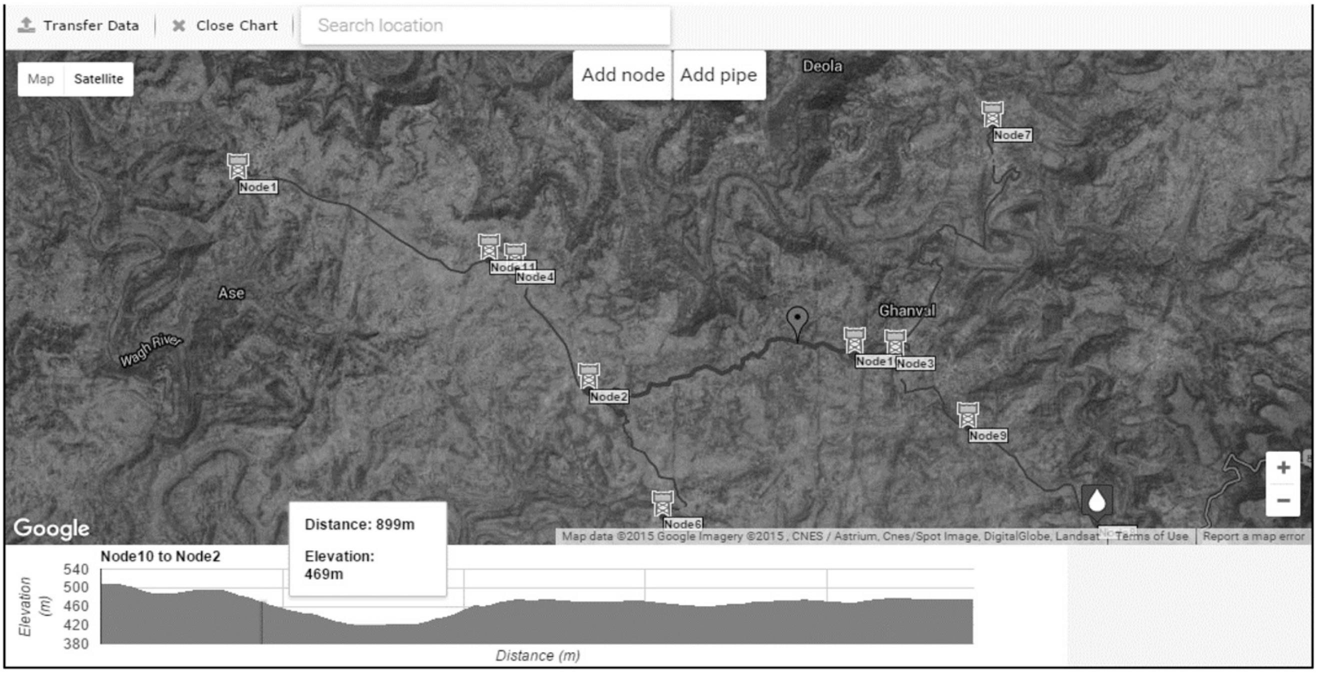
Government Impact

We ran several training sessions with government engineers on using JalTantra. MJP has officially adopted it as one of the software packages to be used in the design of water supply schemes. Maharashtra Environmental Engineering Training and Research Academy (MEETRA), which is responsible for the training of MJP engineers, has integrated JalTantra into its curriculum. MJP has subsequently used JalTantra in the design of several schemes.

Future Work

The introduction of operational cost opens up interesting possibilities in determining the objective function. Currently, we use the standard technique of considering the present value of the entire operational cost and simply adding it to the capital cost. One line

Figure 4. The Diagram Shows the GIS Tool in JalTantra



Distance: 899m
Elevation: 469m

Notes. The tool allows a user to add nodes and links directly on the map. Information such as node elevation and link length can then be exported to the network information tables, which are used for optimization. The tool also allows a user to look at elevation profiles along links as the diagram shows for the link connecting Node 10 to Node 2.

of future work would lie in considering alternative objective functions. In particular, because operational cost is often the cause of schemes becoming obsolete, it might be desirable to consider only the operational cost as the minimization objective and constrain the capital cost so that it does not exceed current government norms.

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First and foremost, the authors thank Milind Sohoni for impressing upon them the importance of the rural water network design problem. The students of the Technology and Development Supervised Learning course did the field survey and analysis of existing and planned water schemes, providing the authors with an invaluable resource for understanding the design process. Several members of the drinking water group from the Centre for Technology Alternatives for Rural Areas, particularly Raj Desai, provided constant guidance and feedback. The authors also thank Ashutosh Mahajan from the Industrial Engineering and Operations Research Department at the Indian Institute of Technology Bombay for various technical insights. Finally, the authors reiterate their thanks to the many engineers from Maharashtra Jeevan Pradhikaran, particularly Santosh Gawankar and Mahesh Patil, whose feedback helped shape and refine JalTantra.

Appendix. Model Details

The pipe diameter selection in the model is represented by the continuous variable l_ij, which represents the length of the jth pipe diameter component of the ith link in the network. This determines the capital cost of the pipes. This length consists of two components, primary l_{ij}^p and secondary l_{ij}^s. The tank allocation is represented by the binary variable s_{ij}, which is true if the tank at the ith node in the network provides water to the jth node in the network. The choice of tank allocation variables fixes the total demand that each tank serves (i.e., the variable d_i). This in turn determines the capital cost of the tanks. Apart from the cost considerations, each node n must also have its minimum pressure constraint satisfied. The head at each node, h_n, is dependent on the head loss hl_i in the links of the network. This head loss depends on the pipe variables l_{ij} and the tank variables s_{ij} we mention above. In addition, the introduction of pumps and valves increases or decreases the head loss, respectively. The details of the parameters, variables, objective function, and constraints of the model follow.

Parameters

NL: Number of links in the network
NP: Number of commercial pipe diameters
D_j: Diameter of jth commercial pipe
C_j: Cost per length of jth commercial pipe diameter
B_j: Base cost of the jth commercial pipe diameter
NN: Number of nodes in the network
NE: Number of rows in the tank cost table
UN_k: Unit cost of the kth row of the tank cost table
UP_k: Upper-limit capacity for the kth row of the tank cost table
LO_j: Lower-limit capacity for the kth row of the tank cost table
CP: Capital cost of pumps per unit (kW)
EP: Energy cost of pumps per unit (kWh)
DF: Discount factor for the energy cost over the lifetime of the scheme
PH: Number of hours of water supply in the primary network
SH: Number of hours of water supply in the secondary network
Y: Scheme lifetime in years
$INFR$: Inflation rate
$INTR$: Interest rate
L_i: Length of the ith link
P_n: Minimum pressure required at node n
E_n: Elevation of the nth node
DE_n: Water demand of the nth node
VH_i: Head reduction by valve in ith link
HL_{ij}^p: Head loss for the primary component of the jth diameter of the ith link
HL_{ij}^s: Head loss for the secondary component of the jth diameter of the ith link
FL_i^p: Flow in ith link if part of primary network
FL_i^s: Flow in ith link if part of secondary network
R_j: Roughness of jth commercial pipe diameter
$T_{\min}$: Minimum tank height allowed
$T_{\max}$: Maximum tank height allowed
ρ: Density of water
g: Acceleration as a result of gravity
η: Efficiency of pump
$PP_{\min}$: Minimum pump power allowed
$PP_{\max}$: Maximum pump power allowed

Continuous Variables

l_{ij}: Length of the jth pipe component of the ith link
l_{ij}^p: Length of the jth pipe component of the ith link if link i is part of the primary network
l_{ij}^s: Length of the jth pipe component of the ith link if link i is part of the secondary network
hl_i: Total head loss across link i
d_n: Total demand served by a tank at node n
z_{nj}: Total demand served by a tank at node n if costed by the jth row of the tank cost table
p_i: Power of a pump installed at link i
pp_i: Power of a pump installed at link i if link i is part of the primary network
sp_i: Power of a pump installed at link i if link i is part of the secondary network
ph_i: Head provided by a pump at link i
f_ph_i: Head provided by a pump installed at link i if link i is part of the secondary network
h_n: Water head at node n
t_n: Height of a tank at node n
h'_{si}: Effective head provided to link i by its starting node s

Binary Variables

e_{nk}: 1 if a tank at nth node is costed by the jth row of the tank cost table
f_i: 1 if link i is part of the primary network and 0 if part of the secondary network
k_{si}: 1 if a source for link i is its starting node s
s_{ij}: 1 if a tank at node i is source for node j
pe_i: 1 if a pump is installed at link i

Objective Function

The objective function is simply the sum of capital cost of the pipes, tanks, pumps, and valves used in the network. In addition, we also consider the operational cost of the pumps. This operational cost is computed as the present value of the total cost over the lifetime of the scheme:

$$O(.) = \sum_{i=1}^{NL}\sum_{j=1}^{NP} C_j(D_j)l_{ij} + \sum_{n=1}^{NN}\sum_{k=1}^{NE} e_{nk} \times (B_k + UN_k \times (d_n - LO_k))$$

$$+ \sum_{i=1}^{NL} CP \times p_i + EP \times DF \times \left(\sum_{i=1}^{NL} PH \times pp_i + \sum_{i=1}^{NL} SH \times sp_i\right),$$

$$\text{where}\quad DF = \sum_{n=1}^{Y}\left(\frac{1+INFR}{1+INTR}\right)^{n-1}.$$

Constraints

The total length of the pipe diameters must equal the total link length:

$$\sum_{j=1}^{NP} l_{ij}^{p} = L_i \times f_i,$$

$$\sum_{j=1}^{NP} l_{ij}^{s} = L_i \times (1 - f_i),$$

$$l_{ij} = l_{ij}^{p} + l_{ij}^{s}.$$

The pressure at each node must exceed the minimum pressure required:

$$P_n \le h_n - (E_n + t_n).$$

Across every link i there is head loss hl_i. This head loss depends on the flow, length, and diameter of the pipe diameter component. We use the Hazen–Williams equation (Williams and Hazen 1933) to calculate the head loss. The head loss across a link also depends on the pump and valve installed across it, if any. The valves are simply input parameters to the model because they are manually fixed. We describe the constraints related to the pump head ph_i below. The flow through the link depends on whether the link is part of the primary or secondary network:

$$hl_i = \sum_{j=1}^{NP}\left(HL_{ij}^{p} l_{ij}^{p} + HL_{ij}^{s} l_{ij}^{s}\right) - ph_i + VH_i,$$

$$HL_{ij}^{p} = \frac{10.68 \times \left(\frac{FL_i^{p}}{R_j}\right)^{1.852}}{D_j^{4.87}},$$

$$HL_{ij}^{s} = \frac{10.68 \times \left(\frac{FL_i^{s}}{R_j}\right)^{1.852}}{D_j^{4.87}},$$

$$FL_i^{s} = FL_i^{p} \times \frac{PH}{\mathrm{SH}}.$$

The head at each node h_e is calculated by the effective head h'_s provided by its parent node and the head loss across the link connecting two nodes. The effective head, in turn, depends on whether the link i has the tank at the starting node s as its source. This is represented by the Boolean variable k_{si}:

$$h_e = h'_{si} - hl_i,$$

$$h'_{si} = (t_s + E_s) \times k_{si} + h_s \times (1 - k_{si}),$$

$$k_{si} = s_{ss} \times (1 - f_i).$$

Next, we look at the constraints relating to the tank allocation. The first tank constraint is to ensure that every tank height is between parameters $T_{\min}$ and $T_{\max}$:

$$T_{\min} \le t_n \le T_{\max}.$$

We then look at the constraints that deal with allocation of demand nodes to tanks.

If a node i does not serve its own demand (i.e., it is part of a secondary network), then all its downstream nodes will also be part of a secondary network:

$$s_{ii} = 0 => s_{jj} = 0\,,\ \forall j \text{ downstream of } i.$$

If a node i does not serve its own demand, then it cannot serve the demand of its downstream nodes:

$$s_{ii} = 0 => s_{ij} = 0\,,\ \forall j \text{ downstream of } i.$$

For every node j, only one upstream node i can serve its demand:

$$\sum_{i \in U_j} s_{ij} = 1.$$

The total demand d_i served by node i is the sum of the demands of the downstream nodes that it serves (i.e., all j such that $s_{ij} = 1$):

$$d_i = \sum_{j \in Do_j} s_{ij} \times DE_j.$$

For a node e, its incoming pipe will have primary flow only if the node serves itself:

$$f_i = s_{ee}.$$

If s_{ij} is true then, by definition, node i serves node j. Therefore, each pipe k in the path from i to j belongs to a secondary network (i.e., $f_k = 0$):

$$s_{ij} = 1 => f_k = 0,\ \forall\, k\ k \text{ is a pipe between } i \text{ and } j.$$

Finally, we have the constraints that relate the demand that a tank serves to its cost variables e_{nj}:

$$LO_j \times e_{nj} \le z_{nj} \le UP_j \times e_{nj},$$

$$\sum_{j=1}^{NE} e_{nj} = 1,$$

$$\sum_{j=1}^{NE} z_{nj} = d_n.$$

Next, we look at constraints related to pumps. The pump power p_i relates to the pump head ph_i in the following way:

$$
\begin{aligned}
p_i &= pp_i + sp_i,\\
pp_i &= \frac{\rho \times g \times FL_i^p \times ph_i}{\eta} \times f_i,\\
sp_i &= \frac{\rho \times g \times FL_i^s \times ph_i}{\eta} \times (1 - f_i).
\end{aligned}
$$

In the above equations, we have a product of two variables, ph_i and f_i. Therefore, the equations are nonlinear. These equations, however, can be linearized because f_i is a binary variable. We introduce a new continuous variable ph_f_i, which represents the product of the two variables. Here, P is the maximum head that a pump can provide:

$$
\begin{aligned}
&f\_ph_i \le \mathrm{P} \times f_i,\\
&f\_ph_i \le ph_i,\\
&f\_ph_i \ge ph_i - \mathrm{P} \times (1 - f_i).
\end{aligned}
$$

Finally, the pump power for each pump must lie between the minimum and maximum allowable pump power. This is implemented using the binary variable pe_i:

$$PP_{\min} \times pe_i \le pp_i \le PP_{\max} \times pe_i.$$

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Verification Letter

S. S. Gawhankar, Executive Engineer, Maharashtra Jeevan Pradhikaran Division, Nagpur, Building “B” Ground Floor, Near C.P. Club Civil Lines, Nagpur 440 001, India, writes:

“The article ‘JalTantra: A System for [the Design and] Optimization of [Rural] Piped Water Networks’ was recently submitted for your consideration by Nikhil Hooda and Om Damani. The purpose of this letter is to verify the use of JalTantra by our department and the benefits that it has provided. Here at Maharashtra Jeevan Pradhikaran (MJP), we are tasked with designing schemes that will provide drinking water to villages in the state of Maharashtra, India. As part of the scheme design we need to size various network components like pipes, tanks and pumps. Existing tools used by our department only optimize the pipe diameters, leaving the other components to be manually determined. This forces us to take a trial by error approach that consumes a lot of time and effort. Besides, the size of the networks are limited to about only 100 nodes.

“In contrast JalTantra allows us to simultaneously determine these components in an optimal manner. Even networks as large as 1000 nodes are solved in a matter of seconds. It is also easy to use since it has an intuitive interface and various options to import/export existing networks. The ability to add nodes and pipes directly from a GIS interface has also proved to be extremely useful.

“The authors had several interactions with us to understand our requirements for the design tool. Based on the feedback provided by us, several features like ESR/pump costing and GIS interface were made.

“We have used ‘JalTantra’ in designing many water supply schemes under Zilla Parishad in Nagpur district, state Maharashtra (India).This software is a very good tool in giving reasonable pipe cost and good service level. It has been a pleasure to work with the authors during these interactions and we express our sincere thanks to them.”

Nikhil Hooda is a PhD candidate in the Department of Computer Science and Engineering at the Indian Institute of Technology Bombay (IITB). He holds a BTech in computer science from IITB. His research mainly focuses on the design and optimization of multivillage piped water schemes.

Om Damani is a professor of computer science at the Indian Institute of Technology Bombay. He is also associated with the Center for Technology Alternatives for the Rural Areas and is coordinator of the Sustainable Development study unit at the Center for Policy Studies, IIT Bombay. His research interests are in the areas of technology for the development of the bottom 80% of the population, with a focus on water and agriculture, and systems thinking and modeling.