Addressing Inequitable Distribution of Water in Urban India: Analytics-Based Solution Approaches – A Case Study

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KEYWORDS
Intermittent supply, Equitable supply, Hydraulic model, Predictive models, Optimization
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ABSTRACT:
India is at great risk for becoming a water-challenged country and faces several hurdles in streamlining and optimally managing this precious natural resource. India's extreme challenges include an ever-increasing demand, intermittent supply, quality that is not managed until the last mile, and distribution that lacks equity. While addressing some of these gaps through better physical infrastructure is imperative, applying IT and analytics is crucial to solve the core issues. We present a case study in which we worked with a city municipality water board on addressing some of their challenges in managing their urban water supply. We analyzed their operations, network, and data to uncover insights into equitable distribution. We propose a solution approach to tackle their challenges, both tactically and from a more strategic viewpoint. We describe a detailed operational view of their system—a water network typical of an Indian city and its challenges in the field. We present a technical approach to tackle them along with a strategic view of what underlying issues should be fixed for better and more efficient operations. Our technical approach is a combination of statistical techniques, predictive analytics, and optimization techniques utilizing a hydraulic model of the water network.
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1. INTRODUCTION

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India has 16% of the world's population, but only 4% of its available fresh water supplies (Planning Commission 2008; Ministry of Water Resources 2012). While on an average, India may be nearing a water-stressed condition, considering the situations of individual river basins, 9 out of the 20 river basins, which together serve a population of 200 million, are already facing a water-scarcity condition (Planning Commission 2008). Hence, while India is considered rich in terms of annual rainfall and total water resources, its uneven geographical distribution and poor infrastructure causes severe regional and temporal shortages. About 64% of the urban population is covered by individual pipe connections and public stand posts in India, as compared to 91% in China, 86% in South Africa, and 80% in Brazil (Ministry of Urban Development 2011). Given the trend of rapid urbanization and the emergence of cities as the centers of growth, the demand on urban water supply is bound to go up much higher.

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To add to these woes, most of India's urban water supply is currently intermittent in nature (McIntosh 2003). As is the case in many parts of South Asia and Africa, Indian urban water supply is not 24x7, and the duration of supply can vary widely from as little as a couple of hours once every other day to several hours every day. Unaccounted for water loss or non-revenue water (NRW) is greater than 50% of the water production, compared to 5% in Singapore, for example. Fig. 1. shows the water balance of a typical city in India (Ministry of Urban Development 2011).

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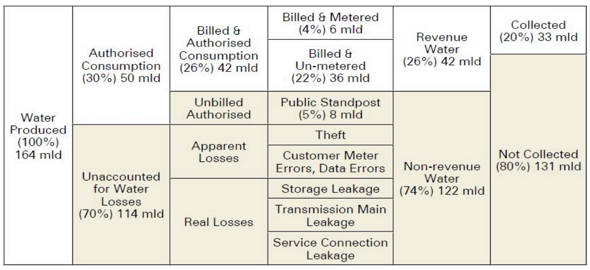

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Figure 1. Water Balance in a typical Indian city; *mld* stands for million litres per day.

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Many cities in India are aiming for a 24x7 water supply goal in urban areas and are working towards satisfying service level benchmarks (SLBs) set out by the governing bodies (Ministry of Urban Development 2010). But even when the supply is sufficient to serve the demands of a city, unless some key issues are addressed, a 24x7 supply will not be sustainable. Fig. 2. shows how an intermittent and unreliable supply exacerbated by water loss and leaks can lead to vicious cycle of demand exceeding supply, despite improvements. The key to a sustainable 24x7 supply starts with an equitable distribution of water in a reliable way and with detecting and controlling water loss.
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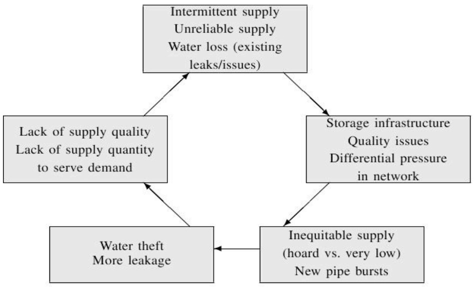

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Figure 2. Vicious cycle of inequitable supply due to demand-supply mismatch.

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2. OVERVIEW

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In the rest of this paper, we describe a systematic approach to address these challenges, starting with the transmission network. This approach has been developed in the context of a pilot with a water utility in India. In a transmission network, the two key challenges we tackle are detecting water theft/loss (by detecting unauthorized valves operations) and ensuring equitable water supply by developing an early warning mechanism for predicting inequitable distribution a few hours in advance so corrective actions can be taken, We present detailed descriptions of the technical solutions to the above challenges along with the benefits and pitfalls they pose. Furthermore, we also address the approach towards root cause analysis and optimal valve schedules, which are important issues in such a setting. In Section 3, we elaborate the problem setting in great detail. In Section 4 we describe a successful IBM engagement in the USA which motivated the approach we took for the problem described in this paper. Section 5 illustrates solution design approaches towards the challenges. Section 6 summarizes our experiences and what we learned from the engagement.
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3. PROBLEM SETTING

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In this section, we describe the scenario in the water utility with which we worked. The water supply network can be partitioned into a) the transmission network, which consists of distribution from the Water Treatment Plant (WTP) to Elevated Service Reservoirs (ESRs) and b) the distribution network, which supplies water from the ESR to the consumers. Typical ESR capacities are of the order of 1 to 2 million litres (ML) and are typically about 10 to 25 meters above the ground, which provides the necessary pressure head for water from the ESR to reach all consumers supplied by that ESR.
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Consumers typically use underground sumps at their end to store the water, which is then pumped to an overhead tank that makes water available 24x7. However, a large section of underprivileged consumers exist. These people do not have permanent storage infrastructures such as sumps, meaning that water needs to be provided to them in early mornings and evenings, when the requirement is high and when they are at home to collect and store the water in containers for the rest of the day. So normally, the water is supplied to consumers in the early mornings (6 am to 9 am) and in the evenings (6 pm to 9 pm).
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3.1. Terms and Definitions

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The following definitions apply to the terms we use throughout this paper.

1. Equitable supply is the supply equal to expected demand based on government estimation, which is 135 *lpcd* for cities in India (Ministry of Urban Development 2011). In the absence of

enough supply to meet demand, equitability is to make sure the share of supply is even.

2. ESR's equitable supply is the ability of each ESR to supply the amount of water required for the equitable supply.
3. Inequitable distribution refers to the situation in which the operating conditions depart significantly from equitable supply.
4. Inlet and outlet valves are valves that are responsible for controlling flow in and out of the ESR, respectively.
5. A bypass valve is a valve that is responsible for taking flow from the input pipe of ESR to its output pipe without passing through it (without filling it). It is meant for use during ESR maintenance and exception situations. To account for a hydraulics mismatch with demand, this is regularly used in some ESRs.
6. Direct connection is a connection drawing water directly from the main line and supplying water to a distribution zone and controlled via a valve placed where it connects to the main line.
7. A throttling valve is a valve that is responsible for the flow control through the transmission line by complete or partial pipe closure mechanism.
8. Valves' schedule is a daily time schedule for inlet, outlet, bypass and throttling valve operations to be followed.
9. An optimal valves' schedule is a valves' schedule that guarantees an equitable supply when such supply is feasible, based on the present design of the network and available water in the network.
10. Unauthorized valve status change is a change in the status of a valve that departs significantly from the valve schedule (depending on the consequential impact, this could even be as small as 10 minute deviations from schedule)
11. A reference model is the one that uses the optimal valves' schedule.

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3.2. Operations

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The starting point in a water network is the source of water. In our pilot, as is typical in India, this is a Water Treatment Plant (WTP) that contains the treated water ready to be distributed to the city. A number of transmission lines emanate from the main WTP sumps (tanks), which lead to a set of connected reservoirs around the city. The focus of our study was on one of these transmission lines and the ESRs on this line. Some of the transmission lines are gravity based in which water flows and fills the ESRs by force of gravity due to elevation differences; and some are pumped lines in which water is pumped to flow at a certain pressure. The scope of our pilot was limited to one of the transmission lines that was mostly a gravity line with a few pressurized zones.

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Junior engineers supervise the operations of ESRs. Each engineer is responsible for about two to four ESR sites. An ESR site may have one, two, or in some cases, three ESRs. An operator at each site is responsible for manually operating valves with respect to the valve's schedule and monitoring water levels in the ESRs.

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3.3. ESR Design and Instrumentation

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Each ESR has one inlet and one or two outlets. In cases of two outlets, they feed different distribution areas. Many ESRs also have a bypass valve, which connects the inlet and outlet pipes "bypassing" the ESR. The inlet pipe opens out at the top of the ESR and the outlet pipe starts at the bottom of the ESR.

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The inlet and outlet pipes are initially horizontal and at ground level as they enter or exit the compound and they turn vertical closer to the ESR. The bypass pipe with the bypass valve connects the inlet and outlet pipes at ground level, before the inlet valve in the incoming pipe and after the outlet valve in the outgoing pipe. The inlet valve, when open, lets water from the transmission line into the ESRs. The outlet valve, when open, lets water from the ESR into the distribution zone. The bypass valve, when open, short circuits the water so it flows directly into the distribution zone from transmission, bypassing the ESR.

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Each ESR has a level sensor, a flow sensor, and a pressure logger. Typically, the flow sensor is placed at the vertical section of the inlet pipe leading into the ESR and measures the water flowing into the ESR. The pressure loggers are placed next to flow sensors.

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3.4. Line Operations

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A mechanical level indicator exists for each ESR. The operator/watchman at each location will close the inlet valve when the ESR is full. A water release schedule exists for each location, according to which water is released into the distribution network one or two times a day.

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To illustrate, Site A has three ESRs. The bypass valves for these ESRs are opened from 5:30 am - 6:30 am. This allows water to flow directly from the main line to the distribution network for that ESR. From 6:30 am - 8 am, the bypass valve is closed, and the outlet of the ESR is opened. The outlet is kept open until the tank empties, meaning all water was supplied. Generally, the outlet and bypass valves are opened to the same extent for a given location, but the extent to which they are opened (measured by the number of turns or angle of flap) varies for different locations. Two types of valves exist—sluice and butterfly. A sluice valve is top down and a butterfly is a vertical flap that moves to allow or constrain water flow. Bypass valves are typically opened no more than 40-50%. Since bypass valves are at ground level, and ESR inlets are at the top of the ESR, the effect of opening a bypass valve is quite large on the network.

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Generally, the schedule is not changed except during critical situations. We did notice that the schedule is disrupted heavily in summer months. During critical water shortage situations, when there is not enough flow/pressure in the main line due to lower water levels in WTP sumps, some ESRs will be affected to a greater extent. The engineers in charge of their ESRs jointly discuss with the executive engineer for the line to update the schedule of valve openings in a way that they judge, based on their experience, will make the water supply as equitable as possible. Hence, currently the equitable supply is managed by leaning on the experience of engineers and ad-hoc discussions that happen when issues arise—reactive.

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3.5. Challenges

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In India in general, and also in this municipality, water is subsidized and the main priority is to ensure everyone gets a sufficient amount for use. Despite having a sufficient amount of water in the network—a supply in excess of demand—many consumers are still not getting the amount of water they require for their basic needs. Thus, the main challenge for this city is to provide an equitable water supply. Such a supply should be strongly based on proper hydraulic design of the network, optimal valves' schedule, the ability of engineers to follow this schedule, and having a system that can track/detect the status and any deviations from norm. At present, the valves' schedule is designed manually based on engineer's knowledge, experience and intuition. It is prone to human errors, lack of co-ordination, and desire for local optima, and hence is far from overall optimal result.

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When the schedule is not optimally planned out, engineers attempt to fix the problems and issues as they occur, which leads to fixing them temporarily at one place and leading to undesirable consequences for others. This in turn leads to problem of water diversion by unauthorized bypass valves' status changes with respect to the valves' schedule. Due to the lack of a stable schedule, lack of monitored valves and a network in flux, theft events are hardly detected. Detecting water diversion is a challenging problem by itself. This problem is important for two main reasons. First, it reduces the amount of the water in the network. Second, it impacts the main transmission line and the optimal valves' schedule. Hence, the transmission line is impacted and some ESRs fall behind on their schedule. Water network management supported by advanced data-driven decision support tools can help detect and solve this problem.

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The tactical challenges we were asked to address were:

- Unauthorized bypass valves openings leading to unaccounted for water loss and hence supply issues for some ESRs
- Predictive warning and alerts to sense trouble in ESR filling that affects supply to the localities
- Impact analysis of issues and what-ifs

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And the actual challenges we faced in the process were as follows:

- Lack of optimal valves' schedule
- Lack of coordination in the valves' schedules
- Different schedules (spring vs. summer) and an extremely volatile network (schedules not

followed and course correction attempted)

- Lack of a calibrated hydraulic model that completely represents the network

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The work and study of the network/data led us to believe that an optimal valves' schedule (or a set of schedules) towards equitable supply is a key requirement for avoidance of issues and to reduce instability in the network. When issues do happen, including water shortage or theft, predicting the impact and analyzing what-ifs is an important requirement, which needs a completely calibrated hydraulic model of the network. This can be viewed as constructing optimal dynamic valves' schedule to react to unforeseen issues.

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4. Pressure Management in Water Networks – A Successful Application of Data-Driven Decision Support Tools

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Our work in India was motivated by a successful IBM engagement in the USA. The problem that IBM tackled in the USA was pressure management of a complex water network with the goals of reducing leaks and bursts in the network, improving maintenance of tanks levels, and improving tanks turnover.

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Since minimal pressure levels in certain locations in a network are required, a tradeoff to meet overall network management requirements exists among pressure reduction, maintenance, and increases. Moreover, real water networks can be huge in size, and their hydraulics can only be mathematically described by non-linear equations. Thus, a need exists for innovative algorithms that can provide a solution of the desired quality within short runtimes. Therefore, a sophisticated pressure management approach is required to fulfill network requirements and to reduce leaks and bursts in the network. IBM developed a system that relies on an optimization platform and on a novel method for solving the optimization problem (IBM Press Release 2012). This optimization platform is scalable, flexible, and component-rich, enabling the system to support different types and sizes of water networks with varied client requirements. The optimization platform was extended during the work in India and will be described later in this paper. An algorithmic approach is a linearization of non-linear equations, and mixed integer linear programming, combined with a hydraulic simulator in the loop. A first client, for which this system was applied, was the Valley of the Moon Water District (VOMWD). VOMWD needed a solution for pressure management to help reduce costs and conserve water. VOMWD is a water distributor in Sonoma County in California, USA, responsible for providing water to approximately 23,000 customers over a complex network comprised of pumps, tanks, valves, and 92 miles of pipes. VOMWD had an NRW of approximately 10% and wanted to reduce this to lower costs and to help with water conservation. Prior to the application of IBM's solution, the changes were carried out in a reactive fashion, changing one valve setting at a time. This resulted in suboptimal pressure management, in which the quality of the solution was primarily based on the experience and intuition of the engineer performing the valves' setting changes.

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The first version of the solution, which included part of the optimization platform described in the next section, was developed to support the needs of VOMWD and has been in operation since April 2012 (a preliminary version was used since November 2011). With the new solution, the customer has the ability to operate the system independently and has been benefiting from the following results:

- A drop of ~16% in leaks and bursts as compared to the previous year and a ~19% drop as compared to the previous three-year average, as indicated by initial measurements, leading to a direct reduction in annual operating expenditure
- Move from reactive pressure management to proactive pressure management
- Ability to change multiple valve settings simultaneously
- Better maintenance of tank levels
- Improved tank turnover

The customer is extremely satisfied with the solution. To quote Paul Gradolph, VOMWD Head of Operations: "I'm very pleased with the recommendations of the system. I've been operating this system for 30 years, and I never thought of making the changes the system recommended. At the beginning of this project, I was skeptical of the usefulness of these techniques in the field. However, now that I have seen the results, I am a strong supporter of this solution."

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5. SOLUTION DESIGN

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In this section, we describe our approaches to solving the problem in the client water network.
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5.1. Optimization Platform

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This subsection describes the optimization platform on which our optimization model and algorithms are implemented.
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5.1.1. Platform Description

The optimization platform is developed as a mathematical programming model. The platform shown in Fig. 3. consists of three libraries: a hydraulic models library (e.g., Hazen-Williams, Darcy-Weisbach); an objectives library (e.g., pressure management, minimization of total pressure in the network, leak detection); and a components library (e.g., pipes, nodes, different types of valves, pumps, tanks, etc.). All components are incorporated with optimization capabilities. The setting, quantity, and locations of the components are defined based on client requirements. The client can also choose to retain its own manual settings by cancelling optimization options for components of its choice. In this case, components chosen by the client will be only modelled hydraulically, and the others will be optimized according to the objective function of the client's choice. Different objective functions are implemented as components, and the client can chose one of them based on requirements.
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The network properties and connectivity are gathered from the client's hydraulic model and a mathematical optimization model is generated automatically. To reach a reasonable correlation between optimization results and the results in the field, this model has to be calibrated. Whereas a calibrated hydraulic model is a necessity, other inputs like Supervisory Control And Data Acquisition (SCADA) data may be required for tasks such as valves status detection. In our pilot, SCADA data is transmitted from the field to agency office's computer and then can be downloaded from there.
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5.1.2. Scheduling Design and Valves Status Detection

The main challenge of the water utility in our pilot is the generation of an optimal valves' schedule. This problem consists of two main aspects. One is the time required for the water supply from the ESRs to the consumers and another is the time required for filling the ESRs. The amount of water that each ESR has to supply daily is determined by the ESR's equitable supply requirements and by the volume of each ESR. This determines the period of time that the outlet valve of each ESR remains open daily. What needs to be determined is the exact hour that outlet valves of each ESR have to be opened (the sequence of outlet valve opening across ESRs). The second part of the puzzle is to determine when each ESR should be filled with water. To determine these periods of time, the following factors must be taken in consideration:

- Outlet valves' schedule
- Inlet, bypass, and throttling valves' locations
- ESR volumes
- Network line topology and elevations

The ESR filling time is determined by the schedule of inlet, bypass, and throttling valves in the network.
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When the design of optimal valves' schedule is the major task, the ability to analytically determine the status of valves (especially bypass valves) is crucial in the sense of identifying one of the major sources of interference to the schedule. For example, if a bypass valve is opened in the time slots when it is supposed to be closed, it impacts the overall water amount in the transmission line and the valves' optimal schedule. The approach to detect unauthorized valves' status changes is as follows:

- Generate the reference model and calculate inlet flow and level values for each ESR based on the optimal valves' schedule
- Obtain flow and level meters data for each ESR when there is a suspicion of unauthorized valves status changes (using SCADA)
- Estimate valve status changes that best explain the differences between the reference model and field measurements

The last item determines the unauthorized valves' status changes mapping.
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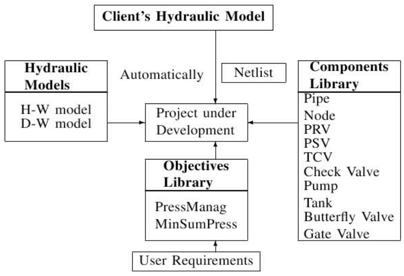

Figure 3. An optimization platform.

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5.2. Advanced Analytics

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5.2.1. Early Warning Application

To improve an equitable supply under abnormal conditions, predicting the status of the network in advance is necessary, so that more time is available to take remedial actions. We explain how analytical techniques can be used to predict the status of the network two to three hours in advance and to propose corrective actions. We highlight the trade-offs that exist, as the reliability of the early warning deteriorates as we attempt to predict further in advance.

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5.2.2. Actionability of Early Warning

As a first step, we need to understand what actions are possible and the need for cooperation among operators. Usually, ESRs start filling around 10 pm, and generally by 5 am, the last of the ESRs is filled. Water supply to consumers begins shortly after, at 5:30 am. At any time between 10 pm and 5 am, should an alert be raised, we apply the principle that the remainder of the flow from the WTP will be distributed in such a way that inequitability is minimized. We propose actions of the type that involve the closing of inlet valves of the ESRs once they reach a specified level—the equitable threshold. In that way, rather than continuing to fill the ESR, the water becomes available to ESRs that have not yet reached their equitable threshold. Therefore, alerts shall be designed to provide an estimate of severity along with the equitable thresholds for various ESRs. Since water from ESRs that are already filled cannot be diverted to affected ESRs to equalize the supply, predicting as far in advance as feasible, when fewer ESRs have been already filled, is important.

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5.2.3. Modeling Approach

The historical SCADA data is used to develop a mathematical model that predicts inequitable distribution a few hours in advance. The inputs to the model would include various SCADA variables. Some of these variables may be direct causative factors such as WTP sump levels. Other causative factors, such as misoperation of throttling valves and unauthorized opening of bypass valves, are not directly observable, but give rise to "symptoms", such as delays in filling some ESRs. Such causative and symptom variables—predictors, in mathematical terminology—are used in the model as inputs, to predict the risk and severity of inequitable distribution. For example, at 2 am, the history of these predictor variables between 10 pm and 2 am could be used to make a forecast of the severity of inequitability at 5 am. Apply the model initially at 2 am and then again at 3 am would be appropriate. At the earlier time, the forecast reliability is lower, but the ability to take effective action is greater, so a partial corrective action may be appropriate. At the latter time, the forecast accuracy is greater, and actions to fully correct the imbalance can be recommended. Fig. 4. depicts the processing stages as a block diagram. The output of the predictive model is a set of alerts, along with a degree of confidence that can be displayed in a dashboard.

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We propose the following approach to build the predictive model. Fig. 5. depicts the procedure as a block diagram.

- Define the target variable: Characterize and evaluate the inequality in distribution, by the variance in achieved equitable levels across ESRs, for example. The target variable value needs to be computed for each filling cycle shortly before the water supply time.
- Identify predictors: Use correlation analysis to identify a subset of variables (levels, flows, and pressures at various points) that show correlation to the future value of the target variable. Review these variables with domain experts or apply domain-level knowledge to ensure that those variables have a plausible connection to the target variable and identify any other variables that domain experts consider important.
- Use a machine-learning toolkit or predictive-modeling software to infer the relationship between the target and predictor variables which fit the historical observations and can be

assumed to be close to the actual/true underlying relationship.
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As an illustration of how to go about identifying predictor variables, refer to Fig. 6. This figure illustrates a correlation between the on-time filling of ESR B and the time of filling of another ESR, P, where ESR P normally fills by 2:30 am. The distribution shown in the figure illustrates that on days in which ESR P fills within 90 minutes of midnight (i.e., by 1:30 am), ESR B is likely to have filled on time. By identifying such relationships, we determine which variables to use as predictor variables. In this case, the filling time of ESR P should be picked as a predictor variable.
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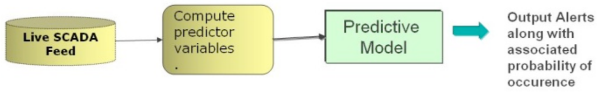

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Figure 4. Processing stages involved in the generation of alerts.

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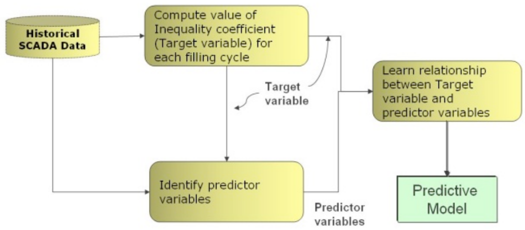

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Figure 5. Procedure for building the predictive model.

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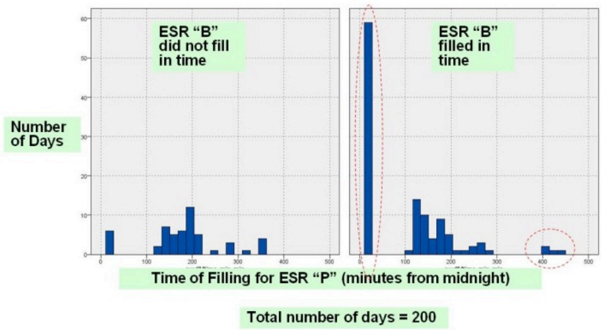

Figure 6. Time of filling of ESR P can be used to predict risk to on-time filling of ESR B.
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5.3. Architecture
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The architecture of the entire equitable water solution is presented in Fig. 7. The underlying architectural framework is a collaboration platform for smarter water solutions (Hidaka et al. 2011). This is an overall framework that comprises components to capture information, anticipate problems through analytics, coordinate a response through automated workflows, and enable cross-team collaboration. Data points that come into the solution as inputs can come from different sources, such as the SCADA system in the case of water. If coming from disparate sources, by using data adapters and semantic models, normalizing this data into a common format that can be retrieved, filtered, and correlated for generating insights becomes possible. Data correlation helps identify key events and incidents through pre-defined business rules or other advanced analytics. These events and incidents can then trigger workflows that can be automatically invoked to provide collaborative responses to the situation.
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Mapping our project demonstration capabilities into the architecture leads to the following components of equitable water supply: data input, early warning models, optimization models, event management and alerting. Currently the SCADA data are provided in a batch mode offline in an excel sheet. If real-time SCADA access is provided, we could use the OPC adapters to pull in the data from the sensors – OPC is Object linking and embedding sensor for Process Control for communication of real-time plant data. For now, we simulate the data coming in from sensors by reading from a *.csv* file and processing them through the pipeline. The key component in the pipeline is the advanced analytics (predictive

analytics and simulation/optimization) component. In the case of early warning, the data are analyzed through predictive models that report an anomalous condition—that the optimal valves' schedule could be missed for the water supply and intervention is probably needed to regenerate a new schedule. The solution component can integrate the anomaly triggers from multiple models or multiple runs of the same model. An anomaly predicted for more than three consecutive time periods could be used to raise an event. The UI presents the event in the context of geo-spatial maps or a location map of the network with other details. Upon early warning events, alerts can be generated and workflows executed to collaboratively address the response to the situation. The simplest implementation would be raising notification by sending SMS alerts to engineers and supervisors when two or more ESRs are expected to miss their scheduled filling time. Customized business rules can be configured to implement these event correlations. The predictive model is built offline by providing a set of training and test data from archives.
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The bypass detection flow is very similar to the above described, in which the optimization model is created by doing an offline import of hydraulic models and SCADA data from the client. Then at any point of time desired, the optimization engine can be run to provide a prediction on the status of the bypass valves. Moreover, based on early warnings and unauthorized bypass status events an optimal valves' schedule can be regenerated at any point of time and used until the problem is fixed.
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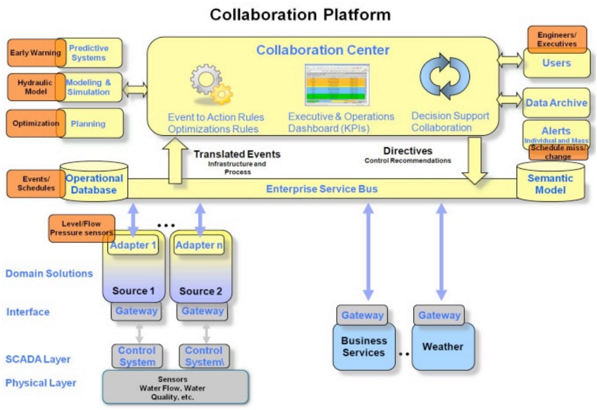

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Figure 7. An equitable water solution in the context of smarter water collaboration architecture.
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6. EXPERIENCES AND LEARNINGS

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In this section, we recap some of our learnings for designing and building solutions for intermittent water supply systems. Our interactions with the water utility provided several insights into the functioning of the water utility and its challenges and opportunities. We present our recommendations to both the water utilities and vendors developing IT-based solutions for these utilities. Since our study was limited to the transmission portion of the water network, our recommendations relate primarily to that part of the network.
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6.1. Instrument Smartly

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Instrumenting a water network and hooking it up to a SCADA system is an expensive affair, and careful consideration needs to be given to selection and placement of instrumentation, keeping in mind the use cases of interest, i.e., how the data collected would drive insights and action. By doing so, the water utility can maximize the benefits for the available budget.
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For example, for selecting the locations to install flow meters, priority should be given to direct connections over the inlets of ESRs, because inflows into the ESR can be estimated from the change in the level of water in the ESR, as measured by the level sensor.
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A limited amount of instrumentation at thoughtfully selected locations can be quite valuable. As additional instrumentation is added, the incremental value progressively reduces. However, when the level of instrumentation reaches a point at which calibrating a hydraulic model of the network is possible, the total value of instrumentation takes a large jump, since prediction and planning become

possible using the approaches described in this paper.
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6.2. Consider Hydraulic Valves Installation
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To follow the optimal schedule, numerous valves ought to be operated manually a few times daily and their settings maintained to keep the pressure and flow as intended. Since the valves are operated manually, the schedule in the field is never the same as defined. To overcome these difficulties, installation of hydraulic valves at the transmission line (at ESRs inputs, over the line, etc...) could be considered. Of important note, this is not always possible technically. Moreover, the pressure at the valves input should be high enough to make them useful. One of the possible candidates that can be considered is a pressure sustaining valve (PSV). These valves are controlled hydraulically based on their pressure settings and operate as follows:

- Pressure on its downstream side is below its setting → partially opened to keep the pressure on its upstream side above its setting (if impossible, fully closed)
- Pressure on its downstream side is above its setting → fully opened

When these valves are installed, the scheduling problem is now different from the one described in the previous section. Instead of defining valves status at each time slot, the setting of PSVs is calculated and that does not change during the day. The idea behind the setting choice is to "guide" the flow through the line and ESRs, by controlling the upstream hydraulic valve's pressure, based on ESRs equitable supply requirements. After the valves' setting is chosen, the valve control is automatic.
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6.3. Governance Models
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As explained in previous sections, in an effort to compensate for reduced water availability locally, numerous ad-hoc adjustments by operators exacerbate the imbalances in the system. Hence, developing a transparent decision support system on top of an existing SCADA system, which empowers a central authority, namely an executive engineer, to drive decision making that considers the impact on the entire network, rather than leaving decisions to junior engineers to based on local optimality, is imperative. Additionally, if everyone has information on network conditions available at their fingertips, via their mobile phones, multiple operators can share a common reference point for negotiating and arriving at better and more equitable solutions.
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ACKNOWLEDGEMENT
We are grateful to a large number of people at the Water Utility and at IBM for their support in our work that resulted in this paper. We would in particular call out A. Tawde, S. Kuckian, and M. Poreddy from the IBM Sales organization who have made it possible for us in Research to work with the client. Among our technical colleagues, Dr. Eitan Israeli has provided valuable guidance and oversight while, Michael Sambur, Gayatri Pal and Sanket Jain have supported the technical work in various ways.
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