A Strategy to Reduce Technical Water Losses for Intermittent Water Supply Systems

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Preface

The present thesis gives an overview on technical problems with the water supply systems of the Al Koura district in northern Jordan. The initial goal was to work out improvements for the complete area - besides the Geographic Information System (GIS) that was created, however, this approach was abandoned due to time constraints.

Instead the paper focuses now on a fundamental problem: The representation of intermittent supply in simulation models of water distribution networks. Intermittent supply is heavily disadvantageous for a number of reasons. Yet it prevails the dominant supply scheme in most of the developing countries throughout the world.

The fact that the majority of the world's population is supplied in this way is already stunning. What is even more astonishing is the fact that there are virtually no applicable simulation models for the intermittent supply of water. Reliable simulation models are a factor for the optimization of water distribution - they enable modern water undertakings to serve their customers around the clock, seven days a week.

This thesis describes the development of a practical simulation model for the intermittent supply of water. Standard software is used to implement the model: ESRI's ArcView GIS and the free hydraulic analysis software EPANET. The model has been applied to the water supply network of the village Judayta and successfully calibrated with a logging campaign.

Declaration

German

Wir erklären hiermit, dass wir die entsprechend gekennzeichneten Anteile der Arbeit selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt haben.

English

Herewith we declare that we have independently written the thesis. We have not used other sources and aids than explicitly mentioned.

Arne Battermann   Steffen Macke

Contents

Terminology

AGWA Amman Governorate Water Administration

API Application Programming Interface

ASCII American Standard Code for Information Interchange

aSL above Sea Level

CASE Computer Aided Software Engineering

CDC Centers for Disease Control and Prevention

COBOSS Billing Software Package programmed in the Cobol programming language

CSS Comprehensive Subscribers Survey

CV Check Valve

DEM Digital Elevation Model

DLS Department of Lands & Survey

DN Diameter Nominal

ESRI Environmental Systems Research Institute

GI Galvanized Iron

GIS Geographic Information System

GNOME GNU Object Model Environment

GNU GNU is Not Unix

GTZ Gesellschaft für Technische Zusammenarbeit

GUI Graphical User Interface

HA Hydraulic Analysis

HDPE High Density Polyethylene Pipes

IRR Internal Rate of Return

IRWA Irbid Water Administration

JICA Japanese International Cooperation Agency

JOD Jordanian Dinar

KfW Kreditanstalt für Wiederaufbau

LEMA Lyonnaise des Eaux, Montgomery Watson, Arabtech Jardaneh, Management Contractor for Greater Amman Water Supply and Wastewater Services

LGPL GNU Lesser General Public License

LS Lump Sum

MWI Ministry of Water and Irrigation

OMG Object Management Group

OMS Operations Management Support Project

PMU Planning and Management Unit

PRV Pressure Reducing Valve

PE Polyethylene

PK Primary Key

RJGC Royal Jordanian Geographic Centre

PSP Private Sector Participation

SCADA Supervising Control And Data Acquisition

SOV Structured Query Language

SQL Shut Off Valve

SOGREAH French Consultant

UFW Unaccounted-For Water

UML Unified Modeling Language

USAID US Agency for International Development

WAJ Water Authority of Jordan

WLRP Water Loss Reduction Program

XML eXtensible Markup Language

1 Introduction

by STEFFEN MACKE

1.1 Jordan

The Hashemite Kingdom of Jordan was populated by 4.9 million people in 1999 [3]. The capital Amman is the biggest city in the country with 1.9 million inhabitants (1999). Jordan covers an area of 89342 square kilometers.[10]

Figure 1 shows the Middle East region with Jordan and its neighbors.

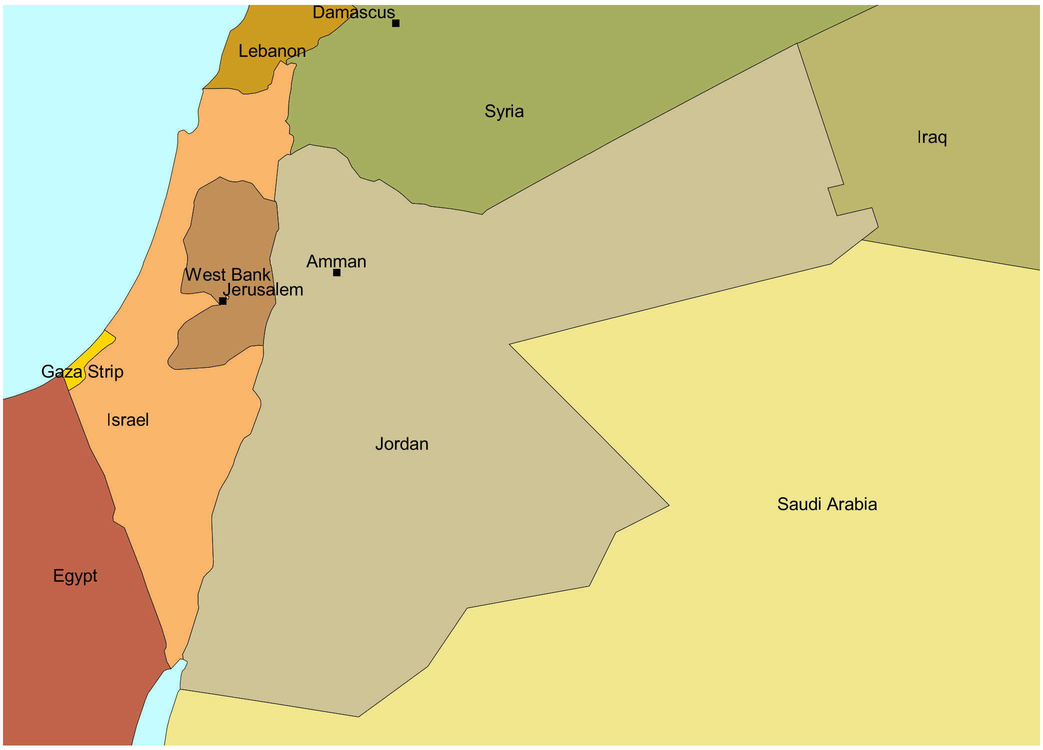


Figure 1: Middle East

To illustrate Jordan's water supply problems, it is interesting to compare the energy consumption figures of Jordan and Austria:

Jordan consumed 971.8 GW/h for water pumping in 1999, while the total current consumption was 5808 GW/h [3]. Nearly 17 % of the country's electricity resource was used for water supply.

In Austria 1990, only 0.3% of the current consumption was used by water undertakings [6]. Though the figures cannot be compared directly as water is not a scarce resource in Austria, this illustrates Jordan's situation.

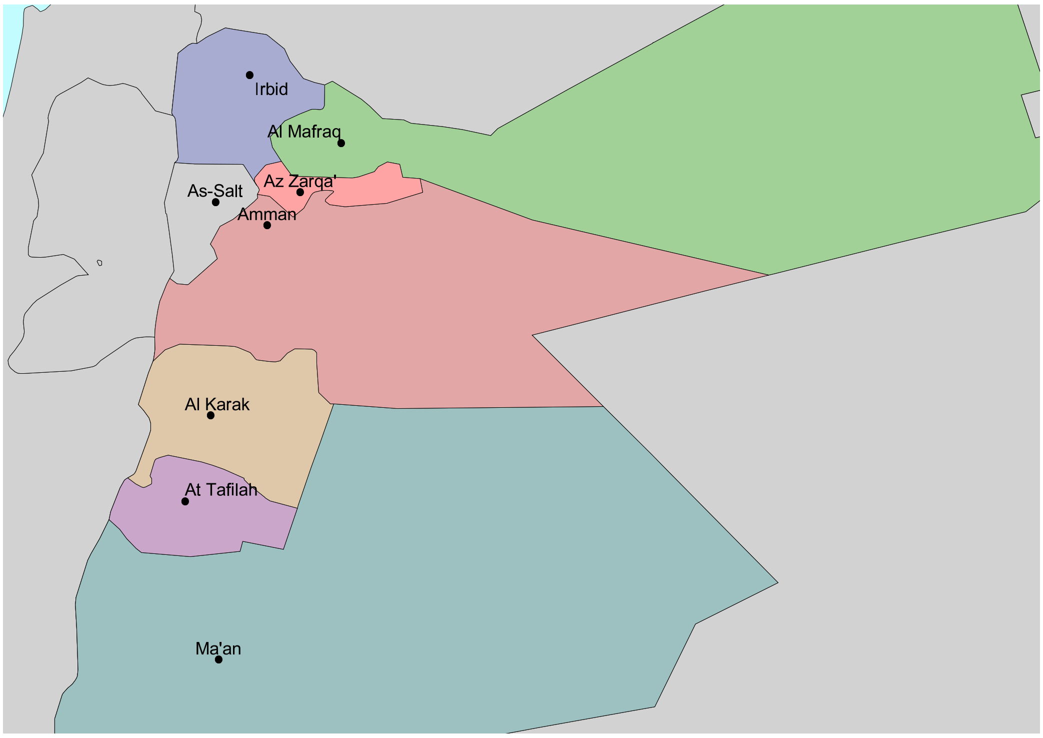


Figure 2: Jordanian Governorates

Figure 2 displays the Jordanian Governorates with their capitals.

1.1.1 Local Currency

Jordanian Dinar (JOD)

1.00 JOD = 3.048 DEM (February 2001)

1.2 Irbid Governorate

Irbid governorate with its capital Irbid forms the northern part of Jordan. It stretches from the Jordan valley in the east to the Syrian border in the west. The size of Irbid governorate is 1621 square kilometers.

Figure 3: Irbid Governorate

Figure 3 shows the location of Irbid city and the location of the district Al Koura within Irbid governorate.

The population of Irbid governorate consisted of 874 200 people in 1999 [3], Irbid is the second biggest city in Jordan. Table 1 contains more detailed population figures including growth rates.

As the available quantities of water are the limiting factor, the population growth will decrease the available amount of water per capita.

Table 2 shows the average number of persons connected per subscription.

Table 3 describes the development of subscription numbers in Irbid Governorate.

Development of Population Rates	Source	Irbid
Population Year 1999	acc. to Dept. of Statistics end 1999	874,160
Population Year 2000	projected in HA (medium growth rate)	913,793
Population Growth 1994-1999	acc. to Dept. of Statistics	3.20%
Projected Growth Rate (SOGREAH HA)	till 2005 low/medium/high	2.41/2.97/3.34
	till 2015 low/medium/high	2.32/2.78/3.06
	till 2025 low/medium/high	2.32/2.78/3.06

Table 1: Population Figures

Persons	Source	Irbid
per family	acc. to HA (1994 Census data)	6.41
per connection	acc. to HA (1994 Census data)	9.18
per connection	acc. to actual fig. and 100% connection rate	8.36-8.74

Table 2: Family Statistics

Subscriber	Source	Irbid
Current #	Status end 1999	104,555
New in 1999		3,716 (3.6%)
average growth since 1995/1996		3.06%

Table 3: Subscriber Statistics

Tables 1 - 3 have been taken from [11].

1.3 Al Koura

The Al Koura district is located in the south of Irbid Governorate.

It consists of highlands east of the Jordan river's great rift valley.

Figure 4: Al Koura Villages

Figure 4 displays the villages that form the district Al Koura.

The Al Koura district is home to approximately 50 000 people.

1.4 KfW Water Loss Reduction Program

1.4.1 Background

The German Kreditanstalt für Wiederaufbau (KfW) is financing a water loss reduction program for the governorates Irbid and Jerash. The project is currently in the tender phase.

On July 2000 specialists have been commissioned to create a water loss reduction program, a study about its feasibility and to work out the outline for a management contract into the direction of private sector participation (PSP) [11]. Administrative changes are the key to improve the losses.

The Al Koura district has been chosen as a pilot area for the private sector participation. The meter reading and revenue collection process will be privatized within the next months.

1.4.2 Benefits

It is the goal of the water loss reduction program (WLRP) to reduce the unaccounted-for water figure from 55% to 15%. As a consequence a water quantity of 33.5 million cubic metres can be saved every year. Selling this quantity would yield additional revenue of 3.2 million per year.

According to [11] an increase of water production of app. 13% between 1999 and 2004 would be necessary to achieve the same service level of 70 litres per capita and day of the implemented WLRP. The implemented program would require this water production from the year 2009 onwards for covering the increased consumption, caused by population growth. Energy savings due to pressure reduction are estimated with 1.0 million JOD per year.

1.4.3 Financial Improvements

It is estimated that a surplus of 1.3 million Jordanian Dinar per year can be reached with the reduction of technical and administrative losses in Jerash and Irbid [11]. With a present annual operating deficit of app. 2.5 million JOD an enormous improvement of the current situation would be realized.

2 Unaccounted-For Water

by ARNE BATTERMANN

Unaccounted-for water is defined as the "Water loss calculated as the difference between the quantity of water fed into a distribution system (drinking water production) and the quantity of water put to legitimate use, which has been metered or can be estimated. Quantities of water put to legitimate yet unmetered public use, e.g. for fire fighting, or distribution system rinsing, have to be estimated.

Quantities of water that are wasted by the consumers or lost through leaking fittings, as well as losses occurring between raw water extraction and input into the distribution system are not considered as unaccounted-for water. Unaccounted-for water includes both physical losses and nonphysical losses"[15] .

The term 'non-revenue water' is frequently used. It describes the quantity of water which is lost or withdrawn from the water network without being paid for.

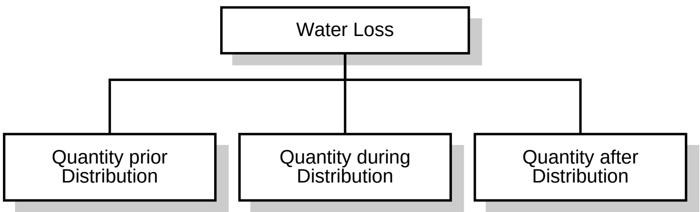


Figure 5: Water Loss

An international standardized definition of the term "water loss" does not exist yet. In [15] it is suggested that "water loss and waste can be defined as the total quantity of water that is lost or put to illegitimate use during the period of its human utilization from the point of its extraction from a natural body of water [...] to the point of its intended consumption." In Germany water loss is fixed in the national standard DIN 4046: "Water loss is that percentage of input that cannot be accounted for by volume and is partially lost. It comprises both physical and nonphysical losses."

In Germany physical water loss are defined as "that amount of water which is lost without being used due to failures and deficiencies in the distribution facili-

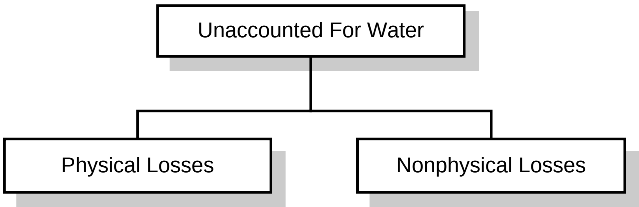


Figure 6: Unaccounted-For Water

ties." [1]. Nonphysical water loss is defined as "that amount of water which is not registered, due to incorrect reading of the measuring instruments installed (measurement errors) and/or absent or inaccurate estimates in the absence of measuring instruments (estimation errors)" [1].

In particular, in developing countries the rate of UFW is extremely high. The analysis of UFW rates shows the efficiency of the economic system and technical part of the water distribution network and its management.

In the following physical losses are called technical- and nonphysical losses are administrative losses. The thesis concentrates mainly on technical losses, even if the administrative part promises a more efficient loss reduction. In section 4 the current situation of the Al Koura water distribution network is described in detail.

3 Data Sources

by STEFFEN MACKE

This section gives a short introduction on the data sources available for the Al Koura area. For the data that has actually been used in the thesis, more detailed description of the nature of the data follows later on.

3.1 Hydraulic Analysis - SOGREAH Study

Between 1995 and 1998 SOGREAH performed a hydraulic analysis study. The study was used as a basis for statistics in addition to sources such as information by the Department of Statistics and the annual reports of the governorates.

As the study is quite comprehensive, the report "Incorporating Water Loss Reduction Program" [11], which summarizes the results of the study has been used most of the time.

The hydraulic simulation models accompanying the hydraulic analysis study do not take intermittent supply into account - they are based on complete network restructuring that do not require the intermittent supply of water any more. As an example, the hydraulic simulation model for Judayta village consists only of the DN 150 pipeline. Comparing such a model with the intermittent supply model that is introduced later on would be pointless due to the different level of detail.

3.2 Comprehensive Subscribers Survey (CSS) Data

The Comprehensive Subscribers Survey that is currently being executed for the whole Irbid Governorate is used to link base maps with customer information.

The link is established over a database field - primary key (PK) - that is shared between the billing system (COBOSS) and the GIS. With the survey, the correct primary key is assigned to each customer.

The process is also used to check base maps and customer data. Corrections are done if necessary.

As the villages in the Al Koura district lack street names, the GIS primary key is the only way to transparently locate customers.

3.3 COBOSS Data

The COBOL-programmed billing system used by WAJ is called COBOSS. In a process of decentralization a new COBOSS system was recently established in Irbid.

After completion of the CSS, the COBOSS data allows to integrate the actual consumption data into hydraulic models as demand. The COBOSS data contains domestic water meter readings for three-month periods.

COBOSS allows exporting the data as plain ASCII text files. These files can be imported into the GIS or into spreadsheets for further analysis.

3.4 DLS Data

The Department of Lands & Survey (DLS)[1] is the source for the base maps in the GIS. These cadastral maps are also used in the Comprehensive Subscribers Survey. The primary key used to link COBOSS and GIS is the same key that the DLS is using.

The DLS cadastral maps are based on the Palestine Grid coordinate system, as they build the base maps for the GIS, the GIS also uses the Palestine Grid coordinate system. Table 4 contains the parameters that describe the coordinate system.

Parameter	Value
Projection	Cassini
Reference Spheroid	Clarke 1880
Reference Point	82 M, x=35 12 43.49, y=31 44 02.749
False Easting	170251.55m
False Northing	126867.909m
K	1
a (Semiminor Axis)	6378249.79m
e	0.082482165485

Table 4: Palestine Grid Coordinate System Parameters

3.5 RJGC Data

The Royal Jordanian Geographic Centre (RJGC)[2] was the source for contour maps.

One problem with the RJGC Data was that the RJGC uses a different coordinate system, the Jordan Transverse Mercator (JTM). The transformation to the Palestine Grid coordinate system was done with ESRI's ArcInfo. The information in [18] is useful to perform geographic coordinate system transformation.

[1] http://www.dls.gov.jo
[2] http://www.rjgc.gov.jo

3.6 Water Quality Data

Water quality data is currently recorded on a per-village basis, the exact location is only known by the employee that is taking the sample. This way the records become quickly, even though they are entered in a database.

A new ORACLE-based database system has been purchased. Hopefully, this will ease the process of linking the available GIS data. That in turn could yield a powerful analysis option, as the spatial distribution of contamination can only be overlooked with the help of a geographic information system.

The Central Laboratories use EPANET V 1.00 to build hydraulic models for quality analysis. Intermittent supply is not taken into account by the models used, thus the calibration of these models is doomed.

A knowledge transfer was hampered by time constraints and the Central Laboratories bureaucracy, requiring official letters.

3.7 Logging Campaign

The Logging Campaign took place from 13th to 15th January 2001 and covered one full supply interval of Judayta village. In cooperation with the leak detection of the Water Authority of Jordan (WAJ) flow and pressure measurements were undertaken.

3.8 Altimeter Surveys

The main purpose of the altimeter surveys was to check the quality of the Digital Elevation Models (DEM) created from the RJGC contour maps (section 3.5).

3.9 Bucket Fill

A 'Bucket Fill'- test was used to assess the tank overflow of the Judayta pumping station.

3.10 Air Release Valve at Customer Meters

A simple water meter test setup including an air release valve was used to evaluate water meter readings for intermittent supply.

3.11 Internet

Figures 1 and 2 use geographic data (shapefiles) that has been downloaded from the web sites of ESRI[3] and CDC[4]. The following web pages have been used as entry points to obtain the data:

- http://www.cdc.gov/epiinfo/EIshape.htm
- http://www.esri.com/data/online/index.html

4 State of the Water Distribution Network Al Koura

by ARNE BATTERMANN

4.1 Overview

Currently the Al Koura water network consists of 210 km pipeline (DN > 50). The major part of the network consists of galvanized iron (GI) pipes, 32% consist of steel pipes (table 5).

4.1.1 Pumping Stations

Two pumping stations are supplying Al Koura - the Judayta pumping station in the south of the district and the Oyoun Al Hammam pumping station in the northern

[3] http://www.esri.com
[4] http://www.cdc.gov

part of Al Koura. These two stations are provided by two wells each. Each well is equipped with a flow meter for a documentation of the well production. Figure 7 shows Judayta pumping station.

Figure 7: Judayta pumping station

Appendix H gives an overview of the installations at Judayta pumping station.

Two additional booster stations are located in the outermost north and west of the district. Two flow measurement locations are defined in the north and south for documenting the flow out of the district for supplying direction Ajloun or Irbid.

Appendix I shall give an overview of the pumping and booster locations of pump and booster stations, wells, water meters and the structure of the distribution network. In spite of extreme elevation differences in the district, capacities of existing reservoirs are not used and high-pressure zones exist in supplying zones.

For the Irbid Governorate the quantity of UFW is estimated with 55% on average. Administrative losses have a share of 60% and technical losses of 40%

	Pipe Length in km	Percentage
Steel	66.867	31.8
Galvanized Iron	118.271	56.1
Unknown	24.640	11.8

Table 5: Pipe Materials in the Al Koura Distribution Network

on UFW[11]. Generally a discussion about influences on technical and administrative losses of water distribution systems is necessary in order to demonstrate possibilities for improving the system.

In the following some influences on UFW in Al Koura are highlighted, which have been observed during field visits.

4.2 Technical Water Losses

4.2.1 Bursts

A great part of the water network in Al Koura is lying uncovered on the ground next to streets without any protection of demolition. It has been observed that some pipes go through house walls and other pipes cross streets without any coverage.

Judayta is a village, which is directly supplied by a pumping station 400 m below. No surge protection is installed - water hammer is likely every time the supply is stopped. This increases the danger of bursts (figure 41).

4.2.2 Corrosion

The water network of Al Koura mainly consists of steel pipes (table 5). Most of them are lying on the ground and directly exposed to weathering.

4.2.3 Leakages

Leakages often result from inadequate repair of bursts. For example, refilling pipe trenches with sand is no matter of course. It might happen that rocks of several tons are used instead. The same applies for new parts of the network.

For the case that the pipe is covered, it is difficult to recognize leakages as the sandstone that forms the terrain contains seams[2].

Leakages are caused by substandard fitting installations.

4.2.4 Zoning

In this report the water network of Judayta is analyzed. Zones are not clearly separated and the existing zones are not operated in dependency to the hydraulic optimum (section 3.7).

Parts of the network are not well documented. 'Wild' connections between supply zones have been installed, without good or any documentation. Staff members, knowing details about the complex network, are few. Within the scope of this thesis 13.1% of pipes in Al Koura have been updated (table 6).

4.2.5 Pressure

Pressures up to 41 bar have been documented during the logging campaign in January, 2001 (section 3.7). Some domestic water meters have to resist pressures of more than 30 bar over complete supply intervals. Currently, no pressure reduction valves are installed.

4.3 Influences on Administrative Water Losses

In the following registered influences on nonphysical water losses (section 2) are discussed briefly.

Reduction of administrative losses goes further than improving measurement methods and procedures in direct connection to the water network. In many cases deficiencies in administrative areas are responsible for a huge percentage of high water losses.

4.3.1 Domestic Water Meter Inaccuracies

A number of the installed water meters do not reflect reliable measurements. Often this results in high pressures. Pressure reduction valves do not exist or are not installed and the meters are not designed to face pressures up to 30 bar (section 3.7).

In section 5.2 the effect of intermittent supply on domestic water meters is analyzed. Inaccuracies have to be confirmed. This survey is described and analyzed in section 5.2.

Frequently the water meters are manipulated by the subscribers. Statistics of the time between January and October, 1999, published in [11] show, that in 70% of illegal cases the water meters in the Al Koura area have been manipulated, in 20% of the cases illegal connections have been installed in front of the meter. This percentage refers to one illegal case out of 88 subscribers.

4.3.2 Bulk Water Meter Problems

- Damages due to of missing manholes are tolerated.
- It has been noticed that oversized or undersized meters have been installed.
- Flow directions in Al Koura vary with the supply of the different villages.
- Readings of the working meters at the well production are unreliable because they are estimated by the responsible operator.

4.3.3 Network Maintenance

According to reports by workers of the maintenance team bursts cannot be repaired or are repaired lately because of missing personnel.

4.3.4 Illegal Consumption

According to [11] the illegal connection cases in Irbid and Jerash are alarming. Twenty-five percent of the subscribers are consuming water illegally. Even worse is, that this percentage reflects the convicted cases only. The real percentage of illegal water consumption might be even higher.

There is no prosecution of illegal water consumption. The reason might lay in the public sector structure of the WAJ. A necessity of being economically does not exist in the same way as on the private sector.

4.3.5 Objection Acceptance

Objections by customers on water bills are accepted by the responsible instances of the water authority. Reasons might be missing responsibilities of the personnel in the public water authority and a lack of interest.

According to statistics published in [11] 14.4% of the summarized objections of the complete Irbid governorate are dismissed. In Al Koura only 12.9% are dismissed. This means that the majority of objections (nearly 90%) succeeded.

5 Surveys in Judayta

by ARNE BATTERMANN

In order to obtain reliable measurements, several surveys have been performed in Judayta village and at Judayta pumping station. The following section shall give an overview on these surveys. The importance of some particular problems will also be discussed. Section 5.1 describes the bucket fill test at the well production of Judayta pumping station. In section 5.2 domestic water meters are tested on accuracy under the influence of intermittent supply.

5.1 Bucket Fill

The pumping station of Judayta takes water from two wells (appendix H). These wells are feeding a storage tank of app. 16 m^3. Each well is producing app. 80

$\frac{m^3}{h}$. Normally only one well is running, while horizontal pumps take the water from the tank to supply the villages. An automatic control for avoiding overflow does not exist.

In figure 8 the tank of the pumping station is shown. The picture shows the erosion that takes place when the tank is overflowing at a rate that could not transported be by the DN 80 pipeline going back to the well.

Figure 8: Storage Tank at Judayta pumping station

Currently the overflow of the tank goes back into one of the wells (figure 9). Another disadvantage of the current situation is that the chlorination is leading into the tank, which means that the back flow into the well is chlorinated.

During several visits at the pumping station the overflow was running and the pipe was approximately three-quarter filled. A water meter is installed by the Water Authority. However, the meter readings are not accurate, as the pipe is not filled completely, caused by free surface flow, while the water meter requires pressurized flow. The "bucket fill"- test was chosen to control the water meter readings. The water meter has been out of order two weeks after its installation.

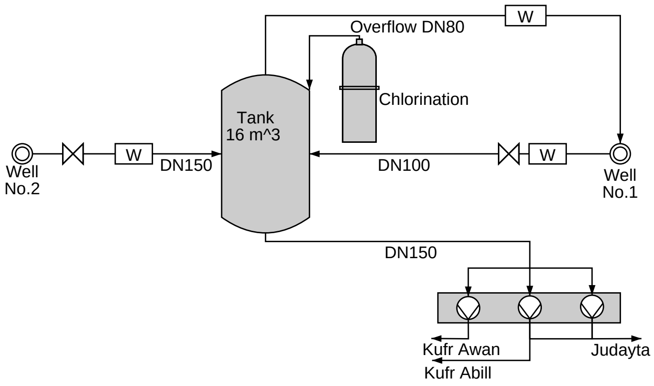


Figure 9: Operation of Judayta pumping station

5.1.1 Realization

On 19th, January 2001 the water meter on the DN80 pipe from the tank to the well has been taken off. Several tests of filling a bucket of 14 l at the opened pipe (figure 10) have been made and the time of filling has been recorded.

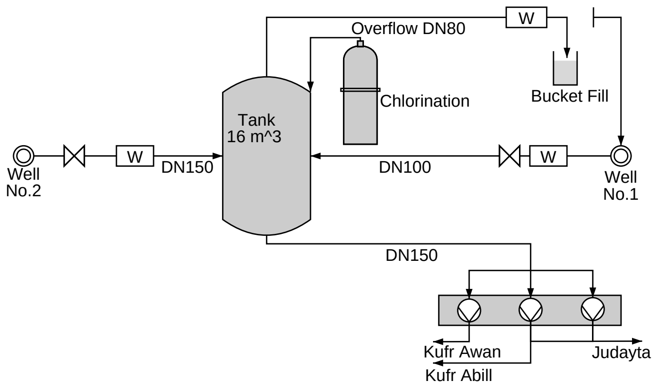


Figure 10: Tank overflow measured by Bucket Fill.

Figure 11 shows the bucket fill taking place. The bucket was the best that could be found on site.

Figure 11: Bucket Fill Photo

5.1.2 Results

During all tests the bucket is filled in app. 4 seconds:

$$Q = \frac{14l}{4s} \cdot 3600\frac{s}{h} = 12600\frac{l}{h} = 12.6\frac{m^3}{h}$$

At the time of the test, the water meter at the overflow showed a flow of 0.3 $\frac{m^3}{min}$:

$$Q = 0.3\frac{m^3}{min} \cdot 60\frac{min}{h} = 18\frac{m^3}{h}$$

This means, that the water meter reading is wrong by 70 %.

Figure 12 shows a repair attempt of the water meter at Judayta well No.1.

5.1.3 Conclusion

At the time of these tests one well was working with a production of app. 90 $\frac{m^3}{h}$. With taking the result of the bucket fill as average back flow, a percentage of 11% of the produced water is running back into the well.

Figure 12: Water Meter at Well No. 1

This means that the well efficiency is reduced by 10% at some times. The total amount of back flow is hard to estimate with the current water meter setup at the pumping station.

Meanings to solve the overflow problem are described in section 9.2.

It is not possible to use the term unaccounted-for water in this case. In section 2 is defined that "[...] losses occurring between raw water extraction and input into the distribution system are not considered unaccounted-for water".

5.2 Air Release Valves at Customer Meters

5.2.1 Background

With intermittent water supply, air is sucked and pushed in reliance with the status of supply period because of empty running pipes. At the beginning of a supply period the air is pressed upward by the water filling the pipe and in the end of the period air should be sucked as a consequence of empty running pipes. The sucked air could turn back the domestic water meters and cause an enhancement of unaccounted-for water.

5.2.2 Locations

Two locations were chosen for examining the reaction of the domestic water meters on air in the network. Both locations (A and B) have an elevation of app. 270 m above pumping station (573 m aSL) shown in figure 13. The domestic meters have been tested over two supply cycles (two weekends).

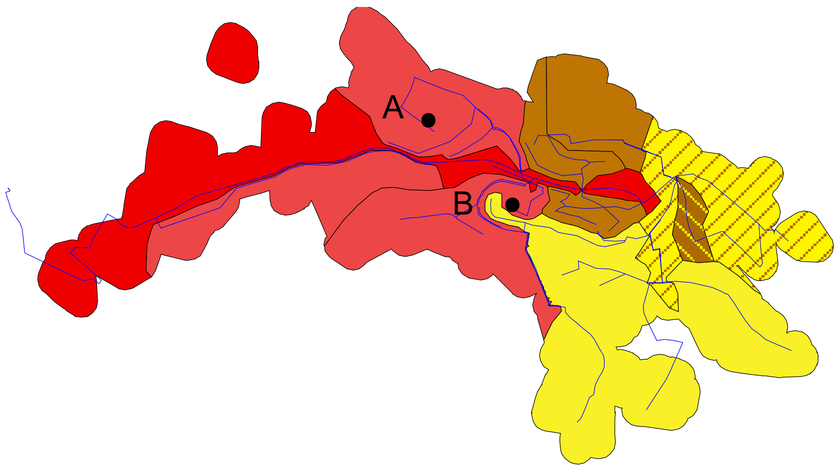


Figure 13: Location of Domestic Meter Tests

5.2.3 Realization

The installed arrangement consists of a check valve, an additional water meter and an air release valve (figure 14). The check valve is installed on a bypass parallel to the regular pipe. The air release valve is fitted behind the domestic water meter and another water meter is installed additionally behind the air release valve.

During the filling period water is flowing over the domestic water meter, which is recording the billed quantity of water. During the supply the bypass is closed due

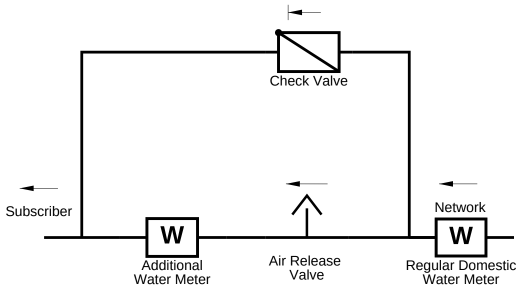


Figure 14: Flow during Supply Period

to the check valve. The air escapes over the air release valve and the additional water meter behind is counting the unadulterated quantity of water flowing to the customer.

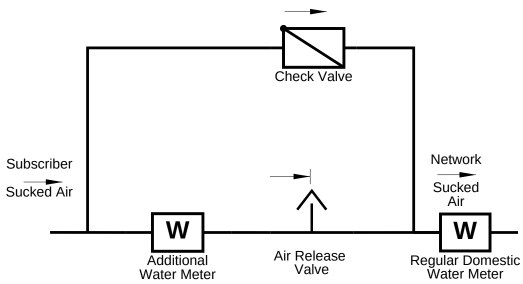


Figure 15: Flow after Supply Period

After changing the valve settings in Judayta for supplying another zone, the feeding pipe is closed app. 20 m below the tested domestic water meter. After this, the pipeline will empty into the lower tanks of the supply zone. The pipeline might run empty because of leakage also. Air is sucked through the inlets of the customer tanks, which stay opened.

The measurement of the additional water meter remains unchanged because the air is sucked through the air release valve or the bypass. The back flow is recorded by the regular water meter.

Figure 16 shows a photography of the fitting installation including the air release valve and the two water meters.

Figure 16: Air Release Valve Installation

5.2.4 Results

The expected shortfalls in receipts can not be confirmed. Exactly the opposite happens in three of four cases. Three times the additional water meter counted less than the domestic water meter.

In Figure 17 a difference between the billed and actual consumption of 11 - 16% becomes obvious. This means that the billed consumption might be higher than the actual consumption by the subscriber.

In Figure 18 the difference between billed and actual consumption is not comparable to the difference at location A, but the tendency exists during the first supply interval. During the second interval the actual consumption is slightly higher than the billed consumption.

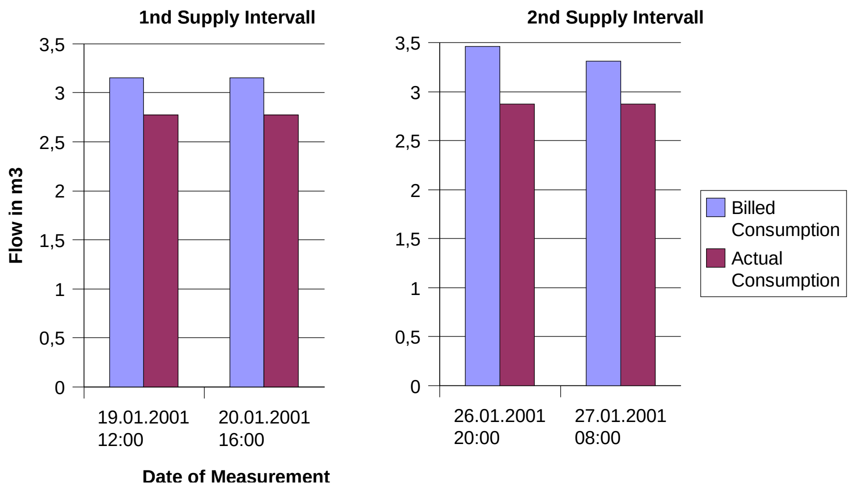


Figure 17: Result of Meter Test at Location A

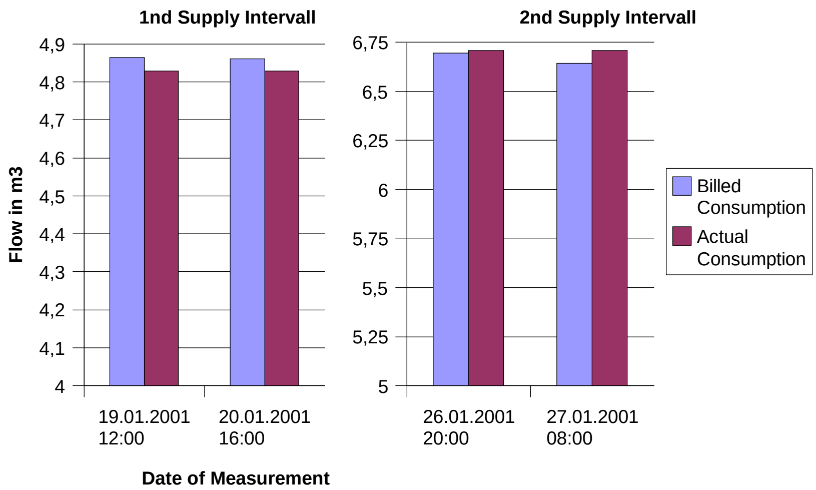


Figure 18: Result of Meter Test at Location B

5.2.5 Conclusion

The span between the actual and billed consumption might depend on the location, the behaviour of the consumer or sudden pressure drops.

Behaviour of Customer If all the consumers open their tanks before starting the supply, the mistake by pushed air at the consumer on a high elevation is lower, because the air escapes at the customers below also. This should be the actual situation because each customer is opening his tank in time to get as much water as possible.

In case the customers below open their tanks lately the mistake at the subscribers above is getting adequately bigger.

Location The mistake of sucked air should decrease with an increasing pressure difference between closed valve and domestic water meter. If the water meter is close to the valve which setting is changed for supplying another zone, the connected pipe main is full of water for a longer time than at a higher house connection, where back flow of air is happening soon.

Sudden Pressure Drops

- Sometimes the horizontal pumps in Judayta have to be stopped, because the network pressure at the pumping station exceeds 40 bar. This causes a pressure drop in the network and in connection with this a back flow of air through opened household storage tank inlets at the consumers.
- Pipeline bursts can cause pressure drops.

In order to get an accurate analysis of the mistake of domestic water meters in areas suffering from intermittent supply, more tests are necessary. The dependencies between location, customer's behaviour, pressure drops, etc. are complex.

The survey results clearly show, that the quality of domestic water meter readings in intermittent supply areas is limited even if the water meters are calibrated and the personnel for the readings is reliable. For a better measurement of domestic consumption, installations of air release valves are an opportunity.

However from the perspective of the water undertaking in this case accurate readings are not desired for the following reasons:

- The air release valves are costly.
- They require additional supervision and maintenance.

- The recorded inaccuracy was in favor of the water undertaking. If the water price is not covering the running costs, it is desirable to increase the water price. In this case the misreading is increasing the water price - even though this increase is not 'fair' as it is not equally distributed.

6 Preparing a GIS for the Al Koura District

by ARNE BATTERMANN

This section describes the sequence of operations for building up a GIS for the Al Koura district. Later on, the GIS data is used as source for hydraulic models in EPANET. The necessary steps included:

- Collection of available digital water network data.
- Software choices.
- Creation of an appropriate database design.
- Conversion of the existing data to the database design.
- Update of the network data, based on paper sketches and field surveys.
- Quality Control.
- Documentation of data, database design and the preparation process.

6.1 Software

by STEFFEN MACKE

Though the GIS software used should not be too important when creating a GIS, a few words are necessary to line out the alternatives in this case. As DORSCH Consult Amman and the Water Authority of Jordan use GIS software from ESRI, it was natural to choose ESRI software.

6.1.1 ArcInfo

ArcInfo is ESRI's high end GIS system. The multitude of programs alone is confusing:

ArcInfo Workstation The traditional command line oriented flavor of ArcInfo. Useful mostly for GIS experts, as the command line appears very cryptic to end-users.

ArcInfo Desktop A modern, Windows NT based version of ArcInfo.

The three core applications are:

- ArcCatalog, an application to preview and manage spatial data.
- ArcMap, map creation and editing software.
- ArcToolbox, a collection of spatial analysis and data conversion tools.

ArcInfo Desktop contains advanced concepts (Domains, Geometric Network) that ease the quality control process. Though ArcInfo is not the target for GIS applications in Al Koura, it proofed to be very useful while checking the data. Some ArcInfo concepts have influenced the database design.

6.1.2 ArcView

ArcView is also a powerful GIS software but targeted at the low-end market. As there is a lot of functionality missing in ArcView, additional software packages, so called 'Extensions' are often required while working with ArcView. Nevertheless, ArcView is suited for a lot of applications in the water utility sector.

6.2 Database Design

The first step to establish a GIS is to create a database design. This becomes clear with the current number of ∼5400 records in the updated water distribution network. Each record has several attributes (fields). As a consequence the number of 5400 is increasing with a multiplier resulting from the amount of attributes.

Existing database designs for Amman and Taiz, Yemen lacked several required features, some inconsistencies would have made it extremely complicated to extend these designs.

6.2.1 User Needs

by STEFFEN MACKE

A water utility GIS typically targeted at several user groups:

- The operations staff (network maps, repair data, etc.).
- Accounting personnel (collection areas, assets management, etc.).
- Management (statistics and reports for decision support).
- Public (general information, file complaints over the internet).

Like the rest of the thesis, also the database design had to focus on the technical part. Knowing that other user needs exist, special care has been taken to ensure a well-documented and extensible database design.

6.2.2 Data Types

by STEFFEN MACKE

GIS software as well as other databases allows the elaborate specification of data types for the attribute fields. Nevertheless when it comes to converting data from one format to another, the conversion process often imposes restraints on the data types used. This is especially true for the conversion process between an ArcInfo geodatabase and ArcView's default data format, the shapefile.

It was therefore practical to limit the number of data types used in the database design to the following:

- spatial data types - represent spatial (GIS) data, so called shapes
  - point - represents a point with x and y coordinates
  - multi point - a collection of points that share their attributes
  - polyline - a line with two or more vertices
  - polygon - an area
- non-spatial data types
  - integer - a number without floating point
  - float - a number that contains a floating point
  - string - a text
  - date - a date

The actual names of these data types differ even between ArcView and ArcInfo - these are the ones used in the thesis.

6.2.3 UML - Unified Modeling Language

by Steffen Macke

UML, the Unified Modeling Language is a standard developed by the Object Management Group (OMG). "The Unified Modeling Language (UML) is a language for specifying, visualizing, constructing, and documenting the artifacts of software systems, as well as for business modeling and other non-software systems. The UML represents a collection of best engineering practices that have proven successful in the modeling of large and complex systems."[7] The OMG web site[5] contains more information on UML.

[5] http://www.omg.org

Background UML has become an industry standard for CASE (Computed Aided Software Engineering) tools. CASE tools allow structuring the often chaotic software development process in a way that it becomes transparent. UML is well suited for modern, object-oriented data models.

UML is quite complex, for example it defines the following diagrams:

- use case diagram
- class diagram
- behavior diagrams:
  - statechart diagram
  - activitiy diagram
  - interaction diagrams:
    - sequence diagram
    - collaboration diagram
- implementation diagrams:
  - component diagram
  - deployment diagram

The database design for the Al Koura GIS as well as the data model for the DC Water Design Extension (section 7) only involved the class diagrams. The following UML introduction will therefore focus on the class diagrams.

Benefits Independent of any programming language or other software involved in the development process, UML allows to create standardized visual representations of data models. Such diagrams can serve as a discussion basis for developers as well as non-developers involved in the design process.

UML capable Applications A number of applications allow UML modeling, Microsoft Visio is probably the most prominent one. Also Visio serves as a UML CASE tool for ArcInfo.

For the present Al Koura GIS database design, dia[6] was chosen as the UML application. Being a free diagram creation software makes dia the first choice not only for UML diagrams.

Like Visio, dia is very extensible. The file format used by dia is XML (eXtensible Markup Language), an industry standard, that is very easy to convert to other file formats.

During the project it was possible to show with proof-of-concept applications that it is possible to load UML class diagrams created in dia to ArcView. Creating SQL tables with such models is also easy. Hopefully these concepts will evolve into practical solutions the future.

Class Diagrams Class diagrams are also known as “static state analysis diagrams” or “static structural diagrams”. The following will only describe class diagrams composed of two elements: Classes and generalizations.

Classes describe objects with similar structure. In the diagram a class is represented by a three-compartment box, with the upper compartment containing the class name. The middle compartment contains a description of the class attributes. The lower compartment is used to describe the methods of a class. Methods are not used in following; the class diagrams of the thesis will only contain classes with empty lower compartments. In such cases the UML software usually allows to switch off the lower compartment in order to create a visually more appealing representation. However, in the following the third compartment is displayed in order to be compliant with the UML standard.

Classes are separated into abstract and non-abstract classes. The difference between them is that abstract classes only exist in the UML model. Non-abstract classes not only exist in the UML model but also in the data itself: They are visible as files or database tables, for example. To reflect the difference, the name of

[6] http://www.lysator.liu.se/~alla/dia/

abstract classes is displayed in italics in the diagram.

Generalizations are used to model the relationship between a more general element (parent) and a more specific element (child). The child inherits all attributes and methods from the parent.

In the diagram a generalization is represented by a line that stretches from the parent to the child. The parent's end of the line is marked by a large hollow triangle.

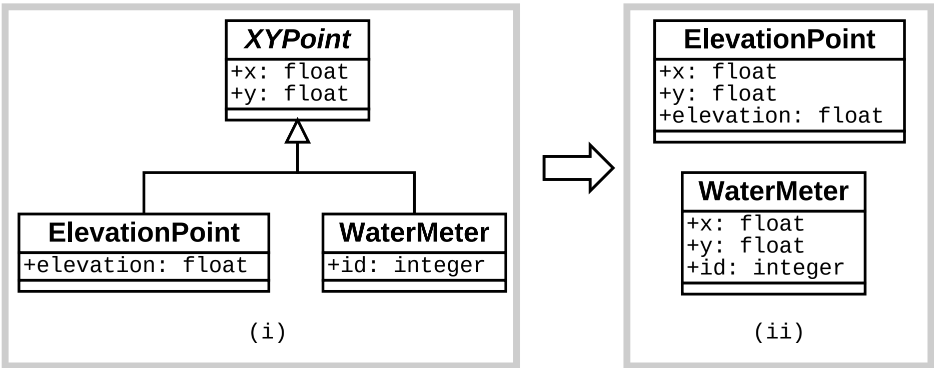


Figure 19: UML class inheritance

Figure 19 explains how UML class diagrams with generalizations should be read:

- In (i) the two classes ElevationPoint and WaterMeter are displayed as the children of the class XYPoint. XYPoint is an abstract class, therefore its name is written in italics. Two generalizations connect the children with their parent. As usual in class diagrams, the generalizations share the hollow triangle.
- (ii) shows the attributes of the non-abstract classes ElevationPoint and WaterMeter. As they both inherit from XYPoint, they contain the attributes of XYPoint (x and y) as well as their own attributes (elevation and id).

The classes ElevationPoint and WaterMeter have the same attributes in diagram (i) as in (ii). As both diagrams are valid in UML and the class XYPoint is only abstract, both can serve as representations of the same data. Yet the diagram (i) is more desirable as it contains the logic that groups the classes.

6.2.4 Implementation

Appendix E contains the structure of the database. Taking the pipes as an example, the UML class diagram will be explained (figure 20):

Together with the Node class the Pipe class shares the attributes of the Feature class, which consists of 4 attributes. The superclass of the Feature Class is the Identity Class. This class contains the most general element dc_ID. The attributes of Identity are inherited by the classes Curve, Pattern and Feature. As a consequence the Pipe class consists of 17 attributes like 'dc_ID', for an identification of each record, 'Installation_date' for a documentation of age of the pipe or 'length' for the length of the pipe.

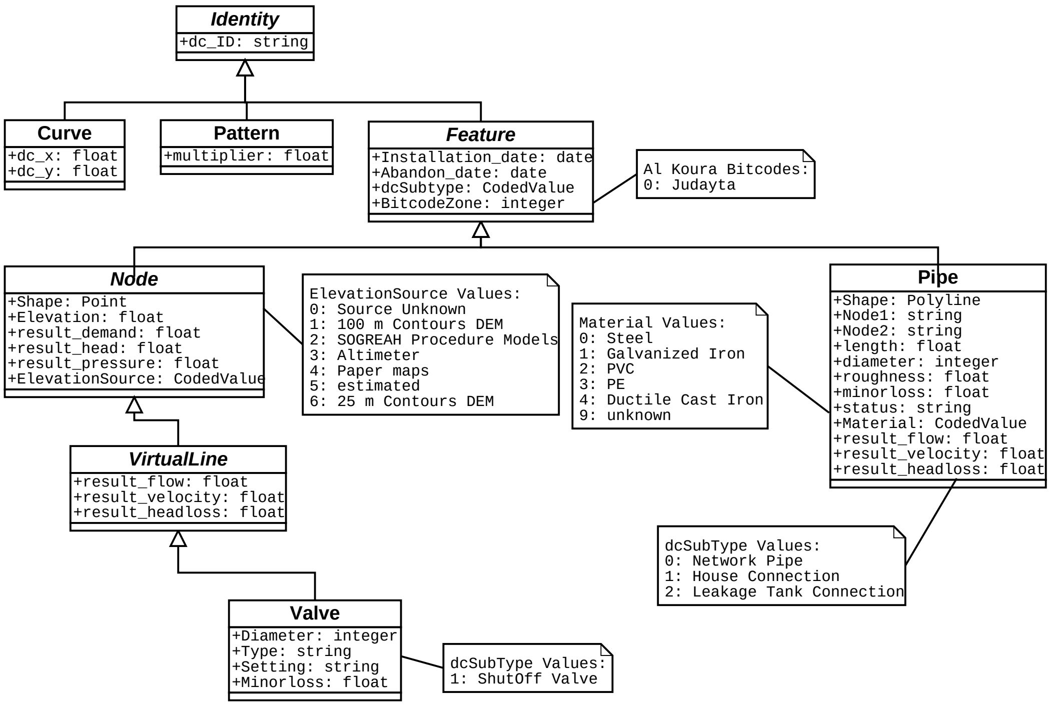


Figure 20: Extract: UML Static State Analysis Diagram

In some cases notes are linked to the attributes of a class. These notes contain domains and further define valid attribute values. They are implemented as coded value domains in the GIS. The sense of these domains is to restrict the input into a record to a defined input and to offer the opportunity to make queries for parts of the network.

As an example the following pipe theme query will select only network pipes.

dcsubtype = 0

Similar to this example any kind of object of the water distribution network can be selected by queries, with a database structure shown in appendix E.

Properties of attributes like different pipe materials under 'Material' can be defined as giving each kind of material a characteristic number.

In the same way the attributes of all other elements of the water network are described in the diagram. The difference between pipes and the other elements is the geometry of the class. While pipes are polylines all the other spatial classes (junctions, tanks, pumps, valves and reservoirs) are points and therefore these feature classes share the properties of the Node class.

6.3 Quality Control

One of the most important parts of GIS work is the quality control functionality. A lot of time can be saved by using the quality-checking tools offered in GIS packages like ArcInfo. Very often digital maps are going to and fro between GIS operators and engineers. If the proper quality checks are missing in this process, time and money are wasted.

The integration of quality control tools into the process of creating and updating digital maps can yield many advantages for the company and the employees, such as:

- Quality improvement of digital maps.
- Time savings for responsible engineers and with it savings in personnel costs.
- Increase of motivation for everybody involved.
- Increase of delivered quality at the client and a resulting increase of esteem.

The integration of functions of ArcInfo into the sequence of operations in working with the GIS is a single effort and might cost time and temper during establishment. Nevertheless the results should justify this effort .

6.3.1 Domains

Domains have been used to ensure data quality.

Coded Value Domains These domains are limiting the inputs into a field of a record to defined values. Pipe materials for example can be defined in a coded value domain. Each material can be coded with a specific number as shown in figure 20. After integration of a domain like this inputs, which are not equal to one of the defined codes, are not accepted.

The advantage of limitations in the input into attributes of the database consists of keeping the records clear. Spelling errors or impossible materials for example can be excluded like this. Moreover the size of the database is decreasing because number-fields are usually smaller than strings. As a consequence the database is getting faster and does not require as much hard disc space as the equivalent database without coded values.

Range Domains Are used for reducing the probability of entering values that are out of a defined range. Also in this case an example can be found in the pipe theme of the created database structure. For excluding mistakes by entering pipe diameters a range is defined between 0 and 500. With a defined range like this it is fixed that pipes below 0 and above 500 do not exist.

Because of the small leakage pipes the lower limit is defined with 0. Over validity checks in ArcInfo all records of the database are selected automatically, which violate the defined range domains.

6.3.2 ArcInfo Geometric Network

In addition to domains other checks have been made for improving the quality of the database. Often GIS maps have their source in CAD drawings. During the digitizing work many mistakes may occur. It might happen that the snapping functions are not focused correctly with the consequence of gaps between elements that should be connected.

Missing intersections are very often the reason for quality loss. For digitizing a connection of one pipe on another one of them has to be intersected, for creating a new junction between the pipes. As mentioned this happens very often because of wrong snapping.

Unnecessary intersections can reduce the quality of the map. Connectivity does not exist anymore, if an intersection is set on a pipe without creating a new junction on this location. Plenty of these mistakes have been present in the network which had to be updated in the scope of this thesis. The most important tool to locate these mistakes has been the Geometric Network of ArcInfo. It allows to check the connectivity of complex networks including pipes, junctions, valves, pumps, tanks and reservoirs.

Connectivity With setting a so called “flag” at one element of the network (junction, pipe, valve, etc.) a trace the can be started in the Geometric Network, which selects all those elements that are connected with the flagged element. For getting an accurate state of the network all selected elements should be marked with a temporary attribute. After un-selecting the elements a query can be started for all those elements, which have not been marked.

6.4 Distribution Network Data Update

The update contains new pipes of the network as well as functional parts like valves, washouts, pumps, tanks, reservoirs, water meters, endcaps, etc. The update includes quality checks for connectivity and automatic validity control of records in defined ranges. The continuous quality control is the key for a good network update. The bulk of work consists of correcting digitizing mistakes.

The quality of the source material of the network has been poor. Zones have not been clear because of missing valves and wrong connections of pipes. Pipes and junctions have sometimes been double at the same location. Quality checks have not been undertaken before handing over the data. Table 6 gives an overview of the quantity of elements added to the network. The table is not reflecting the work connected with updating the network because a great part consists of changing attributes of existing records without adding new records. This is not shown in table 6.

Elements of the Network	State of November ’00	State of February ’01	Percentage of Increase
Pipes DN25 in km	0	2.259	100
Pipes DN50 in km	112.842	130.383	13.4
Pipes DN75 in km	2.955	2.957	0.1
Pipes DN100 in km	33.949	34.927	2.8
Pipes DN125 in km	7.859	7.855	-0.1
Pipes DN150 in km	8.863	12.501	29.1
Pipes DN200 in km	15.789	18.779	15.9
total Pipes in %	182.256	209.616	13.1
Number of Pumps	0	15	
Number of Valves	0	152	
Number of Reservoirs	0	3	
Number of Washouts	0	3	
Number of Water Meters	0	4	
Number of Endcaps	330	339	
Number of Tanks	0	1	

Table 6: Network Data Update Statistics

With the process of correcting present data app. 13% of the network have been updated. 27 km of pipeline are added and 152 valves are placed in the distribution system. Pump and booster stations as well as the locations of wells are integrated into the network. Reservoirs are integrated for the south of Al Koura. Appendix I shows the updated water distribution network of Al Koura.

With handing over the water distribution network the quality checks described in section 6.3 have been passed successfully. The attributes adhere to the domains and the network connectivity is established.

6.5 Check and Integration of Elevation Data

This section describes the steps of checking and integrating the elevations delivered as paper map by the RJGC. The paper maps are digitized and a digital elevation model is build. Interpolation is the key for creating digital maps. The mistake is de- and increasing with the accuracy of the source data. In this case the source consists of 25m-contour paper maps. This means that the maximum mistake can be 25m.

Spot heights are taken for making a cross-check with the delivered data. The spot heights are taken with altimeters [7], which are used differential to get accurate readings. One stationary altimeter is used to correct the atmospheric pressure variation over the time, while the second one is used in the field. The altimeters have an accuracy of $\pm$5m, before using they are calibrated.

6.5.1 Data Check

Figure 21 shows the location where spot elevations have been taken with the altimeter.

Concept The quality check consists of the following steps:

1. Reducing the square error sum of all elevation differences to a minimum by iteration:
   $ES = \lim \rightarrow min \sum (A - B + X)^2$
   with
   ES= minimized square error sum
   A= elevation in m delivered by RJGC as 25m contours in a digitized format

[7] Thommen Barometric Altimeters

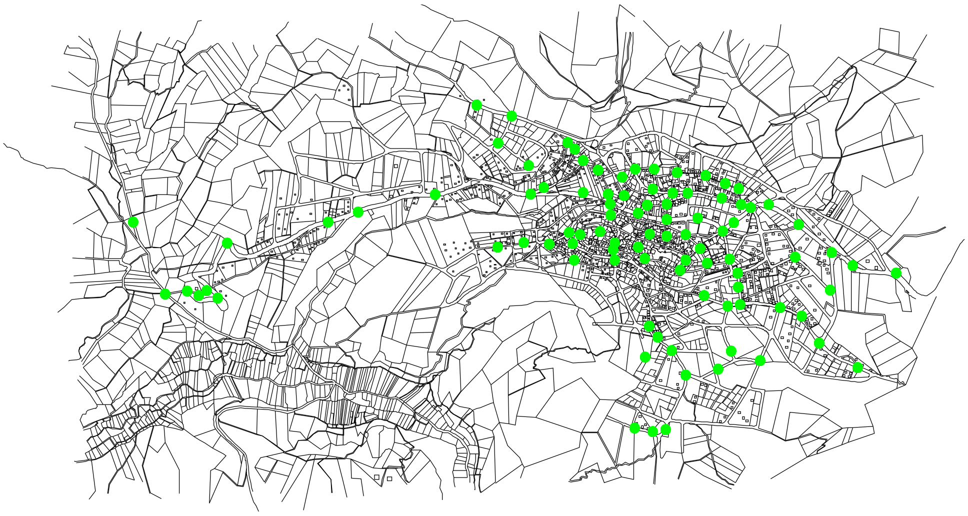


Figure 21: Altimeter Spot Heights in Judayta

B= elevation in m measured during altimeter survey
X= shift in m, produced by iteration to minimize square error sum.

2. Calculating the total mistake:
$TE = \frac{\sum |A - B + X|}{C}$
with
TE= total mistake
C= number of cross-checked elevations.

Results The used DEMs have been created from 25 m contours. Between the contours the elevations are interpolated. The DEMs were made for villages or groups of villages separately. For each DEM quality checks are made. For getting an impression how to value the mistakes, the highest and lowest point of each zone is listed in table 7 additionally.

For giving an example of this elevation check, the compared heights between DEM and Altimeter are listed in appendix F.

Village	Highest Point m above SL	Lowest Point m above SL	Elevation Difference in m	Shift in m	Total Mistake in %
Judayta	713	302	411	22.93	12.92
Kufr Awan, Kufr Abil	521	324	197	14.93	8.96

Table 7: Cross-Check of DEM with Spot-Heights

6.5.2 Integration into GIS

The integration of the checked DEM is done with the DC Conversion Extension.[8] New records in a defined field of a chosen point theme are generated by using the extension. In reliance on the coordinates of points the corresponding grid values are added to the point theme. The elevations of Judayta, Kufr Awan and Kufr Abil are updated. The contours of the centre and northern part of Al Koura have not been bought as DEM yet and consists of elevations taken from a DEM that is based on a 100 m contours.

No matter which area of Al Koura, each point of the point themes got an elevation. The source of elevation is documented for each record in the field 'ElevationSource' as illustrated in appendix C.

6.6 Visualization

by STEFFEN MACKE

The hydraulic simulation of water distribution network is a complex task. For hilly areas a discussion of such simulation models is only possible with the knowledge of the topography.

Modern information technology allows visualizing digital elevation models in real time.

Such Visualization tools are the ideal companions to powerful network analysis

[8]The DC Conversion Extension is Development of DORSCH in ArcView, ESRI

software - the integration of hydraulic modeling software into the GIS will even allow the integration of network analysis and three-dimensional visualization.

The GIS created for Al Koura contains the data to create three-dimensional visualizations. Without further processing, however, the resulting representations, called scenes, will look odd.

An appealing 3D-Visualization requires several steps:

- Interpolate the DEM to a level that was unnecessary for the hydraulic calculation. The accuracy that is accomplished by this operation is virtual - the model is displayed smoother because of this. The observer's eye recognizes less raster patterns in the output.

- Densify the pipelines: In simple words, the pipes had to be split in segments of 1 m length in order to get best display results.

- Draping the DEM with an aerial photograph makes the visualization look more realistic.

Three-dimensional visualizations have been used in the project to check the DEMs.

7 Modeling Intermittent Supply using EPANET and ArcView

by STEFFEN MACKE

The EPANET hydraulic engine is very powerful. However, a 'normal' EPANET model is not suited for intermittent supply analysis. Several steps are necessary to overcome this problem. These steps heavily depend on data preparation with GIS software like ArcView.

The following section will summarize the concepts used to establish an intermittent supply capable hydraulic model using ArcView and EPANET software.

It will also be an introduction to a software module developed during this project that allows the integration of EPANET hydraulic models in GIS data.

The motivation to create such software even though there are software packages available that provide a lot of the necessary functionality is clearly financial:

ArcView is a low end GIS software package, the high end ArcInfo software comes with network trace functionality and connectivity checks but constrains the user to proprietary data model. The proprietary data model in combination with the high price (approximately tenfold the price of ArcView) were the reasons not to use ArcInfo (section 6.1).

After careful consideration, the GNU Lesser General Public License (LGPL) was chosen for the software described hereafter[9]. DORSCH Consult decided to make the software available for free on the internet[9].

The GNU Lesser General License is an open-source license that enables everybody to develop the software further - if the developer agrees in turn to license and publish his additions under the LGPL.

7.1 ArcView Extensions

ArcView GIS software provides a powerful way to extend the software's capabilities: So called 'Extensions' written in ArcView's scripting language AVENUE that seamlessly integrate with ArcView's graphical user interface. ArcView Extensions are typically installed and removed very easily. The user decides which extension to load during the ArcView session - depending on the problems he wants to analyze. The software module developed is called "DC Water Design Extension" and consists of approximately 6000 lines of AVENUE source code.

Appendix A contains the DC Water Design Extension Manual. Appendix B contains the description of the Data Model used by the DC Water Design Extension. In order to model more complex systems, reading the EPANET 2 Users Manual[16] is recommended.

[9] http://dcwaterdesign.sourceforge.net

7.2 Substitution of Demand Nodes with Small Tanks

Intermittent supply yields a fundamentally different demand pattern than continuous supply. In fact, there is no demand pattern: The storage tanks of the customers will fill up whenever the systems provides water, until they are full and the float valve closes[19].

The approach to substitute demand nodes with small tanks in intermittent supply models has been used once in a thesis in Palestine. However it was not possible to get hands on the respective paper.

The software described in [19] utilizes 4 components to model intermittent water supply:

- Demand Model
- Secondary Network Model
- Network Charging Model
- Modified Network Analysis Method

While this approach is far more sophisticated and may provide superior results, it requires more specialized software. The substitution of demands with generalized tanks makes it possible to model pressure dependent demand transparently with a number of existing hydraulic network analysis software packages and is therefore very flexible.

7.2.1 Tank Sizes

The tank sizes depend on whether the network is available down to the individual house connection level or not. If the individual house connections are available in a GIS, each tank in the model should represent one real household storage tank.

In case the house connections are not available in the GIS, generalized house connections should be generated. It is practical to create one tank per junction, which is located at the centroid of the customers that are assigned to it. The one-tank-one-junction relationship resembles the traditional nodal demand of junctions. Additional a 'house connection' pipeline has to be generated that connects the tank with the junction.

7.2.2 Fill Rates

The individual tank fill rates depend mainly on the headloss over the pipeline that connects the tank to the network. For the case that uses generalized tanks it might be necessary to graduate the diameter of the connecting pipeline depending on the size of the tank.

7.3 Pressure Dependencies

The intermittent supply model relies on pressure dependencies in two points:

- The customer demands are pressure-dependent because of their storage tanks.
- Leakage is pressure-dependent.

The substitution of demand nodes with tanks also enforces a pressure-dependency for the customer demands.

7.3.1 Leakage

Leakage is pressure dependent. Especially if the water is supplied intermittent: In times where the system is empty, there will be no leakage at all.

In traditional hydraulic models, leakage is equally distributed with the demand, in general as a factor that increases all demands. (Assuming that there is a lot of leakage where is a lot of consumption.) However, this assumption might not be true for all water networks. A more flexible implementation of leakage is therefore desirable.

Orifice Diameter

$$discharge\ rate\ in\ \frac{l}{m} = 0.9 \cdot (orifice\ diameter\ in\ mm)^2 \qquad (1)$$

Equation 1 has been found through regression from data available in [14].

Pressure Dependency The following equation describes the discharge through an orifice[13]:

$$q_i = K_i \cdot (p_i - p_o)^\beta \qquad (2)$$

where $p_i$is the pressure upstream of the orifice, $p_o$the pressure downstream of the orifice and βa value of 0.5 according to theory and laboratory experience. $K_i$stands for the orifice coefficient, which is orifice-dependent. The following parameters also origin from [13]:

- $p_o = 0$ Leakage is discharge into the atmosphere.
- $\beta > 1.18$ Leakage defects are different than simple orifices. They are deformed by the network pressure.

Implementation Pressure-dependent leakage can be implemented with tanks connected to the network with short pipelines of a very small diameter. Such a setup creates flows that are similar to the discharge into atmosphere. Unlike the tanks used to model the household storage tanks, the tanks used in leakage modeling should never fill up completely - the leakage should only be limited by the headloss over the connecting pipe.

As for the tanks used in demand modeling, EPANET ensures pressure-dependency in this case. The parameter β of equation 2 can not be taken into account, but the results should still be better than those of the traditional network model.

Unfortunately, no literature could be found on the relationship between diameter and average leakage rates per metre of pipeline. The number of defects increases for lower diameters[13], but the number of defects is not necessarily related to the leakage rates.

Section 8.3.5 describes two approaches to overcome this problem.

7.4 Virtual Lines

In the EPANET hydraulic model, pumps and valves are represented as lines. From the hydraulic modeling point of view this makes sense, as the orientation of the valves and pumps is important information. In GIS data, pumps and valves are typically represented as points, as they are also symbolized with point symbols. Point data is lacking the orientation information. Because of the pipe-node duality pipes and valves will be referred to as virtual lines in this section.

The pipe-node duality complicates the creation of hydraulic models from the GIS data. It is possible to overcome the problem with one of the following solutions:

- Storage of orientation information for each virtual line in the GIS
- Take over the orientation of connected pipes

The second possibility has some advantages, as it does not require additional data storage - it was applied in the described application. However, it imposes some restraints on the data. The concept to model virtual lines as points in the GIS can be summarized as follows:

- Each virtual line needs to have exactly two pipes connected
- Both connected pipes must be oriented in the same way: One pipe has to start at the virtual line and the other pipe has to end at the virtual line

Figure 22 shows examples of different pipe orientations at a virtual line. The case a shows a pump with two pipes connected that are oriented in the same way. This allows the creation of the hydraulic model and is therefore considered valid. Case b shows pumps with pipes connected that are not oriented in the same way. This

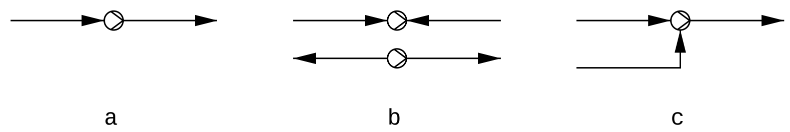


Figure 22: Virtual Line Validity

is invalid as is does not allow the creation of the hydraulic model. Case c is invalid because the pump has more than 3 pipes connected to it. Note that the orientation information of the pump symbol is not necessarily contained in the GIS data.

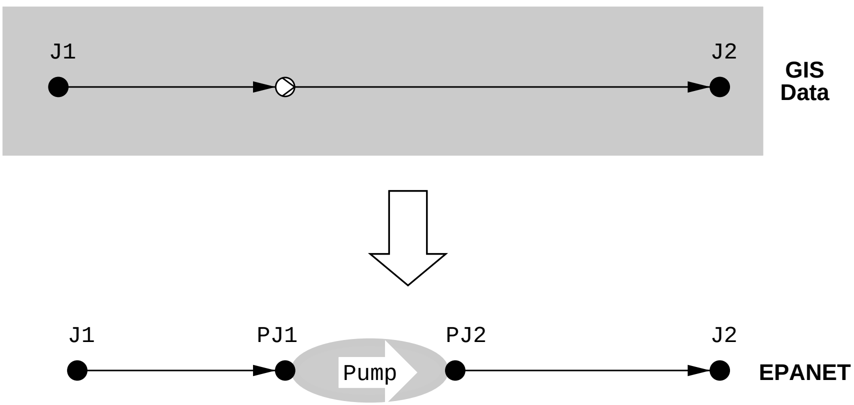


Figure 23: Virtual Line Creation

Figure 23 depicts the conversion process of virtual lines:

1. Number and orientation of the pipes connected to the virtual line are checked for validity
2. The virtual node is replaced with a junction (PJ1).
3. An additional junction is added (PJ2).
4. The pipe from the virtual line to the next node starts at the additional junction. (PJ2 -> J2).
5. The pump or valve is created. It connects the two new Junctions (PJ1->PJ2).

The DC Water Design Extension follows this conversion process when it is creating EPANET models. Additional considerations used in the process are:

- The length of the virtual line is one metre.
- If the pipe starting at the virtual line is shorter than one metre, the virtual line length is set to half of the pipe length.

7.5 Bit codes

Bit codes make it possible to store fields of yes-no information in ’normal’ numbers. Every bit in the number having the value 1 is considered set, every bit of value 0 is not set. Thus making it possible to bit-code several independent pieces of information in one ArcView Number.

As ArcView is using 32-bit (integer) numbers, it should be theoretically possible to store up to 32 pieces of information. This requires that the databases where the data is stored use 32-bit numbers as well. Tests up to 19 sets of yes-no have been successful.

The following example shows how this concept allows storing the network information in one seamless data set and utilizing the same network features in different hydraulic models:

In figure 24 the nodes of three hydraulic models are bit-coded for storage in the GIS. Each zone has its own bit in the bit code, indicating if the node is used in the model or not.

The DC Water Design Extension Manual (appendix A) contains more information bit codes. The DC Water Design Extension provides some functions to work with such bit codes.

7.6 Calibration

The calibration of the intermittent supply model for Judayta village was influenced by a multitude of different factors.

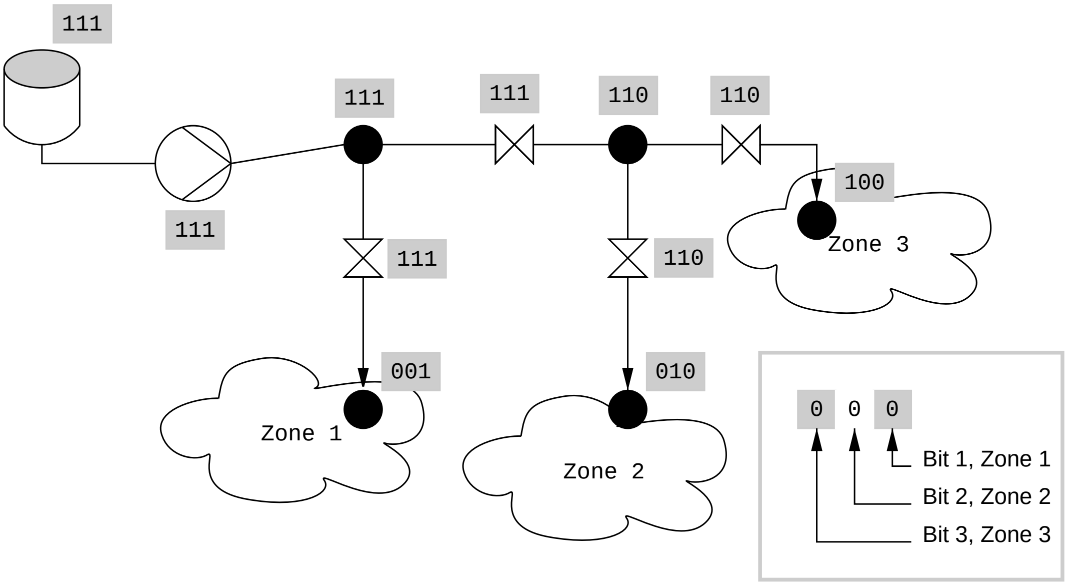


Figure 24: Bit-coding Supply Zones

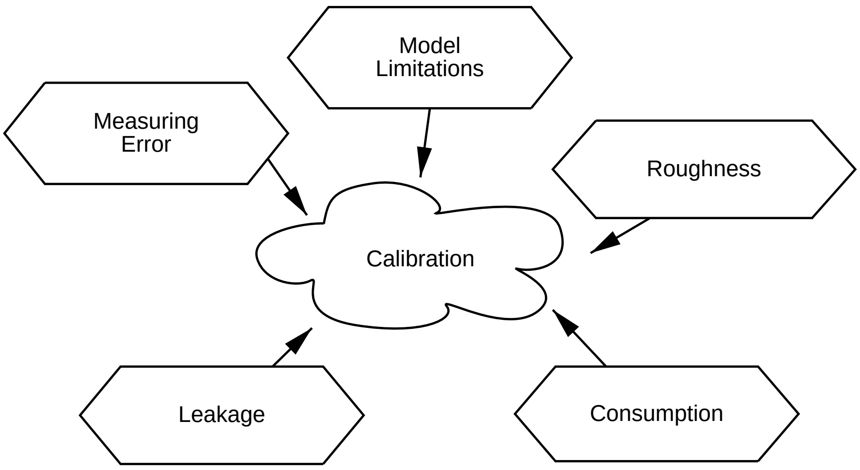


Figure 25: Calibration Influences

Figure 25 shows the influences that have been taken into account.

The following global parameters have been chosen to calibrate the intermittent supply model:

- A factor to adjust the diameters of the leakage pipes
- The pipe roughness

- A factor to adjust the diameters of the house connections
- A factor to adjust the sizes of the household storage tanks
- Three thresholds to distribute the size of the house connections
- A factor to adjust the pump power

This differs from the calibration of a traditional hydraulic model, where only one global factor, the roughness is taken into account.

Though the Windows version of EPANET provides functionality to assess the quality of a calibration, this was not enough to evaluate the multitude of possible parameter combinations.

7.6.1 Genetic Algorithms

Genetic Algorithms are a method to optimize non-linear problems efficiently. For this reason they have become popular with hydraulic analysis and water supply network design software [17, 19]. Genetic Algorithms are based on a process that is similar to the natural evolution: Individuals, which are more 'fit' to solve problems are more likely to be reproduced than other, not so fit individuals. The resulting selection process speeds up the problem solution. The approach itself is very generic, it is suited for many applications.

As the whole concepts stems from biology, the terms used to describe it are also biological:

- Population
- Gene
- Allele
- Reproduction
- Mutation

- Crossover

For the calibration, a gene is a set of parameters that describes one calibrated model. An allele is one of the parameters. A number of genes, called population, reproduces itself to form the next generation of genes.

As the parameters used in the calibration are not discrete, a concept is needed that allows genes with alleles that cover the whole space of possible solutions. For example it would be possible to create a population that is large enough to cover the necessary solutions. However, this would reduce the process to a simple trial-and-error one, as fitness evaluation and reproduction would only take place after the results for the large population have been calculated.

Another concept to increase the diversity of the population are mutations: Mutations allow changing the allele values of a gene. It has proved successful to allow complete mutations of an allele as well as only slight alterations of a value.

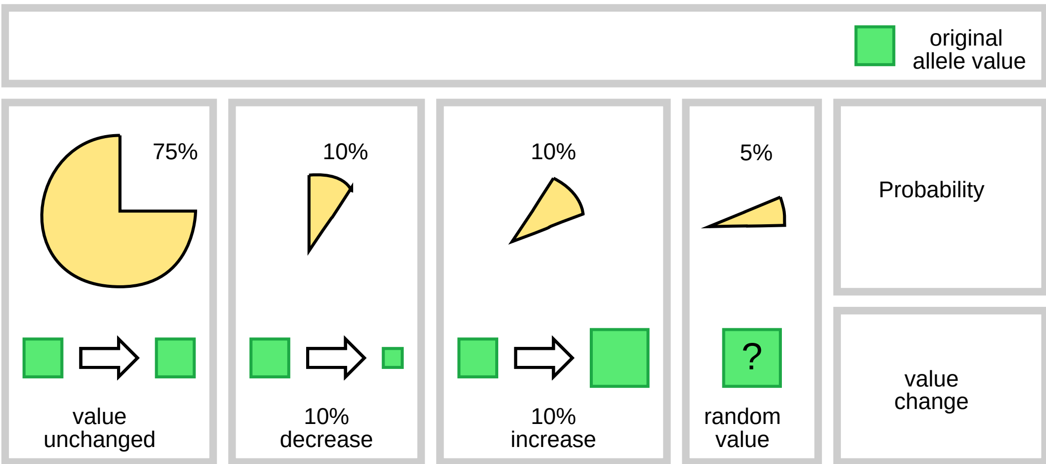


Figure 26: Allele Mutation

Figure 26 shows the allele mutation probabilities that have been used in the genetic program.

Diversity is also increased by the reproduction process itself: The two parents (genes) of a child mix their alleles in a crossover process.

Figure 27 displays the reproduction process. The crossover point is chosen at random.

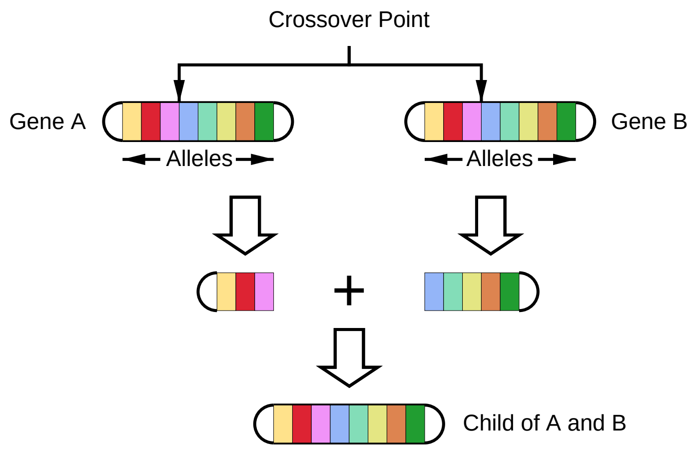


Figure 27: Reproduction with Crossover

7.6.2 Evolution

After several generations of the population have been reproduced, the survival of the fittest takes place: Before the reproduction, a fitness value is calculated for each gene. Genes with a higher fitness, thus representing a better solution, are more likely to reproduce than those with a low fitness.

The complete process can be described as following:

1. Creation of a random population: A given number of genes with random alleles.
2. Calculation of fitness values for all the genes of the population.
3. Reproduction of the population. This includes crossover and mutations. A new population is created.
4. Continue with step 2.

7.6.3 Robust Software

Robustness, performance and development effort and usability are factors that have to be taken into account for any software development. For the calibration software robustness was the ultimate design goal. It was necessary to run the calibration software for many hours unattended - unstable, non-robust software would not have been suited for this task.

The software developed has been split into the following modules:

- Calibration.sh - a shell script that controls the whole calibration. This script calls all other programs (EPANET, genetic, epanet2mysql as well as others) and sends SQL commands to the mySQL[10] database.
- Genetic - a C++ program that takes care of the reproduction and offers a front-end to the calibration data stored in an XML file[11]
- Epanet2mysql - a C program that converts the binary EPANET output into two text files that could be imported to the mySQL.

This approach prevents errors in the genetic and epanet2mysql from breaking the whole calibration process. The errors can only break one iteration. Note that these programs have also been quite stable during the process.

7.6.4 Calibration Process

Figure 28 gives an overview over the automated calibration process.

The chosen process has the following advantages:

- The robust EPANET input validation is utilized
- The genetic program uses the error checking provided by the XML C library for GNOME[12].
- The mySQL database systems provides high performance.
- All described software modules are free software.

The described calibration process was able to test thousands of possible calibration possibilities - providing substantial aid in the engineering process.

[10] http://www.mysql.com
[11] based on a genetic algorithm example from http://www.generation5.org
[12] http://xmlsoft.org

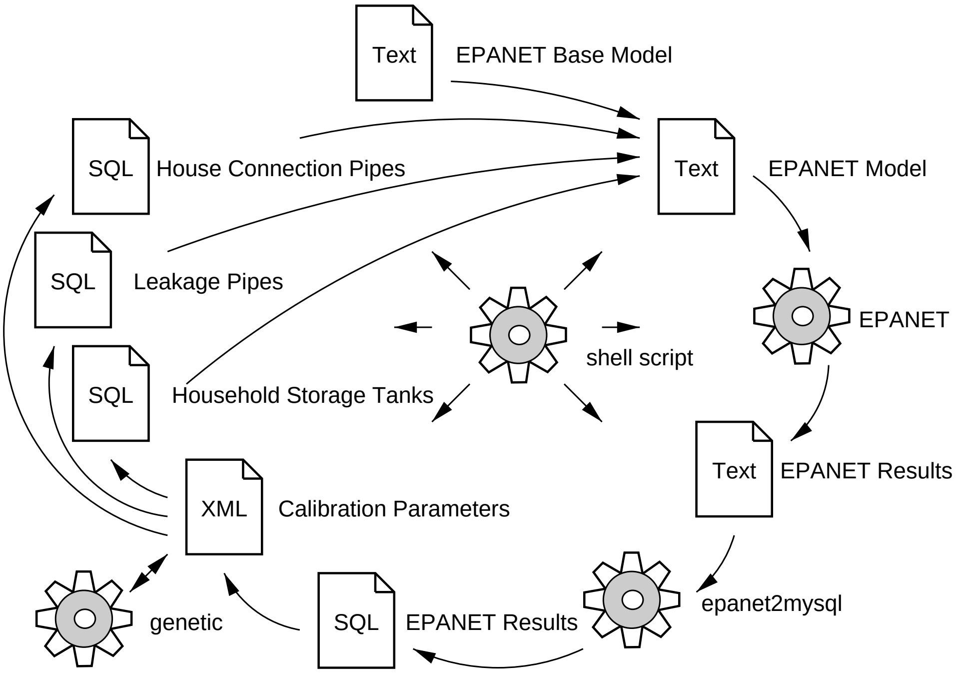


Figure 28: Calibration Process

7.7 Model Limitations

Like every other model, the discussed approach is not able to render reality completely. The following limitations should not hinder the model's functionality:

- Actual consumption is not considered: The consumption of water from the customer's storage tanks is not modeled. This could cause the tanks to empty and refill again. As the tanks are sized to contain the consumption of one week and the supply period is usually shorter than 24 hours, this effect should be negligible.
- Household storage tanks are aggregated.
- No support for empty or partly filled pipes.
- Demands are assigned to the nearest pipe; this might be different in reality.

- The consideration of unequal spatial distribution of leakage requires additional processing.

In addition, the model limitations for EPANET apply, see [16] for a discussion of the limitations.

8 Intermittent Supply Model for Judayta

by ARNE BATTERMANN

This section describes the processes listed below:

- Definition of zones.
- Model creation.
- Logging campaign.
- Calibration.

Section 8.3 is based on GIS operations described in section 6. This section shall describe the way to generate a running EPANET Model.

8.1 Definition of Zones

The zoning of the distribution system Judayta changes from summer to winter time. While Judayta is divided into six zones from April to November (figure 29), the network is operated with four zones in the winter months shown in figure 30.

The different zonings in summer and winter should allow an adjustment to different demand patterns. In fact, the bigger winter zones reduce the pumping head a little bit - higher friction losses are the reason.

During summertime each of the zones 2, 3, 4, 5 and 6 are supplied over 12 hours. Zone 1 is supplied over the whole interval. Missing separation of zones is recognizable between zone 5 and 6. Hazy zones are hatched yellow and brown. The total duration of supply is 60 hours.

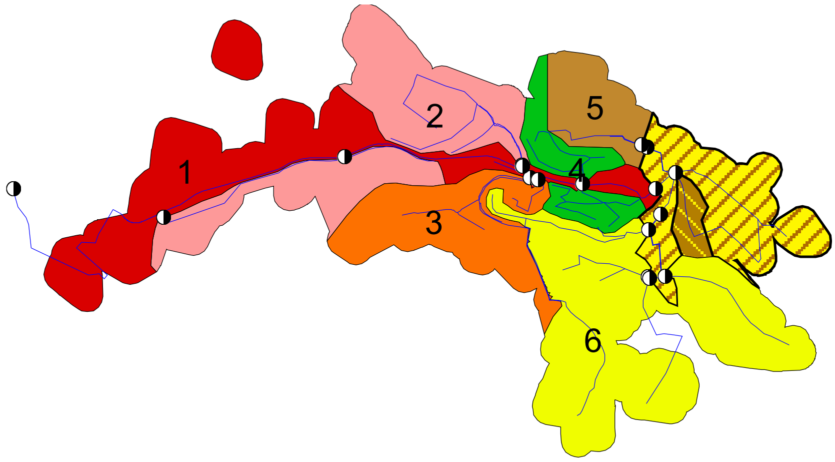


Figure 29: Zoning during Summer Time

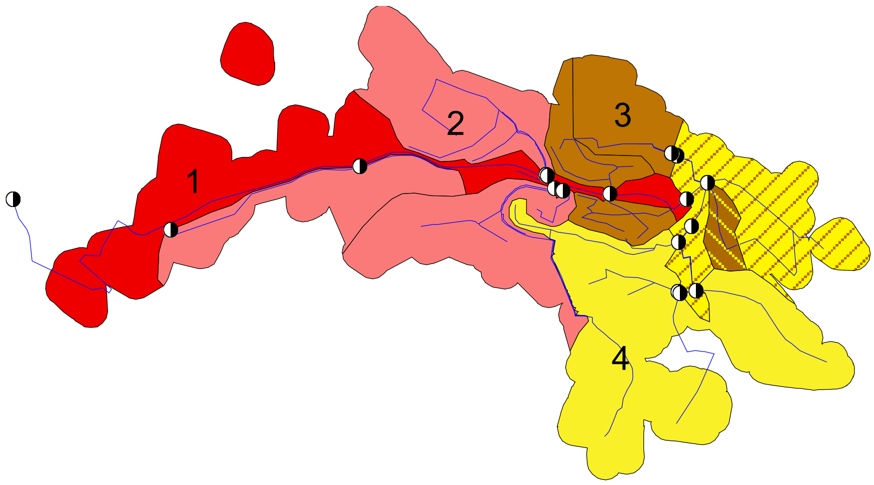


Figure 30: Zoning during Winter Time

The distribution zones are separated with the operation of 16 valves in the village. One of these valves is out of order currently - it is opened all the time because the gate has been taken out.

The first zone is supplied over 60 hours. The second zone is supplied over the first 24 hours and the third zone between the 24th and 48th hour. The fourth zone is supplied over the last 10 hours. As mentioned above a clear separation of zones does not exist. The yellow-brown hatched areas between third and fourth zone are supplied over the last 34 hours.

This schedule may vary depending on necessities. During the logging campaign the scheduled timetable was basically valid.

8.2 Domestic Consumption

For the integration of the COBOSS data (section 3.3) the data needs to be checked (section 8.2.1). Afterwards the consumption of subscribers in Judayta has to be integrated into the GIS. The workflow is described in section 8.2.2.

8.2.1 Data Check

The delivered COBOSS data consists of 4 meter-reading cycles from January 2000 to October 2000. Two of the cycles represent winter consumption and the other two cycles the summer consumption. In table 8 the billed consumption of Judayta village cycle is shown for the mentioned reading cycles.

Judayta has 1212 registered subscribers. In [11] based on the hydraulic analysis study of SOGREAH (Chapter 3.1) 8.5 persons are assigned to one subscriber in the greater area around Irbid.

Consumption	January 2000	April 2000	July 2000	October 2000
in $\frac{m^3}{Quarter Year}$	40141	33537	37623	49140
in $\frac{m^3}{w}$	2867	2395	2687	3510
Average in $\frac{m^3}{w}$		2541		
in $\frac{l}{c \cdot w}$	278	247		341
in $\frac{l}{subscr \cdot d}$	338	308		414
in $\frac{l}{c \cdot d}$	40	35		49

Table 8: COBOSS Data Summary

The values for the consumption worked out in table 8 are within the ranges in Irbid of 180 - 650 $\frac{l}{subscr \cdot d}$ and a resulting per capita consumption of 22 - 76 $\frac{l}{c \cdot d}$ published in [11].

With a measured well production of app. $80\frac{m^3}{h}$ and an estimated back flow of 10% (chapter 3.9) at the well production an estimated average quantity of app. $70\frac{m^3}{h}$ is pumped to Judayta over 60 hours of supply:

Quantity of water pumped to Judayta during one full supply period (logging campaign / winter 2001):

$$70\frac{m^3}{h} \cdot 60h = 4200m^3$$

Difference between pumped quantity and average billed consumption during winter months in Judayta :

$$4200m^3 - 2542m^3 = 1658m^3$$

$$\frac{1658m^3}{4200m^3} \cdot 100 = 39.5\%$$

The result is an UFW figure of app. 40%. This result reflects the expected value according to the tendency of decreasing UFW during the last ten years in Irbid and Jerash Governorate [11].

8.2.2 GIS Integration

In order to integrate the COBOSS data into the hydraulic model a sequence of operations has to take place.

- Import of ASCII data into the GIS.
- Creation of points for each specific consumption.
- Generalization: Creation of tanks with conformist size and spatial relation to the subscribers.
- Connection of tanks and water distribution network.

Tabular and Spatial Data The link between the tabulated COBOSS and the GIS data is the primary key (PK) as used by the DLS. The PK is a unique ID for every single parcel in Jordan. Before the two data source can actually be linked, the following clean-up process has to take place:

The spatial data may contain duplicate primary keys for some reasons. For example, if a house is shown on the parcel, house and parcel will be represented by two records in the database, sharing the same PK. In order to prevent the billed consumption from being duplicated, all GIS records sharing the same PK have to be merged into one record.

There are also duplicated primary keys in the COBOSS data. Every time a parcel is home to more than one subscriber such duplications happen. As for the GIS data, it is necessary to merge all records sharing one PK into one. Additional, the billed consumption has to be summarized in order not to get lost during the linking process.

The steps required for joining COBOSS and GIS data are shown in figure 31.

After summary of equal PKs and concurrent creation of total consumption for each primary key the tabular and spatial data can be joined based on the PK. Now the spatial records in the GIS are completed with the characteristic consumption and the next operation in the sequence for integrating the consumption into the hydraulic model can start.

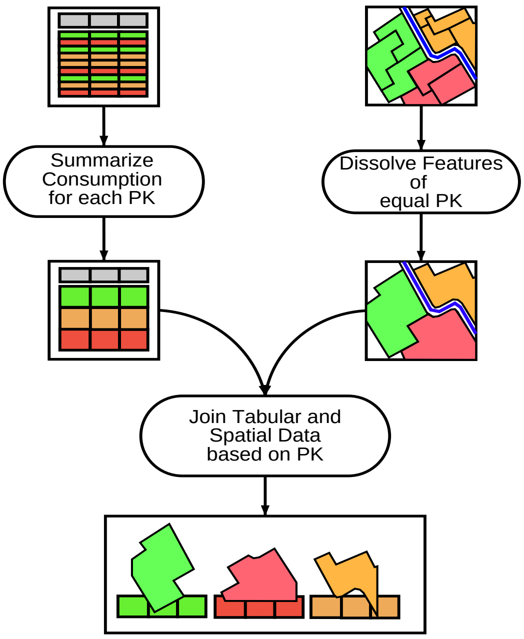


Figure 31: Join of Tabular and Spatial Data

The ArcView functions used have been particularly the ’Summarize’ function for the tabular data and the ’Geoprocessing Wizard - Dissolve features based on an attribute’ for the spatial data.

Consumer Parcel Selection As only the parcels with actual consumption are of interest, these are selected with a query. The following steps will only use these consumer parcels.

Parcel Centre Points Within the next operation shown in figure 32, points shall be created, which contain the specific consumption of its polygons and the attributes of the nearest junction. Afterwards points are created in the centre of each polygon.

These points locate the house tanks. Therefore each centre point has to have the information to which junction of the water network it shall be connected, because house connections will be created between the tanks and the nearest junctions. By joining the attributes of the nearest junction with the consumption in the new generated centre points each centre point has the ID of that Junction and a relation is created.

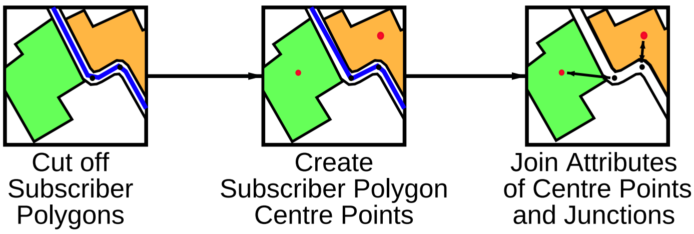


Figure 32: Centre Point Creation

In this operation the ’DC Conversion Extension’ and the ’Geoprocessing Wizard are used. Centre points are created over ’DC Conversion Extension’[13], while the ’Geoprocessing Wizard - Spatial Join’ function is used to join the attributes of junctions with the attributes of the nearest centre points.

[13] A small ArcView Extension developed by DORSCH Consult

Generalization The final operation to create tanks with a realistic size at realistic locations is presented in figure 33. To generalize the tertiary water network the centre points are grouped first. This grouping is possible by creating multi-points of the centre points in the GIS. Multipoint data consists of several points that share the attributes, whereas for point themes, every point has a separate set of attributes.

Afterwards single points are generated by calculating the centre point of the created group. These single points represent the house tanks.

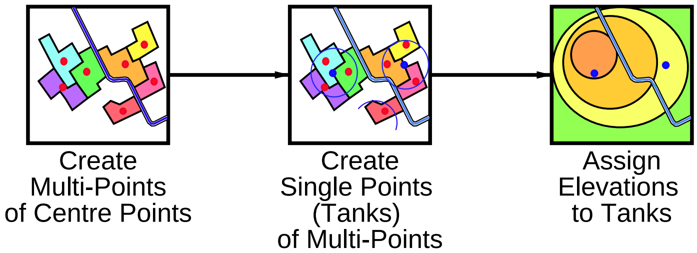


Figure 33: Creation of Tanks with characteristic Elevation

For this operation the 'Geoprocessing Wizard - dissolve features based on an attribute' has been used to generate a multi point theme. The single points are created by using 'DC Conversion Extension - create points from multi points'.

Elevation Assignment As the rest of the nodes in the water distribution network, the tanks need elevations. The elevations can be assigned from the DEM by using ‘DC Conversion Extension - assign point attribute from grid‘.

Connection of Tank and Network The creation of 'house connections' is the final step for integrating the generalized house tanks into the water distribution network. House connections are generated between the tank and the nearest junction. The decisive step is already done before and shown in figure 32.

Attributes are taken over from the nearest junction and integrated into the centre point theme. Afterwards each tank has the same ID as the nearest junction. The DC Water Design Extension (appendix A) is generating pipelines between the tanks and junctions into the pipe theme.

The major part of the work in the GIS is done with the connection of tanks with the distribution network.

8.3 Hydraulic Model Creation

In the present section the steps necessary to create a hydraulic model out of the GIS. The Water Design Extension (appendix A) serves as the interface between ArcView and EPANET several tables and rules (section 8.3.6) have to be integrated into the process of converting the GIS data into an EPANET import file.

Preparing a separated model of Judayta is described in section 8.3.1. The elements of the network are defined in section 8.3.2. EPANET is a complex tool with powerful capabilities, therefore adjustments have to be made for this particular hydraulic model (section 8.3.3). The integration of demand and leakage into the model is explained in the sections 8.3.4 and 8.3.5.

8.3.1 Isolation of Judayta

The isolation of Judayta in the GIS is necessary for creating an EPANET model of this single village. The Water Design Extension provides a function that minimizes the work to cut out the elements belonging to one distribution zone like Judayta. This function for cutting off so called bit-code zones is described in section 7.5.

Once the elements of the Judayta water network or any other village need to be defined with an attribute in each theme. This attribute consists of a particular value for each village of Al Koura (figure 24). This means that the network of each village can be cut out separately and elements that are shared with other models (e.g. the pumping station) are included.

The aim of this method is to automate the process of manually cutting out the villages after updating elements in the GIS (new pipes, new valves, etc.), while still allowing to work on one seamless network map.

8.3.2 Elements of the Model

For creating an EPANET model of Judayta the following network elements are necessary:

- Junctions
- Valves
- Pumps
- Tanks
- Reservoirs
- Pipes

The following paragraphs shall give an overview about the elements of the network.

Junctions Junctions are connected by pipes. The demand of the junctions is set on 0 because in this approach consumption is implemented with the tanks.

Valves Valves allow to define distribution zones in extended period simulations (section 8.3.6). Judayta consists of 16 valves. One of these valves is currently out of order. All the network valves are modeled as Shut-Off-Valves (SOV).

Pumps The operating pump during supply of Judayta has to be characterized. Important pump informations like power (section B.5) and pump curve (section B.15) are integrated over the attributes “Power” and “Properties”. While power is implemented as a value in the pump theme, the pump curve is integrated as an extra table with x- and y-coordinates. The data in the ”properties”-field is a link and contains the name of the pump curve.

Tanks Tanks are integrated to model leakage and demand. To different types of tanks are used:

- House tanks.
- Leakage tanks.

The house tanks generated in section 8.2.2 are reflecting the demand of those subscribers, who are summarized in these tanks. Further explains for integrating the demand into the hydraulic model can be found in section 8.3.4.

The leakage tanks are generated at each junction of the water distribution network. The limiting factor for leakage is not the tank size but the diameter of the connection pipe (section 8.3.5).

Reservoirs A reservoir is necessary at the pumping station to feed the pumps in the EPANET model. It is a simplification of the hydraulic model. The two wells, which are filling the storage tank in Judayta pumping station (figure 9) are not integrated in the hydraulic model. Instead a reservoir is chosen for supplying the operating horizontal pumps. This reservoir resembles the pumping station's storage tank which is filled by the submersible pumps.

Pipes The pipes are structured in three types. The following types are defined:

- Network pipes.
- House connection pipes.
- Leakage tank pipes.

Network pipes represent the updated network of Judayta (section 6.4).

The operations in the GIS for creating house connection pipes are shown in section 8.2.2. The house connection pipes shall supply the generalized house tanks. 125 house connections do exist in Judayta. It has to be made sure that a back flow of water from the house tank (section 8.3.4) is not possible. This has to be defined in the pipes theme of the GIS (section 8.3.6).

Leakage tank pipes are generated between the leakage tanks and the nearest junction. The GIS operations for generating these pipes are equal to the operations for house connections (section 8.2.2). The present hydraulic analysis model of Judayta village features of 157 leakage pipes. Each pipe has a length of 2 metres. The diameter of the leakage pipe is the key for modeling leakage in this approach.

8.3.3 Implementation of Model Adjustments

For running an EPANET model basic adjustments have to be fixed. They have to be defined over the following items:

- Options
- Report
- Times

Options The options table allows to choose the used head-loss formula (in this case Darcy-Weissbach), define flow units (litres per second). The number of trials for finding hydraulic solutions can be specified (section B.11).

Report These adjustments are not of the priority like Options or Times. The scale can be determined for getting different kind of summaries, status or warning reports. The used adjustments are described in appendix B (section B.12).

Times The hydraulic time step and the duration of simulation period have to be defined. The duration is set to 58 hours and a hydraulic time step of 5 minutes is chosen.

Next to these to adjustments further items have to be defined (section B.13)

8.3.4 Modeling Demand

While classical models have a specified demand at each network junction, the described approach is based on tanks which are filling in dependency of the present pressure at the tank (section 7.3).

The creation of house tanks is shown in section 8.2.

For a better visualization of the development of pressure and demand in EPANET each tank is reduced in its height to one metre. Like this a pressure scale from 0.1 to 1.0 in EPANET can visualize the tank fill level during the simulation period. The tank volumes have to be converted. Each tank is of cylindrical shape with a varying diameter and a constant height of one metre:

$$V = \frac{\pi \cdot d^2}{4} \cdot 1.0 \tag{3}$$

$$d = \sqrt{\frac{V \cdot 4}{\pi}} \tag{4}$$

with

d = Tank diameter

V= Volume of tank established in section 8.2.

The house tanks are supplied over the so-called "house connection pipes". The diameter of all the house connections was initially chosen with 25mm. This global diameter yields a mistake because the diameters for house connections vary in reality. To overcome the problem, the calibration script provides functionality to graduate 4 diameters based on the size of the house tank. Such a model represents the reality much better than a global diameter - it is still an error source, though.

To prevent a back flow of water out of the house tanks check valves are integrated into the model. Each house connection pipe is equipped with a check valve as shown in Figure 34.

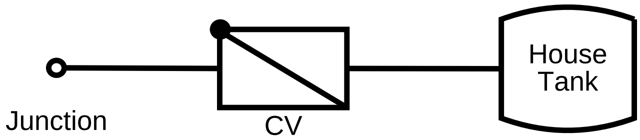


Figure 34: Check Valves

8.3.5 Modeling Leakage

For integrating the leakage into this approach of modeling intermittent supply, tanks are created at each junction of the water distribution network. The rate of leakage depends in this approach on the pipe length connected to the junction.

Two neighboured junctions are sharing the connected pipe with 50% of the length each. The diameter of the leakage pipe should depend on the resulting pipe length of the distribution network. Two approaches have been tried for integrating leakage into the model.

- Dependency between network pipe surface and leakage.
- Dependency between network pipe length and leakage.

The second approach seems more promising.

Repair statistics, published in [12], show that the majority (more than 90 %) of the repairs have been done on pipes of DN50 and smaller. The network of house connections is not integrated into the computed model and therefore this statistic can not be reflected. This is not the case in the represented hydraulic model. House connections are present, but they are unreal. Consumers are summarized and the real total length of house connections behind a particular tank of the hydraulic model can be much bigger than defined by the length of the modeled house connection.

$l = \frac{l_1+l_2+l_x}{x}$

$d_L = f \cdot l$

Where $d_L$is the diameter of the leakage pipe and $f$is a factor that has to be adjusted in the calibration process. The first choice of the multiplier depends on the resulting leakage pipe diameter. The pipe diameters covered a range from 0 to 30 mm in the calibration.

8.3.6 Implementation of a Rule Based Simulation

EPANET allows to create rules in extended period simulations. For example a valve control can be implemented which opens and closes valves for supplying particular zones.

During the process of creating a functional hydraulic model of intermittent supply in Judayta also several problems were faced. Irregularities in the computed pressure and flow during the first time intervals of the simulation period in EPANET happened. Pressure and flow changed in areas of the network, which have not been supplied yet. These model irregularities have been resolved.

Valve Operation The network valves are declared as 'shut off' valves. They are used for opening and closing the distribution zones during operation of the network (section 8.1). Adequately the valves are used in the hydraulic model shown in the following. The three zones of Judayta are analyzed with one EPANET model.

Valve Rules In this case the operation of the zones in the village shall be reflected by the settings of the valves. The status of the valves can be either 'open' or 'closed'. The so-called simple rule allows to change the setting of a valve at defined moments of the simulation period.

```
LINK V121 CLOSED AT TIME 00
LINK V101 CLOSED AT TIME 24
LINK V106 OPEN   AT TIME 48
```

It might confuse that the first column contains “link” instead of “valve”. Shut off valves are represented as a pipe in EPANET.

Pipe Rules Similar to the valve rules in the paragraph above rules have to be implemented for pipes also. Due to irregularities in connection with pressure and flow in zones of no supply because of closed valves a rule is necessary. Pipes are closed during hours of no supply and opened during hours of supply.

```
LINK L2524 CLOSED AT TIME  0
LINK L2516 OPEN   AT TIME 24
LINK L2617 CLOSED AT TIME 48
```

Each pipe (link) owns a dc_ID (section 6.2.4) listed in the second column of the rule above, followed by status of the pipe and the time of setting this status. The irregularities stopped after integrating these rules.

8.4 Logging Campaign

As mentioned in section 3.7 a logging campaign has been undertaken in Judayta. The flow was measured by two ultra-sonic flow meters [14]. In addition, five pressure meters [15] have been used. The two flow meters stay at the same locations over the whole time of the supply interval. The locations of the pressure meters were changed over the supply time.

In the following an overview will be given for:

- The realization of pressure and flow measurements.
- The results of the logging campaign

8.4.1 Flow Measurements

Flow measurements are intended at the pumping station and on the main pipe leading through the village in the centre of Judayta (figure 35). Problems occur with the flow meter at the pumping station (M1). The pressure readings are stopped after the first hours, because of pressure far above 30 bar.

[14] CONTROLTRON/ USA
[15] SEBA/Swiss

The flow readings are not complete and error-prone due - partly due to turbulence and air inside of the pipe. At least 24 hours are not documented.

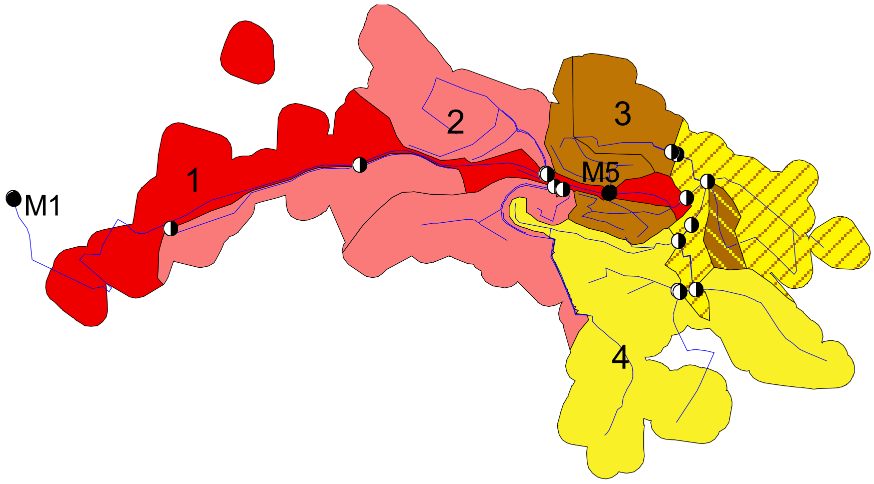


Figure 35: Flow Logger Locations

The readings of the second flow meter M5, shown in Figure 35, are realistic and used for calibrating the hydraulic model in EPANET.

8.4.2 Pressure Measurements

During the logging campaign 12 locations of Judayta (M1-M12) are measured depending on the operation of valves and the resulting supply zones (figure 36).

The pressure meters are installed at the domestic water meters.

8.4.3 Measurement Results

Pump Curve Because of unrealistic flow measurements behind the pumping station a characteristic pump curve for the operated pump cannot be obtained from the logging data. Pump measurements would have been necessary, but due to limited time these measurements have not been possible. In figure 37 the pump curve of the operated pump is shown. The data for this curve is delivered by the pump manufacturer [4].

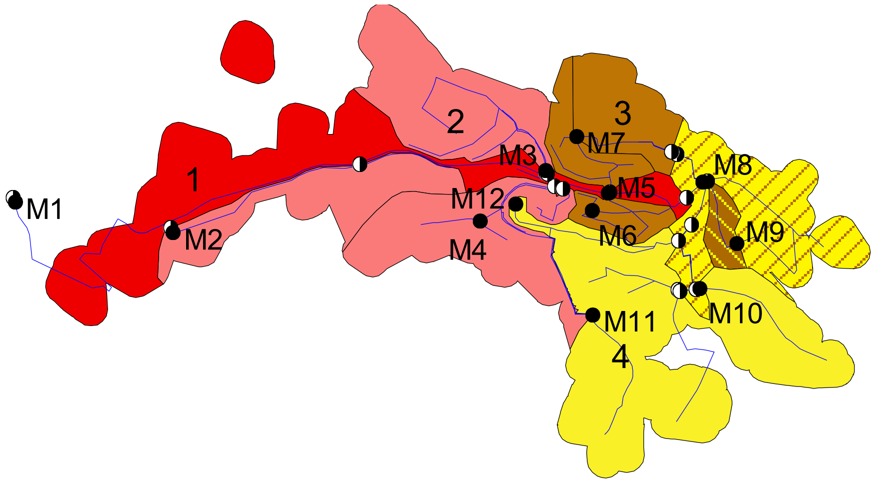


Figure 36: Pressure Logger Locations

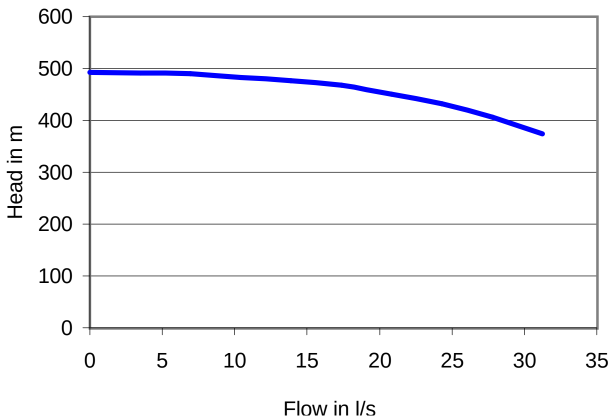


Figure 37: Pump Curve

First Supply Zone The tendencies of the pressure measurements are matching in all cases. During the first 24 hours the pressure is increasing slightly with an ascent of app. 4 metres per hour.

After 24 hours some valve settings are changed for supplying the second zone, this causes a pressure drop at the fixed ultra-sonic flow meter in the centre of Judayta.

Second Supply Zone The rapidly increasing pressure at M7 and M9 is noticeable. A reason might be the previous supply of the subscribers in the second zone

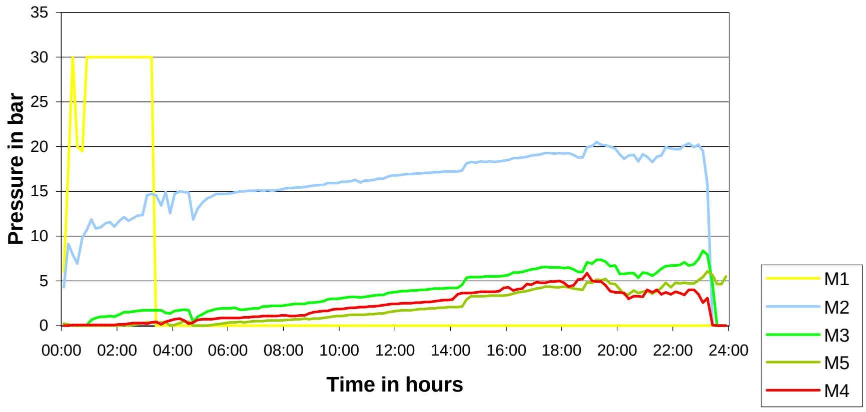


Figure 38: Pressure on the first Day

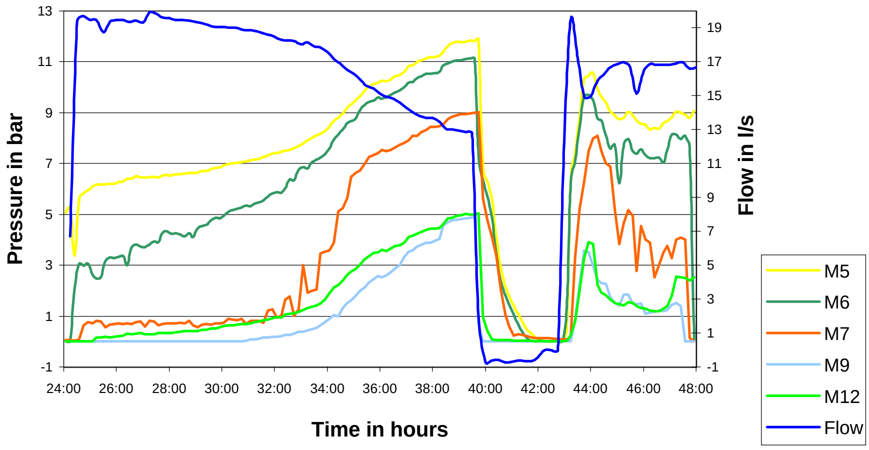


Figure 39: Pressure on the second Day

next to the third zone. After 33 hours this demand seems to be satisfied and the pressure at M7 and M9 increases.

The flow starts at M5 24 hours after pumping started. The flow of 70 $\frac{m^3}{h}$ is falling down to 45 $\frac{m^3}{h}$ during the following 16 hours.

The reason for the decrease in flow at M5 (figure 40) and pressure at all measurement locations (figure 41) lies in a pump shut down. Three hours later the pump is switched on again. The pressure is rising nearly to the level before the shut down and is decreasing while the flow goes up until changing the valve settings are changed.

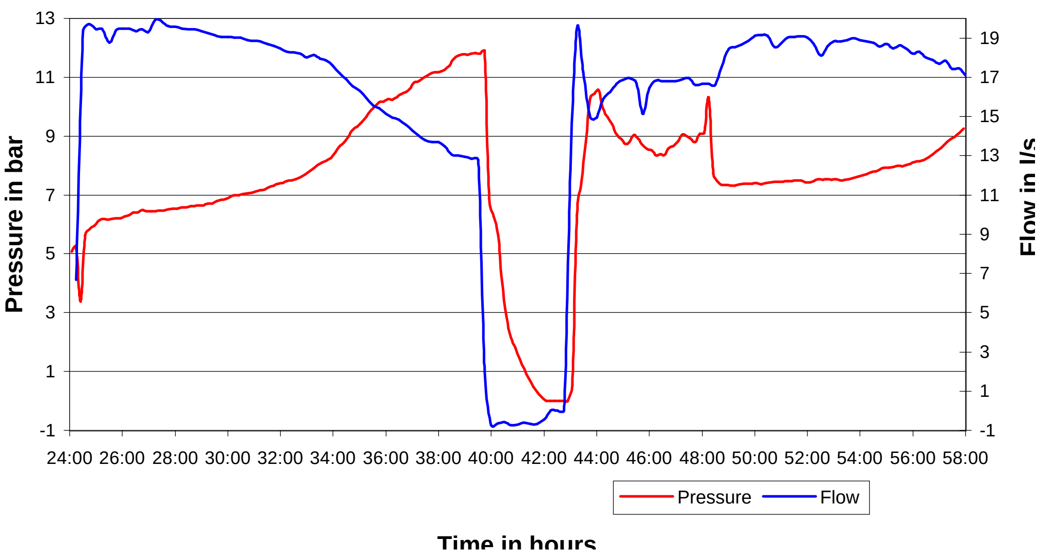


Figure 40: Pressure an Flow at Logger M5

Third Supply Zone The flow during the last ten hours is constant at 65 $\frac{m^3}{h}$. It is decreased slightly (0.5 $\frac{m^3}{h}$) while the pressure is taking up by approximately 1 $\frac{m}{h}$.

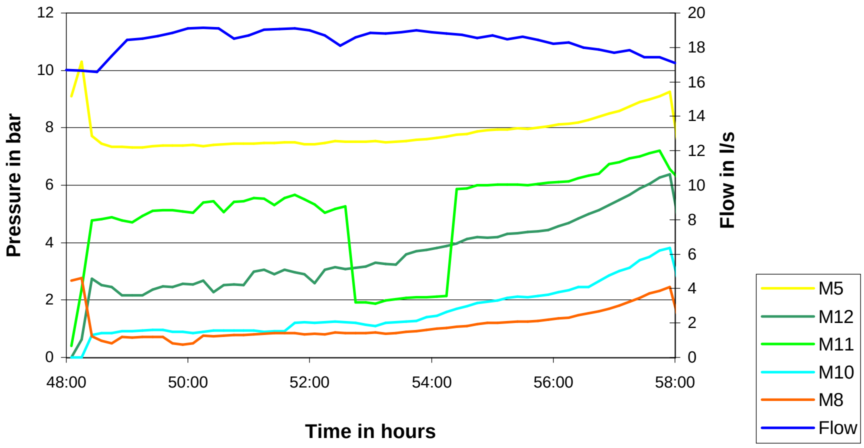


Figure 41: Pressure during the last 10 hours

The pressure at M11 drops for 1.5 hours in the middle of the last supply period. A reason could be a large consumer, located downstream on the same pipe. The steep incline in pressure after 1.5 hours can be a sign that the consumer's demand is fulfilled. The pressure measurements are fitting together and are reliable. They are reflecting the elevation differences of the locations quite good.

Conclusion Except for the measurements at Logger M1 (figure 35) all measurements are of value for a model calibration. The supply interruption for 3 hours during the second day will cause difficulties in calibrating the model, because the pressure drop and the development of pressure and flow after this event are difficult to model and have therefore been disregarded.

A summary of all measurements is given in appendix G.

8.5 Calibration

On the basis of the measurements presented in section 8.4 the calibration of the EPANET model can start. In the following the steps towards calibrating the model are explained. Section 8.5.1 describes the preparation of the calibration files. The different operations and changes for reaching a better conformity of the computed and measured values are following in section 8.5.2. The results of calibrating the model with the final values of the themes are listed in section 8.5.3.

8.5.1 Preparation of Calibration Files

This section describes how to integrate the results of the logging campaign into the hydraulic model. Two ASCII files have to be generated consisting of flow and pressure measurements. The structure of the files is easy and shown in the following examples. The calibration file for the flow consists of the location of the measurement, the time in hours and the measurement of flow in $\frac{l}{s}$.

```
J2410 25:45 6.688055556
J2410 26:00 19.4225
J2410 26:15 19.69444444
```

The calibration file above consists of the measurements at M5 (figure 35) only. The measurements of the logger at location M1 are unreliable and useless for a calibration. The calibration file consists of 120 records in intervals of 15 minutes and reflects the flow in figure 40.

The pressure calibration file - which is structured in a similar way - is shown with the following example:

```
J2429 1:05 42.72
J2429 1:15 91.47
J2429 1:25 79.49
```

The pressure-calibration file consists of location, time and pressure measurement in m. Measurements of all locations are listed sequentially. Altogether $\sim$1650 pressure measurements in intervals of 5 minutes at 12 locations of the distribution network can be used for calibrating the hydraulic model.

Before running a calibration in EPANET some irregular values have to be eliminated. In the beginning and end of the pressure and flow measurements values exist, which should not be used for a calibration. Zones have been closed already or the measurements are distorted by air in the filling/emptying network.

8.5.2 Calibration Workflow

An improvement of calibration results, which are generated in EPANET has been managed by changing attributes of the pipe, pump and tank themes. The following attribute values have been varied in the calibration process:

1. Pipe theme
   - diameter of leakage pipes
   - diameter of house connections
   - roughness

2. Pump theme
   - pump power

3. Tank theme
   - diameter of house tanks

Each variation of the values in ArcView/GIS requires to create a new EPANET import file over the DC Water Design Extension. Despite this very comfortable interface between EPANET and ArcView the calibration of a model like this with many unknowns needs time. Many models have to be build for succeeding in approximating the computed model and measured values.

After creating an import file for EPANET over the DC Water Design Extension the calibration files (section 8.5.1) have to be loaded into the EPANET import file and a "Run" of the model has to be started. With this run EPANET is calculating the development of pressure, flow, etc. during the defined simulation period. The comparison of the computed and measured values for flow and pressure can be illustrated as a graph showing the mistake of all locations or as graph for each measurement location. In reliance on the development of pressure and flow at the different locations further variations in ArcView have to be done for improving the current calibration results.

Because of the complexity of variation and combination the achievements in approximating the computed model to measured values have been limited even if the tendencies were getting better and better. The support of the calibration process by genetic algorithms (section 7.6.1) eased the process. Additionally different classes of house connections could be applied in a graduated manner.

8.5.3 Results

The winter time supply periods could be summarized as follows:

- Zone 1 is supplied over the first day (0h - 24h).
- Zone 2 is supplied over the second day (24h - 48h) .
- Zone 3 is supplied over the last 10 hours (48h - 58h).

For the presentation of the results after finishing the calibration process 6 figures of flow and pressure measurements are shown as examples of this approach. Some of these examples are presenting the problems some are showing a successful approach.

Through the calibration process the model quality improved. The listed parameters in table 9 represent the best calibration of the model. They are the result of the calibration process. All multipliers are described in section 7.6. First estimations of a roughness between 1.5 and 2 are confirmed by the genetic algorithms.

Parameter	Value
Leakage Pipe Diameter Factor	1.455924
Roughness	1.626
House Connection Diameter Factor	0.900000
House Tank Size Factor	0.813000
Pump Power	99.595
1” Threshold	1.754000
1.5” Threshold	7.216000
2” Threshold	9.516000

Table 9: Best Calibration Parameters

Figure 42 depicts an example of the how the solutions improve during the Genetic Algorithm calibration process as described in section 7.6. Smaller fitness represent better solutions.

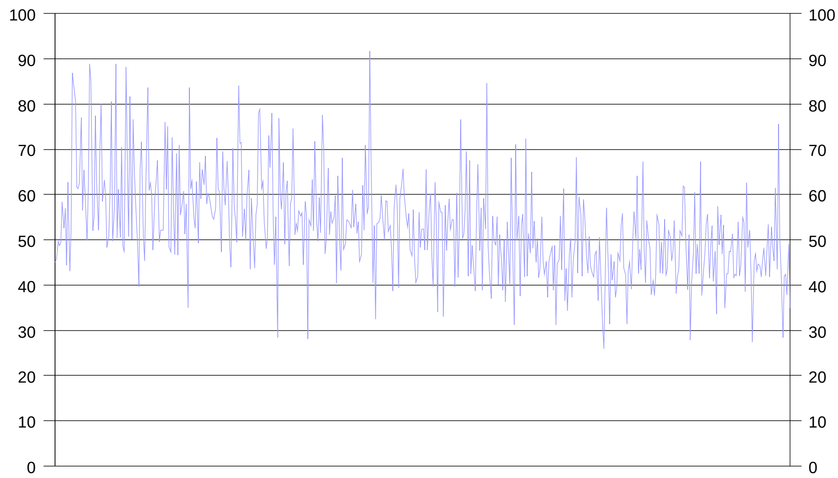


Figure 42: Genetic Algorithm Calibration Fitnesses

In figure 43 the computed flow is compared to the measured flow at M5 (figure 35). During the first day no flow is happening because the zone behind the logger has been closed. A maximum difference between measured and computed values of $5\frac{l}{s}$ is given in the second zone. During supply of the third zone the computed values are lying close to the measurements.

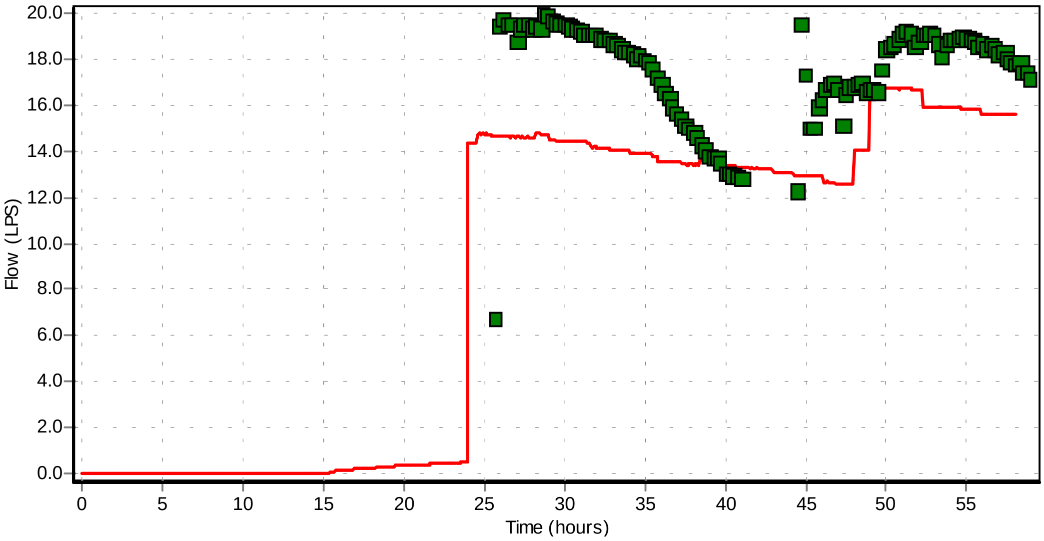


Figure 43: Calibration results for flow at M5

The pressure measurement at M5 between hour 6 and 42 is fitting with the computed model in the tendency (figure 44). The computed values differ approximately 5 - 20 m from the measured values during the first day. With the opened zone behind the location M5 and after 24 h the difference between model and measurement is increasing. After 42 hours a gap of calibration measurements is noticeable. Due to high pressure at the pumping station the operating pump has been stopped for 4 hours. This was not be modeled in EPANET. The drop of measurement data is deleted in the calibration file to avoid mistakes as mentioned in section 8.5.1.

The consequence on the stopped pump is a complete pressure loss. After the pump operation starts again the pressure recovers on the computed flow level and increases similarly to the computed pressure.

Figure 45 is representing the location M3 (shown in figure 36). The measured pressure is close to the computed model and the tendency is good.

A reason for the differences between computed and measured values shown in figure 44 and 45 could lay in the modeling of house tanks. The house tanks of the

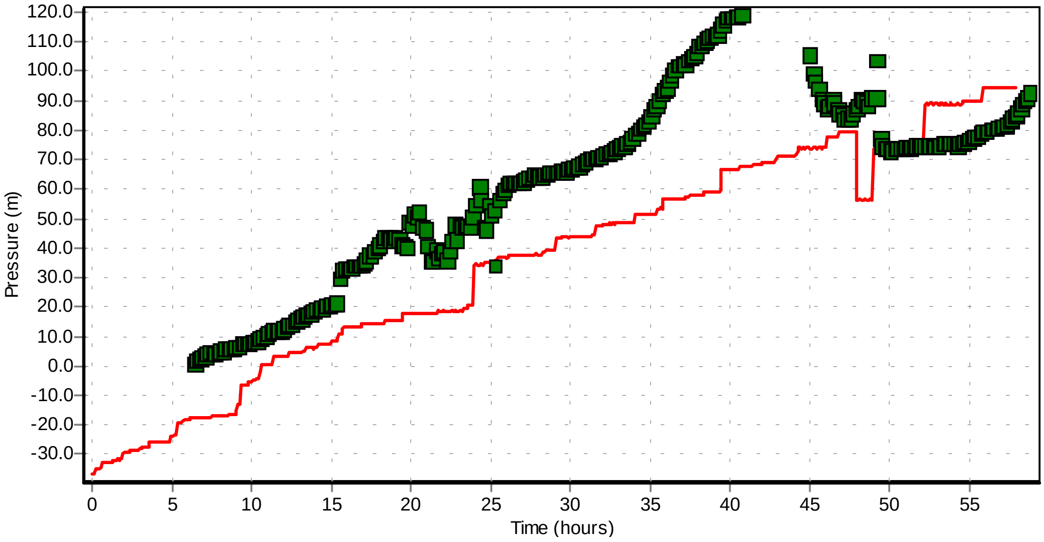


Figure 44: Calibration results for pressure at M5

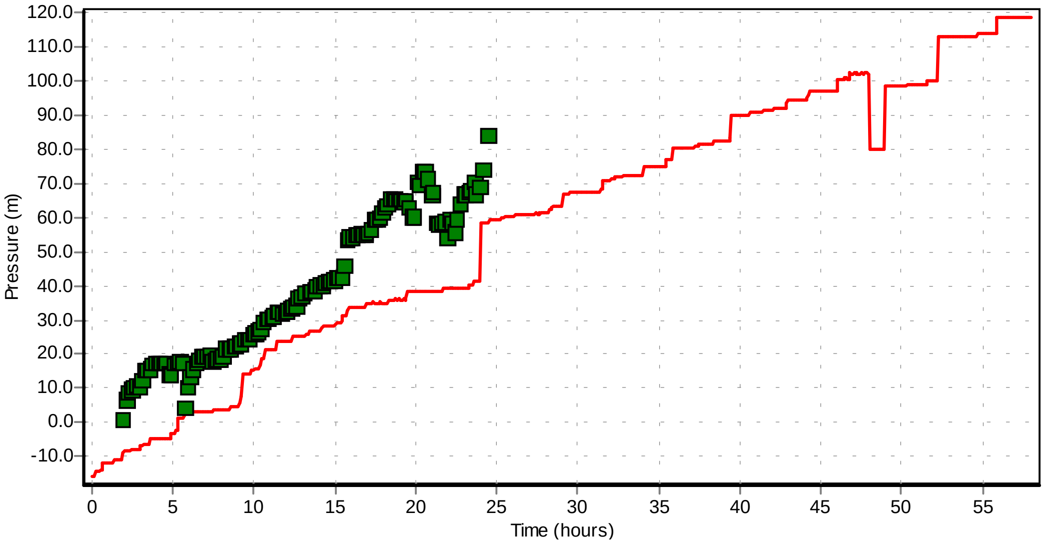


Figure 45: Calibration results for pressure at M3

model are not equivalent to the house tanks hanging on a particular pipe in reality to 100%.

Some tank sizes of the model are too big, others are too small. This situation has an effect on the pressure of course. An even higher influence on the inaccuracy might stem from the distribution of leakage tanks in the network. Besides the elevations have an accuracy of app. 25 metres only. The DEM is cross-checked but differences have been ascertained. The measurement locations might lay up to 25 metres higher than fixed in the model.

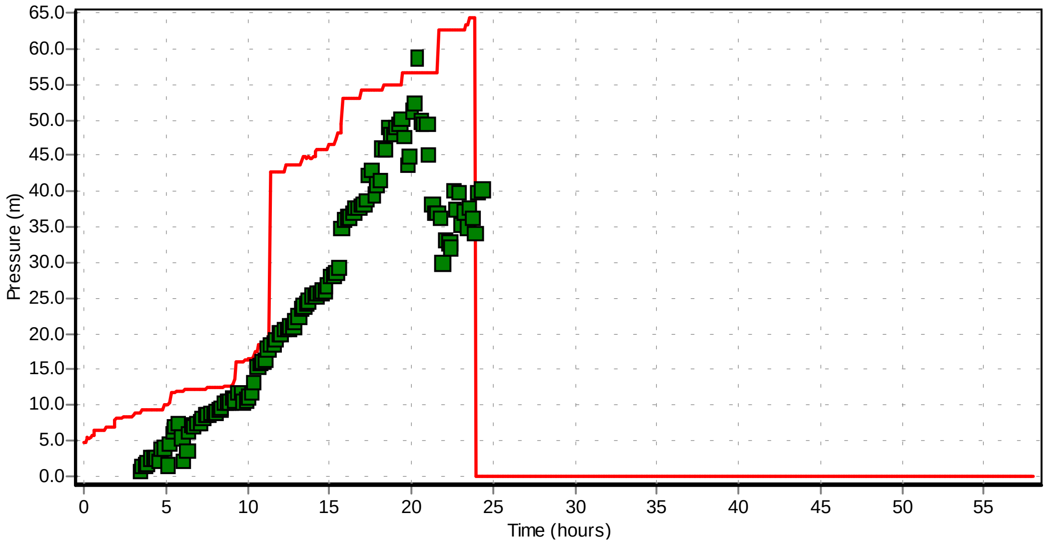


Figure 46: Calibration results for pressure at M4

Measurement locations in the village can not be reflected with the computed model easily. M4 and M7 are lying in densely populated areas. Despite the computed pressure is close to the measured values.

The constant positive pressure over the first 24 h shown in figure 47 is a problem of EPANET which is not designed to model intermittent supply. It happens in periods of empty pipes that EPANET shows pressures, even if the pipes are set on “closed” (section 8.3.6) because the zone is not supplied yet.

Nevertheless, the tendency of the model is fitting with the measurements. This is also shown in figure 47 representing location M7. Pressure level as well as tendencies are fitting between computed and measured values.

Figure 48 represents a pressure measurement at location M2. This location is the first on the way to Judayta and at the lowest point of all measurements. The

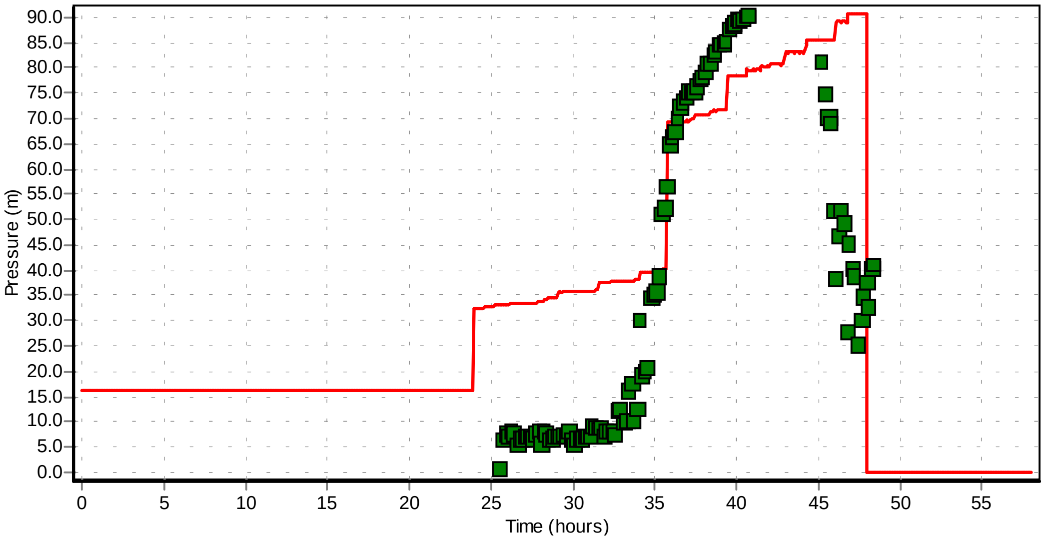


Figure 47: Calibration results for pressure at M7

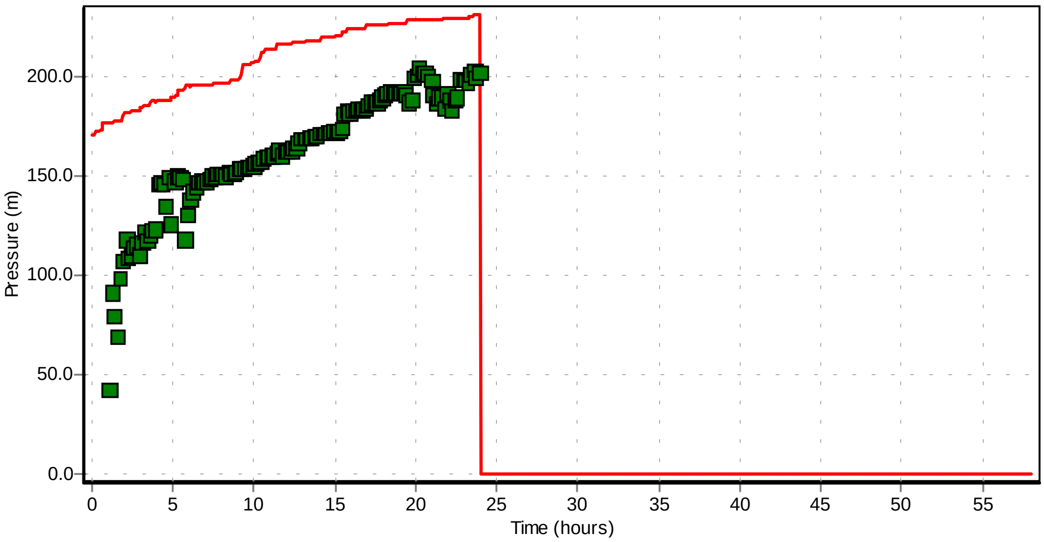


Figure 48: Calibration results for pressure at M2

computed pressure is much higher than the measured pressure. Possible reasons for the differences can be found for example in the accuracy of elevation. The mistake of 25m contour maps can be high due to the topography.

8.6 Comparison with a traditional Hydraulic Model

The necessity for creating hydraulic models of intermittent supply becomes clear by the comparison with traditional network analysis models. The tolerated inaccuracy of traditional models in areas of intermittent supply shall be demonstrated. In the following two traditional approaches to model the Judayta network are shown.

The first approach tries to simulate intermittent supply as far as possible with nodal demands. It models the different zones in separated hydraulic models (section 8.6.2). The demand of nodes depends on the operation of zones.

The second approach resembles the design of a continuous supply network. It is described in section 8.6.3. It consists of a one-zone model with a demand calculated directly out of the billed consumption. The operation of zones and the resulting change of demand are ignored.

8.6.1 Traditional Model Creation

The following parameters have to be adjusted in order to realize a traditional model with nodal demand:

- Junction demands.
- Supply duration.
- Roughness.
- Pressure zones.

Junction Demands The process is similar to the process described for the generation of the generalized household storage tanks.

Supply duration Judayta can be divided into three zones while elements of the network have to be shared by zones (e.g. pumping station). In this context the important elements are the nodes (junctions). The junction theme gets a new attribute "Duration" in the Database.

After selecting the nodes, which are supplied over the first 24 h, the “Duration” for the selected elements is set on 24. All the other records stay set to 0. With selecting the next supply zone a duration of further 24 h is added to the nodes, which are supplied over the first day already:

existing value + 24

Like this nodes are defined which are supplied over 48, 24 and 0 h. With doing the same for the third zone the duration of supply is defined for each node of the network.

Roughness The roughness is defined with 1.63 mm for each pipe of the network (according to the previous calibration of the intermittent supply model; section 8.5.3, table 9).

Model Separation For the traditional model of Judayta described in section 8.6.2 the three zones shown in figure 49 have to be analyzed separately. Therefore the zones are cut out of the complete Judayta village data and presented as compact zones, which are supplied over different durations. The zones share elements for example the nodes and pipes between the pumping station and the western part of the village.

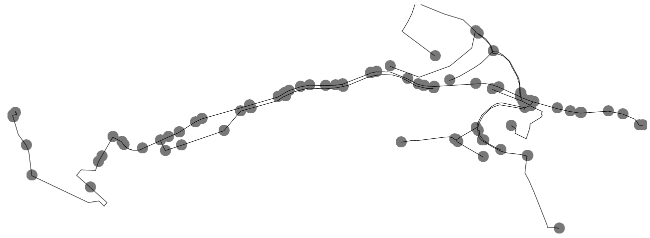
The EPANET models are shown in figure 49.

8.6.2 Modeling Continuous Supply over Separated Zones

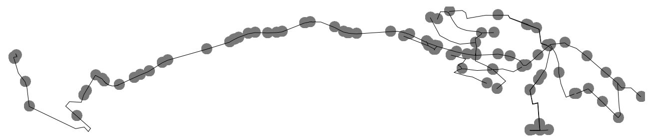
As mentioned above this model is used to model existing networks in intermittent supply areas usually.

In the following the calculation of nodal demand is described. Afterwards some examples of the computed model shall be shown with some figures.

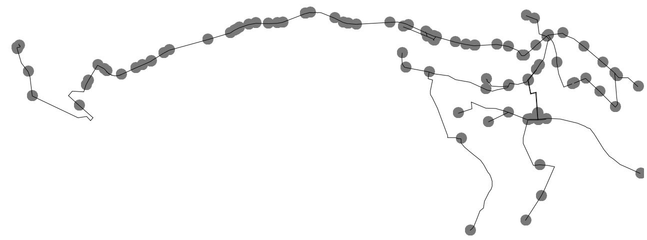
Junction Demands The demand is implemented into the junction theme by recalculating the tank volume. Besides the demand has to be converted into $\frac{l}{s}$. A time simulation of continuous supply can be created on the basis of this demand



(a) Fist Zone



(b) Second Zone



(c) Third Zone

Figure 49: Traditional Model Zones

over $58\frac{h}{w}$. This duration is chosen for getting the opportunity of comparing results of the traditional model with the approach of modeling intermittent supply.

$$mQ_s = \frac{Q_{3m}/14}{h_s/h_{t,s}} \cdot \frac{1}{58\frac{h}{w} \cdot 3600\frac{s}{h}} \cdot 1000 \cdot m_S \cdot m_L$$

with

mQ_S= Average demand in $\frac{l}{s}$

Q_{3m}= Consumption according to COBOSS during 3 month of the year in $\frac{m^3}{3month}$with 14 $\frac{w}{3month}$

h_S= Time of supply according to operation of zones in h (24 h, 10 h)

$h_{t,s}$= Total time of supply interval (58 h)

m_L= Multiplier for considering Losses, estimated with 40%

m_S= Peak factor

The peak factor is estimated as 1.4 [5]. The multiplier for considering losses is justified by measurements of back flow at the pumping station. UFW are estimated with 40% (section 5.1).

Results A calibration of the model is difficult because of its condition. The demand is not changing over the day because of house tanks in the distribution network. Therefore the system is static.

Figure 50 represents one of the best results of this model with a pressure of 7.4 bar. The computed pressure is close to an average value of the measurements. During the first supply interval the computed values of the other locations are of similar quality.

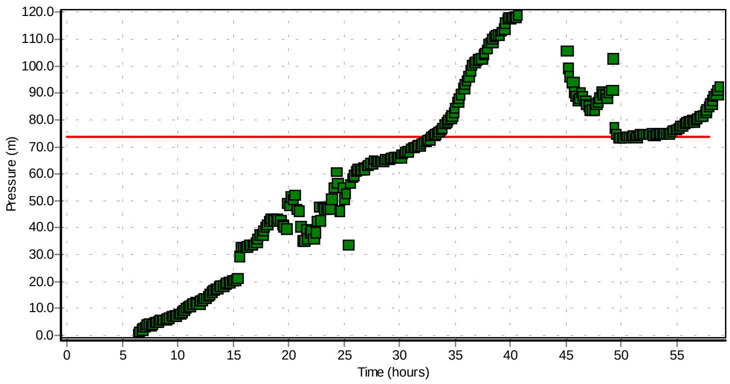


Figure 50: Pressure at M5

Especially during the supply of the third zone an extreme sub-pressure can be noticed at several locations (an example is given with figure 51). Warnings because of negative pressures are given by EPANET especially for this zone. In cases like this the pump size or parameters for increasing the power are changed usually. For reaching better results the pump speed has to be increased with 50%.

This essentially means that the respective models are broken.

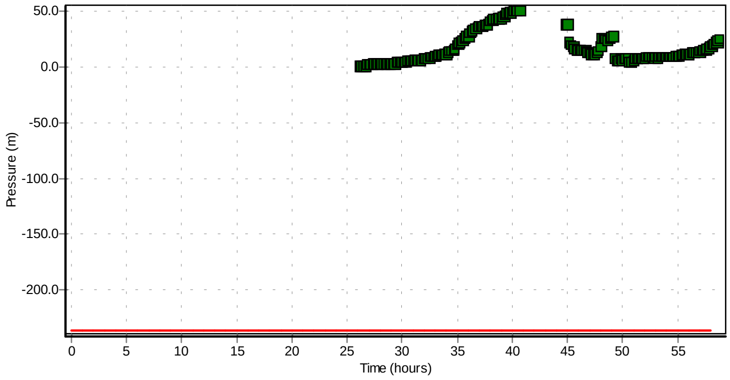


Figure 51: Pressure at M8

8.6.3 Continuous Supply as Designed

This model consists of one zone as mentioned above. The demand is calculated directly out of the billed consumption without differentiation of nodes, which are supplied 24 h, 48 h or 58 h in reality. Each node is getting the demand in dependence on the specific consumption.

Figure 52: Traditional Model of Node Demand

Junction Demand This approach is a simplification of the model described in section 8.6.2.

$$mQ_s = \frac{Q_{3m}}{14} \cdot \frac{1}{58\frac{h}{w} \cdot 3600\frac{s}{h}} \cdot 1000 \cdot m_L \cdot m_S$$

mQ_s= Average demand in $\frac{l}{s}$

Q_{3m}= Billed consumption during 3 month of the year in $\frac{m^3}{3month}$ with 14 $\frac{w}{3month}$

m_L= Multiplier for considering unaccounted-for water, estimated with 40%

m_S= Peak factor, estimated at 40%.

Results The results are similar to the results of the first traditional model, presented in section 8.6.2.

The flow at M5 shown in figure 53 lies far below the measured values.

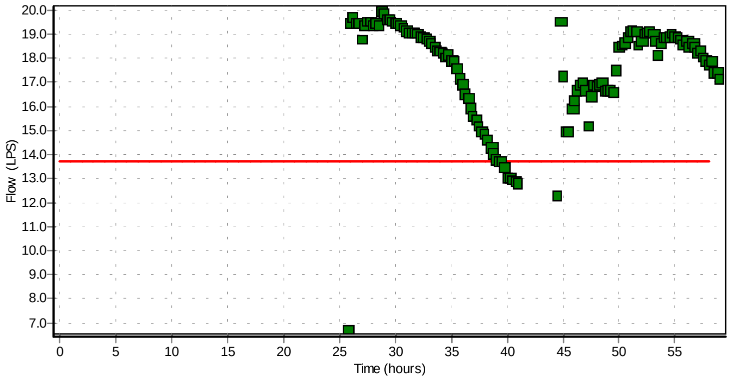


Figure 53: Flow at M5

Also the computed pressure is to high and does not reflect the measurements as shown in figure 54.

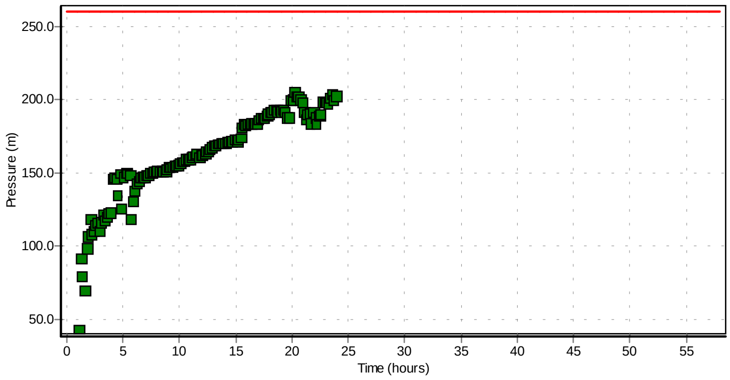


Figure 54: Flow at M2

8.6.4 Model Comparison

Both traditional models have been analyzed. These models do not reflect intermittent supply. The point is that in reality tanks are filled in dependence on the present pressure. The traditional model ignores this by modeling the consumption as a nodal demand, which is pressure independent. As shown in figure 51 this continuous demand cannot be satisfied sometimes.

With the presented model of intermittent supply each node is getting that quantity of water, which is offered at a specific time and location. The quantity of water, which is running into a tank, depends on the pressure at this location and the pressure is influenced mainly by filling tanks and quantity of leakage below.

In addition to this mistake of traditional models in intermittent supply areas, the development of pressure, demand and flow over the time cannot be represented. However the present approach can deliver these informations as shown in section 8.5.3. Advantages of the intermittent supply model are listed in the following:

- It is possible to show the filling level of house tanks over the time.
- The characteristic of intermittent supply to get water, if water is available, in reliance to the pressure is implemented.
- The complete village can be modeled in one system based on valve control rules for operating the zones automatically.
- The total mistake between computed model and measured values can be cross-checked by pressure and flow diagrams, which can be created for each location of the network (e.g. figure 47). A calibration of traditional models can be done over the total mistake only, because of linearity (see figure 50).
- UFW is implemented as leakage with spatial reference. The traditional models are implementing losses into demands.

9 Optimization of the Judayta Water Supply Network

by Steffen Macke

A lot of problems with the water supply network in Judayta village are obvious even without an hydraulic analysis. The extremely high pressure in the lower supply areas is likely to cause a lot of damage to the expensive water meters as well as leakage.

9.1 Background

To compare the current leakage rates in the Judayta network, the specific characteristic loss can be used. The specific characteristic loss relates the leakage to the supply time and length of the water network. Table 10 displays diameters and lengths of pipelines in the Judayta water network.

DN	Length in m
25	159
50	12959
100	1875
150	4339
200	16

Table 10: Pipelines Judayta

As the calculation of the specific characteristic loss does not take house connections into account the total length of water network amounts to 6.23 km. One supply period in Judayta lasts 58 hours in which 1658 cubic metres are unaccounted-for. Hence the specific characteristic loss is:

$$q_v = \frac{1658}{58 \cdot 6.23} = 4.58 \frac{m^3}{m \cdot km}$$

In the literature, the following specific characteristic loss is given as a high value for underground containing seams[8]:

$$q_v = 0.6 \frac{m^3}{km \cdot h}$$

$$q_v = 0.6 \frac{m^3}{km \cdot h}$$

However, with the yet unknown amount of illegal consumption it can only be estimated how much leakage participates in the unaccounted-for figure. The privatization of meter readings in the Al Koura district is likely to reduce illegal consumption and ensure more reliable figures.

It is very important to realize that most of the actions described hereafter only have a chance to succeed if the administrative actions succeed also. The administrative measures are a precondition for the technical ones.

Figure 55: Leakage

As there are many leaks visible in Judayta (figure 55 shows an example), a technical loss reduction program is likely to succeed. But the decision on technical actions like a leak detection campaign should be delayed until more reliable meter readings are available for both the customer side and Judayta pumping station.

9.2 Pumping Station

Technicians reported that the Judayta pumping station is “one of the best” throughout Irbid Governorate - in terms of leakage and operation. However the following practical improvements can be made with only little effort.

9.2.1 Bulk Water Meters

One of the most important actions to be taken is the installation of the necessary bulk water meters in Judayta pumping station. The current setup does not allow to record the consumption of the villages properly: The unmetered back flow into the well as well as additional overflow - which is also unmetered, make it impossible to calculate a reliable water balance (appendix H).

In addition, the current records rely on the operator at the pumping station: He has to record the supplied village together with the well production readings - a process that is very likely to produce unnecessary errors.

The introduction of separate meters for the two pumping directions should also be used to move the valves that operate the pipelines into the pumping station: Currently they are located right in front of it. It should be evaluated whether it is more practical to move the fence or to move the valves.

Only those new bulk meters will allow an accurate assessment of tank overflow and back flow to the well.

Alternatives Water meters capable of operation under a pressure of 40 bar are expensive, the water meters should therefore be installed between storage tank and pumps. However this will still allow the operator to pump with the same set of pumps into different directions.

Alternatively, the meters could be installed on a higher location in the network - such a setup is not recommended as it would not allow to meter water losses on the way from the pumping station to the meter location. Also a water meter located within the pumping station grounds is more secure than other locations. An incident during the logging campaign illustrates this: A logger was set on fire.

9.2.2 Storage Capacity

Currently the back flow from the tank to the well decreases the well pumping efficiency by up to 11% (section 5.1). The main problem is that the overflow takes place in a way that is hardly noticeable by the operator: The noise of the pumps does not allow to hear the water overflowing.

An automated pump control is not likely to succeed, as it would require proper maintenance, which can not be guaranteed under the current circumstances.

The following actions could be used overcome the problem:

- Installation of an additional steel tank to increase the storage capacity. Overflow situations will be less likely with it.
- Installation of an overflow activated horn on the well.
- Motivation of the operator to takes measures against the overflow.

The operator motivation is the crucial part: Currently it is not possible to use bonus salaries to motivate the personnel.

As the horn is much cheaper than the tank it should be installed first to avoid a costly bad investment with the tank: With horn the operator has a chance to minimize the overflow. The additional water meters will allow the supervision of the operator.

9.3 Rehabilitation of the Existing Reservoir

The existing (but currently unused) reservoir with a capacity of 200 cubic metres that was discovered during the altimeter survey makes it possible to change the

Figure 56: Existing Reservoir

mode of operation from intermittent to a continuous supply of water. Figure 56 shows a photo of the reservoir.

Again, such an action is only likely to succeed if administrative actions take place before: The intermittent supply is currently used as a rationing system that prevents excessive illegal consumption by only providing water one or two days a week. Continuous supply would allow the illegal consumers to waste more water.

Under the assumption that the privatization of the meter readings succeeds and reduces the illegal consumption, the intermittent supply rationing could be abandoned.

The capacity of the reservoir is big enough to provide the average demand for 9 hours. This should be sufficient as the household storage tanks will not be abandoned immediately and hence the demand curve will be relatively flat.

9.4 Establishment of a Booster Station

The existing Reservoir is not able supply the whole village because it does not supply sufficient pressure. By establishing a booster station next to the reservoir this problem could be solved.

In case the empty parcel next to the reservoir is not available for the booster station, the installation of pumps on top of the reservoir can be evaluated as well as submersible pumps in the reservoir.

The booster station will also allow to serve additional customers in the north-eastern part of the village which can not be supplied currently - the pipelines are already in place in this area.

According to table 8, the average consumption of Judayta village was 2865 cubic metres per week in the 2000 reading cycle. Assuming 30% UFW for the future (section 9.7), this yields a total demand of 6.16 litres per second for continuous supply. A simple network model based on reservoir supply and the demand has been created.

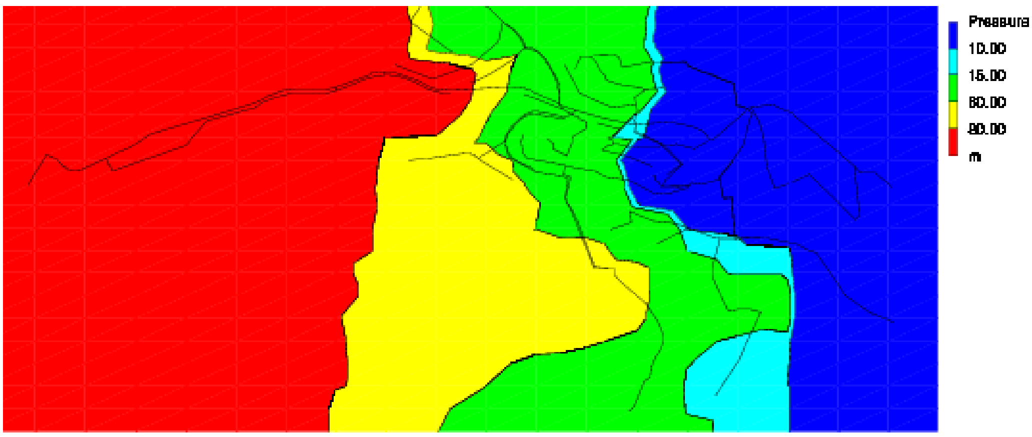


Figure 57: Reservoir Supply Pressures

Figure 57 shows a map containing the network pressures distribution obtained from the network simulation model. The areas of pressures below 15 m in the west of the village need to be supplied by the booster.

9.5 Pressure Reduction

The re-use of the existing reservoir will reduce the pressure in the network. For example, the peak pressure at the eastern village boundary - the most problematic area - will drop from above 30 bar to approximately 20 bar. As the pressure influences leakage over-proportional (equation 2, section 7.3) the pressure reduction will reduce the amount leakage accordingly.

The decision whether to use a pressure reduction valve (PRV) or not is a difficult one. One the one hand, the huge elevation differences in the Judayta network require different pressure zones, on the other hand, such valves are expensive and need appropriate maintenance in order to function properly.

Orifice plates should be evaluated as alternatives to pressure reduction valves - their advantage is that they are inexpensive. However they are not able to reduce static network pressures and may therefore not be well suited for Judayta's lower supply zones.

Though pressure reduction valves or orifice plates may help to reduce the critical network pressures further, the decision whether to use them or not should only be taken after intensive evaluation together with the personnel in charge - it is inevitable that they support the ideas and have the knowledge maintain the installations.

9.6 Cost Rating

The cost rating is based on a cost estimate in [5]. The unit rates are based on recently completed contracts in Irbid governorate.

Only one pump is considered, as it is still possible to pump directly into the network in case of a booster pump failure.

9.7 Cost Benefit Analysis

Some of the benefits from the described actions can not be expressed in monetary terms - for example the continuous supply of water, the possibility to serve

Measure	Quantity	Unit rate in JOD	Amount in JOD
Reservoir rehabilitation	LS	-	3000
Additional steel tank	1	3000	3000
Water meter at pumping station	1	1500	1500
Water meter at reservoir	1	1500	1500
Overflow horn	LS	-	500
Network reconnections	LS	-	5000
Pipeline DN 100	1500 m	15	22500
Pumps Q=10m^3/h, H=90m	1	4000	4000
Total			**41500**

Table 11: Cost Rating

additional customers or the ability to obtain reliable flow measurements.

Similar pressure reduction measures in another village of the Al Koura district - namely the Al Taibeh System - are expected to yield a reduction of the unaccounted-for water figures from 50% to 30%[5]. Assuming the same increase in efficiency for Judayta, it would be possible to increase the revenue from water by 20%.

The average revenue for water in rural areas is 0.140 JOD per cubic metre[5]. The estimated surplus revenue is:

$$0.140\frac{JOD}{m^3}\cdot 0.20\cdot 149000\frac{m^3}{a} = 4170\frac{JOD}{a}$$

This indicates a pay back period of 10 years. For the example in [5] the pay back period was less than two years - due to a reduction in pumping costs. For the proposed actions the pumping costs will also decrease slightly due to the reduced back flow to the well - this is not yet considered.

As Judayta pumping station also supplies other villages, it is likely that the cost benefit analysis will improve if similar actions are taken for the remaining villages.

10 Acknowledgments

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A DC Water Design Extension Manual

by Steffen Macke

This Manual describes the DC Water Design Extension Version 2.00.

This Document uses Terminology from ArcView and EPANET. Please refer to the respective documentation for in-depth explanations.

A.1 What is the DC Water Design Extension?

The DC Water Design Extension is an Extension to ESRI's ArcView GIS software. Version 2.00 integrates the EPANET 2.00 hydraulic modeling software with ArcView. It allows to store, edit and retrieve EPANET hydraulic models including all options in ArcView. Also it is possible to run the EPANET hydraulic analysis from ArcView and load the results into the GIS. Loading of EPANET models to ArcView is not yet implemented.

A.1.1 Concepts

Network Traces Network Traces are be useful to solve problems related to the network geometry. It is possible for example to check the connectivity of the network features in a model. Through specifying network features at which the trace should stop, it is possible to isolate supply zones.

Bit codes Bit codes are stored as integer numbers in GIS data. They provide a powerful method to store hydraulic models in GIS data. The underlying principle is very simple:

- The models are numbered
- Each bit represents one supply zone

- If the bit is set (1) than the network feature is used in the respective model. Otherwise (0), the feature is not used in the model.
- The different values are assembled by arithmetic addition.

The bit numbering starts with 0. A temporary field should be used in order to correctly perform the addition of two bit codes.

Virtual Lines Virtual Lines provide a concept to convert GIS point data (pumps or valves) into the lines used by the hydraulic analysis software. The conversion is done automatically when the GIS data is exported to the hydraulic model. Virtual Lines require exactly two pipes connected to each pump or valve. In addition, the two pipes must have the same digitizing direction (which will be the flow direction in the hydraulic model).

A.2 Installation

A.2.1 How to obtain the DC Water Design Extension

For DORSCH Consult staff, the DC Water Design Extension is available from the DC GIS Database (Lotus Notes).

All others can obtain the DC Water Design Extension including documentation and source code from the DC Water Design Extension homepage:

http://dcwaterdesign.sourceforge.net

To ease the installation process, the installer executable (setup program) is usually the best choice.

A.2.2 Requirements

- ArcView 3.0 or higher
- Windows 95, 98, ME, NT or 2000 in order to export EPANET files

- EPANET 2.0 or higher is needed in order to run a hydraulic analysis
- An (ANSI SQL compliant) ODBC connection is needed in order to import hydraulic analysis results

A.2.3 Setup

In order to install the DC Water Design Extension, one has to run the installer executable. After accepting the license (section A.5), the installer prompts the user to select the installation path. The installation path should be the path to ArcView's EXT32 folder. Usually this should be the default path (c:\ESRI\av_gis30\arcview\EXT32). It might differ for custom ArcView installations. Than it has to be chosen which components of the extension should be installed. In general, one should install all the components of the extension.

If it is intended to use e.g. a newer version of the XSLT parser and the new version is already installed, the user might choose not to install the XSLT parser that comes with the extension. However, this option should be left to the advanced user.

A.3 Usage

A.3.1 General Usage

Extension loading

1. Start ArcView
2. Open the Extensions Dialog (File->Extensions ...)
3. Select the DC Water Design Extension (Put a checkmark in the box on the left side).
4. After the Extension is loaded, the Setup Dialog provides information about several settings. The settings should not be changed without profound knowledge of their functionality.

A.3.2 Quick Start Guide

1. Load the Extension
2. Open a View
3. Add Themes to the View. The themes should describe the water supply network. Junctions, pipes and reservoirs would comprise a simple network. The attributes of the themes must adhere to the ArcView/EPANET Data Model (appendices B,C). ArcView field aliases can be used to map the fields correctly.
4. Click on the EPANET Themes button. Select the appropriate Themes.
5. Choose “Make EPANET Model” from the DC Water Design menu
6. If the last step does not yield any errors, an EPANET input file can be created now. Choose “Write EPANET File” from the DC Water Design menu. Choose filename and location.
7. Fire up EPANET and open the created file (*.inp).

A.3.3 Project GUI

The DC Water Design Extension extends the Project GUI by adding a new Menu, called DC Water Design Extension. The Menu contains the following choices:

Setup Shows the Setup Dialog.

The Setup Dialog includes an option to choose the language of the Extension. Currently supported are the following localizations:

- English
- German

Note that the Localization is not completed yet. It is therefore recommended that the language is set to English.

EPANET Tables Displays the EPANET Tables Dialog.

The Tables in the dialog are used to to store non-spatial EPANET data with ArcView. Typical examples of such data are pump curves or hydraulic analysis options. Before it is possible to use a table with the DC Water Design Extension, it has to be loaded into ArcView. Refer to the ArcView documentation for information on how to load tables into ArcView.

Result Tables Opens the Result Tables Dialog.

The Result Tables are used to store the results of a hydraulic analysis. There are two tables, one for node results and one for link results. For performance reasons it is recommended to use a RDBMS such as mySQL for storing the data. As of version 2.00, the DC Water Design Extension has only been tested with mySQL result tables.

About DC Water Design Extension Displays information about the DC Water Design Extension License. SectionA.5 contains details on the license.

A.3.4 View GUI

The DC Water Design Extension extends the ArcView View GUI with the following elements:

- A new Menu called “DC Water Design”
- Buttons
- Tools
- Three pop-up menus

The pop-up menus are available through clicking the right mouse button over a network feature.

The additional functionality is explained below.

Write EPANET file Exports the hydraulic model to an EPANET input file.

The model has to be complete, running “Make EPANET Model” and “Check EPANET Model” is advisable especially for the novice user before exporting the EPANET input file.

The resulting EPANET input file has the extension *.inp. The *.xml-file is just an intermediate format (temporary file).

Run EPANET Calculation Exports the hydraulic model to an EPANET input file, runs the analysis and loads the results into ArcView.

The model has to be complete, running “Make EPANET Model” and “Check EPANET Model” is advisable especially for the novice user before exporting the EPANET input file.

After the analysis has been completed, the report created by EPANET is displayed in a window and the user is prompted to select a time step for which the results will be loaded.

Load Results for step ... Loads the results of an EPANET hydraulic analysis to ArcView.

The hydraulic analysis has to be run from ArcView in order to to enable this feature. The user is prompted to select the time step for which the results should be loaded.

Make EPANET Model Creates the line-node structure required by EPANET.

This function fills the fields node1 and node2 in the links table with the dc_ids of the connected nodes. The fields will be overwritten by this function, therefore the user has to confirm the action before the script run.

After completion, a report gives an overview of the created model. Model creation errors are also reported. In case of such errors, the features in question are selected after the run.

If there are reports about inconsistent flow direction at pumps or valves, the “Flip Polylines” tool of the extension can be used to correct the errors.

EPANET Themes Opens the EPANET themes dialog.

The themes dialog is used to select the themes used in the hydraulic model. The line and node theme are required, other themes are optional and can be switched off with the check boxes on the right side.

Most of the extension functions require that the EPANET themes are properly set up in this dialog. Setting up the themes should be the first step when using the extension. The settings of the EPANET themes dialog are also used to determine which themes should be edited.

EPANET Tables Displays the EPANET tables dialog.

The tables in the dialog are used to to store non-spatial EPANET data with ArcView. Typical examples of such data are pump curves or hydraulic analysis options. Before it is possible to use a table with the DC Water Design Extension, it has to be loaded into ArcView. The ArcView documentation contains information on how to load tables.

Valve Control Allows to set valve states according to EPANET Controls.

If a controls table is registered with the Extension (see EPANET Tables Dialog), the user is offered to select the controls he would like to apply. All chosen controls are applied: The status of the respective valves is set to “open” or “closed” depending on the controls. This is very useful in combination with Network Traces as the extension allows to stop traces at closed valves.

Make House Connections Creates a straight pipe between tanks and junctions which share an id.

This function requires some preparatory work: Each tank of the tanks theme needs to know to which junction it should be connected. This is expressed with a field in the tanks attribute table that contains the dc_id of the junction the tank should connect to. Such fields can be established e.g. by using the spatial join function of the ArcView Geoprocessing Wizard.

Note that this functionality has been included mainly for the purpose of modeling intermittent supply with household storage tanks. It might be taken out or in future versions of the DC Water Design Extension. In fact, the best solution will be to create another extension specialized on intermittent supply modeling that depends on the DC Water Design Extension.

Create Supply Strings Calculates a coded text that shows when a node is supplied with water.

This might only be used after successfully running an EPANET hydraulic analysis from ArcView. The function will query the the nodes results table for pressures above zero. Each pressure above zero will yield a “1” in the supply string, a pressure below or equal zero will yield a “0” in the supply string. For each node, the supply strings are written to a user-selectable text field. The field has to been long enough to contain as many characters as there are time steps in the EPANET results.

Note that this functionality has been included mainly for the purpose of modeling intermittent supply with household storage tanks. It might be taken out in future versions of the DC Water Design Extension. The ideal solution will be to create another extension specialized on intermittent supply modeling that depends on the DC Water Design Extension.

Calculate Pipe Length For Junctions This function calculates the length of the pipes connected to a junction.

A user selectable number field in the junctions attribute table is filled with the length of the pipes connected to each junction. In order not to double the overall pipe length, each pipe length is divided by two. Thus every part of a pipe is assigned to the nearest node.

Clip Themes by Bitcode Creates new themes with features which have the same bit set in a bit code.

The functions works with all active themes in the view. First, the user is prompted to select the bit which has to be set for the clipped themes. Then the field containing the bit code has to be chosen. (The script assumes that the bit code field names are the same throughout all the active themes.) The user can select the filename and location for each clipped theme. He can also choose whether the new themes should be added to the view.

Bit codes make it possible to use the same network features in different supply zones. This requires extraction of the features into separate themes. See section A.1.1 for details on bit codes.

About DC Water Design Extension Displays information about the DC Water Design Extension License. See sectionA.5 for the license details.

Flip Polylines This tool allows to flip the digitizing direction of lines.

The theme containing the lines to be flipped has to be set up as the pipe theme in the EPANET themes dialog. Simple clicking on the line will switch the digitizing direction.

Tip: ArcView's symbology can be used to display the digitizing direction with arrowheads.

Move Nodes A tool to move network nodes including rubber-banding.

With this tool it is possible to move network nodes (junctions, tanks, reservoirs, pumps, valves) along with the connected pipes. The network stays intact and fully connected (rubber-banding).

The respective themes have to be registered with the extension in the EPANET themes dialog.

Split Pipe (Add Junction) A tool that allows to split a pipe into two pipes. Adds a new junction at the split point.

The two new pipes inherit the attributes from the original pipe. However, the length gets recalculated based on the shapes.

Pipe and junction themes have to be chosen in the EPANET themes dialog.

Edit Pipe Vertices Allows to re-shape pipes.

Vertices determine the route of a pipe. The tool makes it possible to move all the vertices of a pipe. Additional, it is possible to add vertices to the pipe. Unlike the ArcView tool “Vertex Edit”, “Edit Pipe Vertices” ensures network connectivity - it is impossible to disconnect a pipe from a node with this tool.

The pipe theme has to be set up in the EPANET themes dialog in order to use this tool.

Note that the pipe length is not recalculated. The pipe length has to be calculated manually in the pipe theme attribute table. The Questions and Answers section of this manual contains an entry that deals with calculating the pipe length.

Change Node Class A tool to convert nodes from one class to another.

The Change Node Class tool allows to convert e.g. a junction into pump. Attributes shared between the two classes are copied. After selecting an existing node, the user is prompted to select the class to which the node should be moved. The old node is deleted in order to prevent node duplication that would corrupt the hydraulic model.

Obviously, the respective themes have to be registered with the extension in the EPANET themes dialog.

Delete Feature A tool to delete network features.

Allows one-click deletion of network features. The user is prompted to confirm the deletion. It is important to know that there’s no undo support with the DC Water Design Extension.

The themes containing features that should be deleted have to be selected in the EPANET Themes dialog.

Digitize Junction The Digitize Junction tool is used to digitize junctions.

The junctions are added to the junction theme selected in the EPANET themes dialog.

Digitize Pipe The Digitize Pipe tool is used to digitize pipes.

The pipes are added to the pipe theme selected in the EPANET themes dialog. In order to maintain the network integrity, the tool automatically adds junctions at the pipe end if the pipe end does not snap onto an existing node.

Digitize Tank The Digitize Tank tool is used to digitize tanks.

The tanks are added to the tank theme selected in the EPANET themes dialog.

Digitize Valve The Digitize Valve tool is used to digitize valves.

The valves are added to the valve theme selected in the EPANET themes dialog. The tool is disabled if the valve theme is not enabled in the EPANET themes dialog.

Digitize Reservoir The Digitize Reservoir tool is used to digitize reservoirs.

The reservoirs are added to the reservoir theme selected in the EPANET themes dialog. The tool is disabled if the reservoir theme is not enabled in the EPANET themes dialog.

Digitize Pump The Digitize Pump tool is used to digitize pumps.

The pumps are added to the pump theme selected in the EPANET themes dialog. The tool is disabled if the pump theme is not enabled in the EPANET themes dialog.

Show Pipe Table Entry Pop-up menu item that allows to show the attributes of a pipe.

Right-clicking on a pipe and selecting this menu item opens the pipe attribute table, selects and promotes the pipe.

The appropriate pipe theme has to be selected in the EPANET themes dialog.

Edit Pipe Table Entry Pop-up menu item allowing to edit the attributes of a pipe.

Right-clicking on a pipe and selecting this menu item opens the pipe attribute table, makes it editable, selects and promotes the pipe record. After that, the attributes of the pipe can be edited. The DC Water Design Extension currently provides no undo functionality.

Select Connected Pipes Pop-up menu item that allows to trace the pipes connected to the selected pipe.

Right-clicking on a pipe and selecting this menu item opens a dialog that offers node types at which the trace should stop. Multiple types can be selected. During the trace, the status bar informs what percentage of the network has been covered by the trace so far. The progress bar will not make it to 100% unless the network is fully connected and no stopping features have been selected. The connected pipes up to all stop points are returned as the selection.

Show Node Table Entry Pop-up menu item that shows the attributes of a node.

Right-clicking on a node and selecting this menu item opens the node attribute table, selects and promotes the pipe.

The appropriate node theme has to be selected in the EPANET themes dialog.

Edit Node Table Entry Pop-up menu item that allows to edit the attributes of a node.

Right-clicking on a node and selecting this menu item opens the node attribute table, makes it editable, selects and promotes the node record. After that the attributes of the node can be edited. Important notice: Undo is not supported by the extension.

Select Node Selects the current node.

Adds the current node to the selection in the node theme.

The appropriate node themes has to be selected in the EPANET themes dialog.

A.3.5 Table GUI

Bitcode Calculator The Bitcode Calculator is accessible from the button bar of the table GUI. It is disabled unless the table is editable and a numerical field is selected.

- Upon clicking on the Bitcode Calculator button, the user is prompted to select the bits he wants to set.
- After choosing OK, the bit code will be calculated and written to all the selected records.
- If no records are selected the bit code is written to all the records in the table.

The field used to store the bit codes should have no decimal places.

Bitcodes are a concept that allows to transparently share network features in multiple supply zones. Section A.1.1 contains more information on bit codes.

A.3.6 API Documentation

This section documents extension scripts that could be used from the field calculator or in queries. In Addition, the script responsible for the localization (extension dictionaries) is documented. In general, the API (Application Programming Interface) documentation should only be of concern for programmers.

DCWatDes.Bitcode.or performs a bitwise or operation on integer numbers

integer DCWatDes.Bitcode.or(integer a, integer b)

a bit-coded integer

b bit-coded integer

Returns: the result of the bitwise a or b as an integer

The following AVENUE code can be used in the field calculator to perform of a bitwise or-operation on the fields a and b:

```
av.run("DCWatDes.Bitcode.or", {[a], [b]})
```

DCWatDes.Bitcode.and performs a bitwise and operation on integer numbers

integer DCWatDes.Bitcode.and(integer a, integer b)

a bit-coded integer

b bit-coded integer

Returns: the result of the bitwise a and b as an integer

The following AVENUE code can be used in the field calculator to perform of a bitwise and-operation on the fields a and b:

```
av.run("DCWatDes.Bitcode.and", {[a], [b]})
```

DCWatDes.Bitcode.isSetAsNumber return whether the n-th bit of an integer is set or not

integer DCWatDes.Bitcode.isSetAsNumber(integer a, integer n)

a bit-coded integer

n number of the bit to check

Returns: an integer of value 1 in case the n-th bit is set, 0 otherwise

The following AVENUE query can be used to select all the records which have set the 4th bit in the example field (usable with the query tools of view and table GUI):

```
av.run("DCWatDes.Bitcode.isSetAsNumber",{[example], 3}) = 1
```

Note that the bit numbering starts at 0. “= 1” is used to convert the numbers 0 and 1 to the boolean values to true or false, respective.

DCWatDes.i18n.createDictionaries Creates the localization dictionaries of the extension.

In order to add another dictionary, the new dictionary has to be created first:

dicNew = `Dictionary.make(100)`

Next, dictionary entries can be added to the new dictionary:

```
dicNew.add("English Term", "New translated term")
```

The German dictionary contains most of the terms that have to be translated. After all the terms have been added to the new dictionary, the Dictionary has to be added to the Dictionary of Dictionaries:

```
_dcwDicDictionaries.add("tr", dicNew)
```

Where “tr” is the text that shows up in the setup dialog of the extension.

A.4 Questions and Answers

Why is there no graphical user interface to the DCWatDes.Bitcode.* functions? The provided AVENUE functions are more flexible this way. Bit codes can be useful for quite a number of operations. Try using the functions with the field calculator and the query. Examples are given in A.3.6.

What is the Setup Dialog for? The Extension depends on several software packages. The Setup Dialog allows to choose other versions of these software packages than the ones supplied with the Extension itself.

Why is Version 2.00 not working with Pipe 2000 anymore? The Pipe 2000 data model, API and documentation are inferior to EPANET. Full integration of Pipe 2000 into ArcView was impossible. With EPANET it is possible to store the complete model, including all hydraulic analysis options in the GIS.

How do I recalculate the pipe length for all the pipes?

1. Open the attribute table of the pipe theme.
2. Make sure that the pipe theme is editable.
3. Make sure that no records are selected.
4. Click on the heading for the length field.
5. Click on the field calculator button.
6. Enter the following line into the value field:
   `[Shape].returnLength`
7. Click OK.

I get strange errors when I try to create the EPANET model. What can I do? Try the following:

- Try "Check EPANET model". This helpful to resolve duplicate IDs.
- Have a close look at the erroneous features: Often accidentally duplicates features cause trouble.

I made a mistake. Why is undo not working? Undo support had to be taken out for the sake of editing multiple themes at the same time. Make frequent backups. You have been warned.

I found a bug in the Extension. What should I do? Please send your bug reports to Steffen_Macke@dorsch.com.jo

A.5 Copyright

Appendix D contains a copy of the GNU Lesser General Public License.

B ArcView/EPANET Data Model

This document describes version 2.00 of the ArcView/EPANET Data Model. Note that the units will change if EPANET is not set to use litres per second (LPS) as units. Refer to the EPANET documentation (especially the toolkit help) for further information.

B.1 Identity

Inherited by Feature
Inherited by Pattern
Inherited by Curve

- dc_ID: *string* Unique ID throughout the whole database. Should not contains spaces.

B.2 Node

Inherits from Feature
Inherited by Junction
Inherited by Tank
Inherited by Reservoir
Inherited by VirtualLine

- Shape: *Point* Spatial data.
- Elevation: *float* Elevation above Sea Level in m.
- result_demand: *float* EPANET analysis result: Demand in litres per second.
- result_head: *float* EPANET analysis result: Total Head in m.
- result_pressure: *float* EPANET analysis result: Pressure in m.

- ElevationSource: *CodedValue* Integer field containing a coded value that describes the origin of the elevation information for this node. The following values have been used in the Al Koura project:
  - 0: Unknown Source
  - 1: 100 m Contours DEM
  - 2: SOGREAH Procedure models
  - 3: Altimeter Survey
  - 4: Paper maps
  - 5: estimated
  - 6: 25 m Contours DEM

B.3 Junction

Inherits from Node

- Demand: *float* Base demand flow in litres per second.
- Pattern: *string* Demand Pattern ID. If no demand pattern is supplied then the junction follows the Default Demand Pattern provided in the Options Table, or Pattern 1 if no Default Pattern is specified. If none of the patterns exist, the demand will remain constant.

B.4 Tank

Inherits from Node

- Initiallevel: *float* Initial water level above the tank bottom level (the elevation field) in m.
- Minimumlevel: *float* Minimum water level above the tank bottom level in m.

- Maximumlevel: *float* Maximum water level above the tank bottom level in m.
- Diameter: *float* Nominal Diameter of the tank in m. If a volume curve is supplied this can be any non-zero number.
- Minimumvolume: *float* The minimum volume of the tank in cubic metres. Can be zero.
- Volumecurve: *string* The id of the volumecurve - for non-cylindrical tanks.

B.5 Pump

Inherits from VirtualLine

- Properties: *string* EPANET properties of the pump. Keyword(s) followed by value(s). Keywords consist of:
  - POWER pump power in kW
  - HEAD id of the head curve describing this pump
  - SPEED relative speed of the pump: 1.0 is normal, 0 means that the pump is off.
  - PATTERN id of the time pattern describing pump operation.

- power_kw: *integer* The power of the pump in kW.

B.6 Valve

Inherits from VirtualLine

- Diameter: *integer* Diameter of the valve in mm.
- Type: *string* Type of the valve. The following EPANET valve types are valid:

  - PRV pressure reducing valve
  - PSV pressure sustaining valve
  - PBV pressure breaker valve
  - FCV flow control valve
  - TCV throttle control valve
  - GPV general purpose valve

  Additional valve types supported by the DC Water Design Extension:

- CV check valve
  - SOV shutoff valve

EPANET models these as pipes. The extension will create them on the fly.

- Setting: *string* Valve type dependent setting. The setting field takes the following values for the different valve types:
  - PRV the pressure in m
  - PSV the pressure in m
  - PBV the pressure in m
  - FCV the flow in litres per second
  - TCV the loss coefficient
  - GPV the id of the head loss curve
  - CV the setting value will be mapped to the status field of the pipe
  - SOV the setting value will be mapped to the status field of the pipe

- Minorloss: *float* Minor loss coefficient of the valve.

B.7 Pipe

Inherits from Feature

- Shape: *Polyline* Spatial data.
- node1: *string* Start node dc_id.
- node2: *string* End node dc_id.
- length: *float* The length of the pipe in m.
- diameter: *integer* Nominal pipe diameter in mm.
- roughness: *float* Pipe roughness coefficient in mm.
- minorloss: *float* Minor loss coefficient.
- status: *string* Status of the pipe. The following values are valid:
  - OPEN
  - CLOSED
  - CV (check valve)
- Material: *CodedValue* Integer field containing a coded value describing the material of the pipe. The following values have been used in the Al Koura project:
  - 0: steel
  - 1: galvanized iron
  - 2: PVC
  - 3: PE
  - 4: Ductile Cast Iron
  - 9: unknown
- result_flow: *float* EPANET analysis result: The flow in litres per second.

- result_velocity: *float* EPANET analysis result: Flow velocity in metres per second.
- result_headloss: *float* Headloss over the pipe in m.

B.8 Reservoir

Inherits from Node

- Head: *float* The hydraulic head of the reservoir. Elevation + pressure head.
- Pattern: *string* Optional head pattern id.

B.9 Feature

Inherited by Node

Inherited by Pipe

Inherits from Identity

- Installation_date: *date* The date of installation. If this is a date in the future, the feature is planned.
- Abandon_date: *date* The date when the feature was abandoned.
- dcSubtype: *CodedValue* Integer field containing coded values describing the feature. Different Domains are applied to the Feature classes.
- BitcodeZone: *integer* Integer containing a bit-coded that describes the zones in which the Feature is used. The following bitcodes were used in the Al Koura project:
  - Bit 0: Judayta village

B.10 Pattern

Inherits from Identity

- multiplier: *float* The multiplier that describes how to adjust the base quantity.

B.11 Options

- Units: *string* LPS (litres per second) should be used. See the EPANET documentation for other flow units. Using other flow units will render the units specified in this document invalid.
- Headloss: *string* Headloss equation. D-W (Darcy-Weissbach) should be used.
- Hydraulics: *string* Allows to specify a filename for the hydraulic solution. Leave empty.
- Viscosity: *float* The kinematic viscosity of the fluid being modeled relative to that of water at 20°C. The default value is 1.0.
- Diffusity: *float* The molecular diffusity of the chemical being analyzed relative to that of chlorine in water. The default value is 1.0.
- Specificgravity: *float* The ratio of the density of the fluid being modeled to that of water at 4°C.
- Trials: *integer* The maximum number of trials used to solve the network hydraulics for each time step. The default is 40.
- Accuracy: *float* Convergence criterion that describes when a hydraulic solution is found. The default is 0.001.
- Unbalanced: *string* Determines what happens if no hydraulic solution can be found within the prescribed number of time steps. The following values are valid:

  - STOP
  - CONTINUE
  - CONTINUE n

  The default is STOP

- pattern: *string* The default demand pattern id that is applied to all junctions that do not have a pattern specified. If this is empty, the default `"1"` is used.
- Demandmultiplier: *float* Global Demand multiplier. Applied to all base demands of junctions. The default value is 1.0.
- emitterexponent: *float* Specifies the power to which the pressure at a junction is raised when computing the flow issuing from an emitter. The default is 0.5.
- tolerance: *float* The difference in water quality level below which parcels of water are considered of equal value. The default is 0.01.
- map: *string* The name of a file containing junction coordinates.

B.12 Report

- Pagesize: *integer* The number of lines on one page of the output report. The default is 0 meaning that no limit of lines per page is in effect.
- File: *string* The name of the report file. Leave empty if the DC Water Design Extension is used.
- Status: *string* Determines whether hydraulic status messages should be written to the report file. The following values are valid:
  - YES
  - NO
  - FULL

The default is NO.

- Summary: *string* Determines whether a Summary is generated. The following values are valid:

  - YES
  - NO

  Default is YES.

- Messages: *string* Determines whether warning and error messages are written to the report. The following values are valid:

  - YES
  - NO

  The default is YES.

- Energy: *string* Determines whether energy and energy cost reports for pumps should be written to the report file. The following values are valid:

  - YES
  - NO

  The default is NO.

- Nodes: *string* Determines which nodes will be reported on. The following values are valid:

  - NONE
  - ALL
  - dc_id1 dc_id2 dc_id3 ...

  The default is NONE.

- Links: *string* Determines which links will be reported on. The following values are valid:

- NONE
- ALL
- dc_id1 dc_id2 dc_id3 ...

The default is NONE.

B.13 Times

Times can be specified in SECONDS(SEC), MINUTES (MIN), HOURS or DAYS. Just enter the unit name after the value. The default time unit is hours.

- Duration: *string* The duration of the simulation.
- Hydraulictimestep: *string* Determines how often a new hydraulic solution is computed. The default is 1 hours.
- Qualitytimestep: *string* Determines how often the water quality is computed. The default is 1/10 of the hydraulic time step.
- Ruletimestep: *string* Used with rule-based controls. Defaults to 1/10 of the hydraulic time step.
- Patterntimestep: *string* The interval between time periods in all time patterns. The default is 1 hour.
- Patternstart: *string* Describes when the pattern cycle will be started. Defaults to 0.
- Reporttimestep: *string* The interval in which results will be reported. The default is 1 hour.
- Reportstart: *string* Determines the time when reporting starts. The default is 0.
- Startclocktime: *string* The time of the day at which the simulation starts. The default is 12 AM (midnight).

- Statistic: *string* Determines the type of statistical post-processing. The following values are valid:
  - NONE
  - AVERAGED
  - MINIMUM
  - MAXIMUM
  - RANGE

B.14 VirtualLine

Inherited by Pump

Inherited by Valve

Inherits from Node

- result_flow: *float* EPANET analysis result: The flow in litres per second.
- result_velocity: *float* EPANET analysis result: Flow velocity in metres per second. result_headloss: *float* Headloss over the pipe in m.

B.15 Curve

Inherits from Identity

- dc_x: *float* X value.
- dc_y: *float* Y value.

C ArcView/EPANET UML Class Diagram

D GNU Lesser General Public License

Version 2.1, February 1999

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E UML Database Design Al Koura

F Digital Elevation Model Check

329.00	322	7
818.00	777	41
730.00	713	17
697.00	681	16
677.00	658	19
669.00	651	18
657.00	641	16
676.00	637	39
677.00	636	41
652.00	620	32
633.00	614	19
625.00	612	13
645.00	615	30
637.00	603	34
621.00	580	41
657.00	619	38
659.00	617	42
652.00	607	45
633.00	594	39
612.00	571	41
612.00	572	40
617.00	574	43
605.00	573	32
605.00	574	31
582.00	564	18
572.00	551	21
605.00	603	2
597.00	592	5
589.00	581	8

DEM Elevation in m aSL	Altimeter Elevation in m aSL	Difference in m
575.00	571	4
581.00	564	17
568.00	551	17
553.00	521	32
568.00	563	5
572.00	578	6
582.00	582	0
577.00	550	27
584.00	559	25
597.00	558	39
640.00	617	23
640.00	614	26
642.00	603	39
625.00	590	35
625.00	600	25
635.00	612	23
654.00	638	16
678.00	660	18
624.00	588	36
620.00	594	26
596.00	565	31
595.00	605	10
570.00	563	7
565.00	548	17
590.00	556	34
590.00	563	27
580.00	567	13
554.00	532	22
542.00	527	15
560.00	540	20
566.00	527	39

DEM Elevation in m aSL	Altimeter Elevation in m aSL	Difference in m
635.00	612	23
639.00	598	41
602.00	560	42
612.00	609	3
635.00	612	23
610.00	607	3
605.00	603	2
610.00	582	28
608.00	570	38
615.00	572	43
596.00	558	38
580.00	578	2
575.00	553	22
560.00	533	27
540.00	523	17
550.00	529	21
565.00	520	45
595.00	549	46
550.00	550	0
550.00	512	38
360.00	316	44
644.00	606	38
462.00	458	4
413.00	447	34
372.00	398	26
327.00	320	7
332.00	302	30

G Logging Results

H Judayta Pumping Station

I Al Koura Water Supply Network

J Judayta Spot Heights

K Judayta Logger Locations

L Hydraulic Analysis Model Judayta