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ADVANCED FIRE FLOW RISK ANALYSIS USING EPANET

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Abstract

A water reticulation system is key infrastructure that enables hydraulic water services. It is therefore a critical component in providing the full level of water service to a city's consumers. Extended water outages and below minimal pressure is a risk for the water network and especially for fire flows.

GLS has developed and implemented a multi-threaded client-server software application based on the latest open-source EPANET 2.2 hydraulic analysis engine which now enables city-wide fire flow risk analyses on a property-by-property basis in reasonable time.

Previously it has been virtually impossible to assess the risk on a city-wide basis, for each and every property, and to consider the improvement of such risk in the master plan (MP) of the water distribution system. Hence, the focus of the MP has been the provision of flows and pressures for the peak hour demand scenario in the network. Consequently, many township developments, densifications, and land use re-zonings require a separate and focussed specific fire risk analysis to ensure the existing system is capable of providing the requisite fire flow and pressure. If not, specific additional MP items related to the fire requirements of the specific property have to be investigated and considered for implementation.

The fire flow risk analysis produces a GIS-based heat map displaying a Fire Risk Compliance Score (FRCS) of areas and properties where the current system is inadequate to deliver the fire flows and pressures. Such a heat map provides valuable information that can be used to improve and prioritise the MP and minimise future additional ad-hoc analyses for specific properties or developments.

The fire flow risk analysis also allows the identification of pressure management zones where adjustments to the pressure regime are required in order to ensure requisite fire flows/pressures are achieved.

Various methodologies based on Pressure Driven Analysis and Demand Driven Analysis have been evaluated and tested on models from South African cities. Great care has been take to optimise the multi-threaded communication of the application with the EPANET engine to streamline performance and support concurrent hydraulic analyses.

In addition, a concept of automatically creating unique fire events to reduce the number of analyses, has been introduced for large models.

This has resulted in smaller cities that can be analysed on modern PCs with few processor cores in a few minutes and large cities that can be analysed in reasonable time on high-core cloud-computing platforms.

Visualisation in GIS-based software greatly helps to control the analyses and interpret results visually. Critical areas can be identified on a broader scale and allows for a rational approach to decide where to focus on network augmentation, or alternatively to provide on-site fire fighting capabilities.

Keywords
Fire flow simulation, EPANET, PDA, Wadiso.

1 INTRODUCTION

The water reticulation system is key infrastructure that enables hydraulic water services. It is therefore a critical component in providing the full level of water service to a city or town's consumers. Extended water outages and below minimal pressure is a risk for the water network and especially for fire flows.

GLS has developed new functionality in their *Wadiso* [1] software which enables system-wide fire flow risk analysis on a property-by-property basis.

Whereas it has previously been possible to assess the risk of providing the requisite fire flow and pressure at a specific property, up until this development, it has been virtually impossible to assess the risk on a city-wide basis, for each and every property, and to consider the improvement of such risk in the master plan (MP) of the water distribution system. Hence, the focus of the MP has been the provision of flows and pressures for the peak hour demand scenario in the network. Consequently, many township developments, densifications, and land use re-zonings require a separate and focussed specific fire risk analysis to ensure the existing system, in combination with the implementation of certain (peak hour demand) MP items, is capable of providing the requisite fire flow and pressure. If not, specific additional MP items related to the fire requirements of the specific property have to be investigated and considered for implementation.

A fire risk analysis provides a heat map of areas and properties where the current system is unable to deliver the fire flows and pressures. Such a heat map provides valuable information that can be used to improve and prioritise the MP and minimise future additional ad-hoc analyses for specific properties or developments.

As part of Water Conservation and Water Demand Management (WCWDM) initiatives pressure management zones are often proposed, requiring Pressure Reducing Valves (PRVs) to reduce pressures and hence reduce leakage and water consumption. This is commendable practice, but is often proposed without considering the potential negative effect it might have on fire flow risk. The fire flow risk analysis allows the identification of such pressure management zones where certain adjustments to the pressure regime are required in order to ensure requisite fire flows and pressures are achieved.

This paper covers the Software Development, Model Preparation and Result Presentation.

2 SOFTWARE DEVELOPMENT

2.1 Using the EPANET 2.2 Toolkit

EPANET [2] is a software application and programmers toolkit that was originally developed by the US EPA for modelling the flow of drinking water and constituents within distribution systems. The most common release is 2.00.12 released in 2008. More recently EPANET 2.2 was released in December 2019 and is managed as an Open Source initiative by OpenWaterAnalytics [3] to maintain and extend EPANET. Two key improvements of EPANET 2.2 toolkit are the ability to analyse multiple projects in parallel in a thread-safe manner and the ability to use pressure dependent demands in hydraulic analyses [4]. Both these improvements have been utilised in the *Wadiso FireFlowServer* application. The documentation of the OWA-EPANET Toolkit [5] provides detail on the usage.

2.2 Choice between Demand Driven & Pressure Driven Analysis

Pipe network hydraulic analyses tools and engines have historically only supported Demand Driven Analysis (DDA), where fixed demands are given at all nodes in the model. This type of analysis will often result in large negative pressure heads calculated at nodes as a result of excessive frictional head losses in pipes. In reality this is not possible, as the demand at nodes will drop.

Modern hydraulic analysis software such as EPANET 2.2 also provide the option of performing a Pressure Driven Analysis (PDA), where the demand is defined by a power function of pressure, up to the point where the full demand is met.

The *Wadiso FireFlowServer* has been developed to support both analysis options, DDA and PDA.

2.3 Formulation of DDA fire flow analysis

Before the analysis, each property is assigned a specific fire risk category which states the requisite fire demand and pressure as well as the number of hydrants required within a prescribed distance to enable fire fighting. The closest nodes to the hydrants are retrieved for each property, and together with the proportionally distributed fire demand, is then assigned to a node set which constitutes a fire event. Each fire event will be analysed in a separate analysis run/processing thread.

A base demand DDA simulation is performed, i.e. before any fire demand is superimposed. This could be the peak hour or peak day demand scenario, as per the relevant city's fire flow criteria.

For each fire event the fire demand is superimposed on the nodes, and a DDA analysis is performed. If however the resultant pressure for the base analysis is below the requisite pressure as defined by the fire event's risk category, then a Fire Risk Compliance Score (FRCS) of 0% will be assigned to the fire event and the fire event will not be analysed.

If the requisite fire pressure is achieved at all nodes in the node set for the fire event, then the FRCS is 100%. If the resultant pressure is below the required pressure at any of the nodes, then a heuristic calculation is employed to calculate the fire flow demand that could be achieved at the prescribed pressure, by utilising the base analysis and the fire event results. Both a linear and power function headloss curve is considered, and the averaged flow at the prescribed pressure between the two curves is reported as the achievable fire demand considering the prescribed fire flow pressure value. The FRCS is then the ratio (%) of the fire flow that can be achieved at the requisite pressure, e.g. the required fire flow is 50 L/s @ 20m, but at 20m a fire flow of only 30 L/s is achievable, then the FRCS is 30/50x100 = 60(%).

The FRCS score can be further expanded to include other criteria. For example, the distance to the nearest fire station. This, however, is beyond the scope of this paper.

2.4 Formulation of PDA fire flow analysis

The fire event creation phase is identical to that of the DDA, with the addition of providing the PDA analysis settings required for the EPANET solver.

PDA assumes the demand delivered is a function of nodal pressure as follows [6]:

$$d = D\,[\frac{p - P_{min}}{P_{req} - P_{min}}]^{P_{exp}} \tag{1}$$

where d is the delivered demand, D is the full required demand, P_{min} is the pressure below which demand is zero, P_{req} is the pressure required to deliver the full required demand (before reduction occurs) and P_{exp} is an exponent (typically 0.5). When $p < P_{min}$ demand is 0 and when $p > P_{req}$ demand is equal to D.

As with the DDA, a base demand PDA simulation is performed, i.e. before any fire demand is superimposed. If the achieved demand for the base analysis is below the base demand then a FRCS of 0% will be assigned to the fire event and the fire event will not be analysed.

For each fire event the fire demand is superimposed on the nodes, and a PDA analysis is performed. The FRCS is then the ratio (%) of the achieved demand compared to the fire event demand (base demand + superimposed fire demand).

2.5 Developing a multi-threaded analysis server software

The software is currently designed to run on a server accessible from the Local Area Computer Network. The server-side software has been developed in the latest edition of Delphi programming language. A folder is monitored for input files (*.ffinput) to be processed in a queue. The typical format for the input file is:

```
NodeSet,NodeCode,FireDemand
```

NodeSets are numbered and represent a set of nodes that should have a *FireDemand* fire flow demand superimposed to a base demand, for every *NodeCode* node. A single period steady state analysis is then performed on the hydraulic model for every *NodeSet*.

A matching EPANET text-based input file (*.inp) represents the hydraulic model. Coordinates of nodes are not required in this file. Optionally a meta file with additional parameters controlling the analysis (e.g. the choice between DDA & PDA analyses and convergence parameters) can be provided. Additional control files can be placed in the folder to stop or restart a running process. Once the process is complete a (*.ffdone) marker file is written, together with an output file (*.ffoutput). The output file typically has this format:

```
NodeSet,NodeCode,FireDemand,ResStatus,ResPressure,ResDemand,ResRatio
```

where in addition to the input fields that are repeated for readability, *ResStatus* stores the EPANET balanced status information and other critical error conditions, *ResPressure* stores the resulting pressure head, *ResDemand* the resulting demand, and *ResRatio* the FRCS for the specific node.

MaxHeadloss & *MaxVelocity* for all the links in the model is also exported in a separate file for additional verification by the engineer.

2.6 Performance comparison of multi-threaded server software

For larger cities, such as the City of Cape Town in South Africa, the number of modelled nodes can exceed 100,000. In addition, the City of Cape Town has in excess of 500,000 stands.

Performing 100,000+ analyses on a 100,000 node sized hydraulic model can take a considerable amount of time. The development of a multi-threaded and highly optimised analysis engine capable of running on fast multi-core servers was therefore essential.

Using multi-threading code of Delphi, in a 64 bit compiler and ensuring thread-safety is maintained at all times, a performance optimised application has been developed. One thread is used for a complete hydraulic analysis at a time, through the EPANET 2.2 Toolkit.

The application has been tested on various Windows environments. Figure 1 shows result where the maximum number of Concurrent Threads to be used and selected in the software is displayed on the x-axis and the number of completed hydraulic analysis per minute, of the 138,073 node CoCT sample model, is shown on the y-axis.

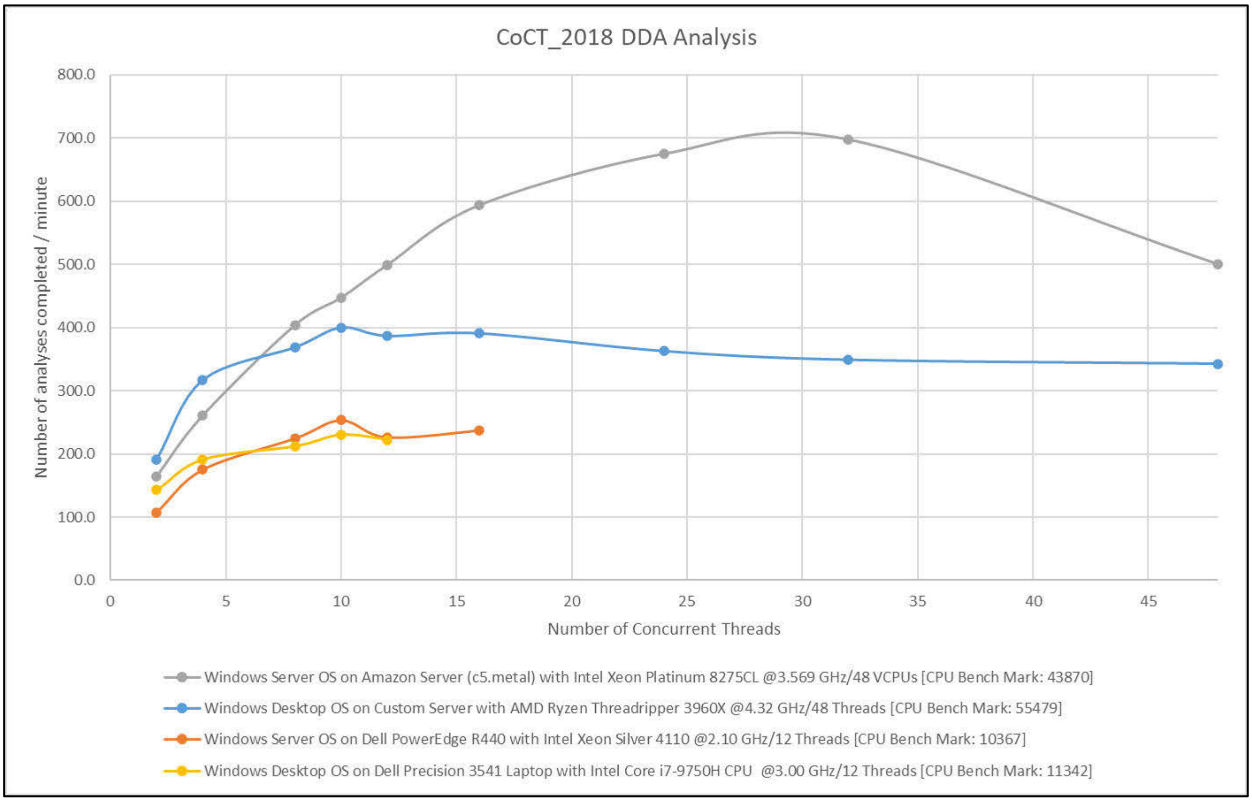

Figure 1. Performance of the Wadiso FireFlowServer.

The following observations are made:

Even a high-end laptop is capable of running up to 250 analyses per minute using 10 of the 12 computing threads available in the computer (yellow line). An older 16 computing thread server performs similar (red line).

A custom server using a mid-range 48 computing thread processor can reach 400 analyses per minute, but interesting also only at around 10 computing threads. This implies that other hardware in the computer such as the speed of the SSD hard disk, speed of memory, size of CPU cache and the bus architecture play a role (blue line) in performance, not allowing scaling to all computing threads with this specific model.

The superior server architecture of a cloud computing server is clear. Although at under 8 concurrent threads the faster CPU of the custom server outperforms the cloud computing server, the latter scales to about 32 concurrent threads before other overheads catch up. A maximum of about 700 analyses per minute was recorded (grey line).

2.7 Visualisation in GIS-based hydraulic modelling client software

The GIS-based visualisation of input and output data from the Wa*diso FireFlowServer* is critical for the engineer to ensure the input is correct and the results are meaningful. This was best accomplished using the *Wadiso* hydraulic modelling software, which is also based on the EPANET 2.2 engine. Individual analyses can be verified in the software. For comparison a single steady state analysis of the CoCT model within the GIS-based environment, with updating of the result map display (e.g. pressure head) takes normally about 50 seconds on the laptop mentioned before. The industry standard non-GIS EPANET 2.0 takes about 20 seconds for comparison. The *Wadiso FireFlowServer* on the cloud computing server is therefore 233 faster than attempting to perform the analysis manually in the EPANET 2.0 UI and 583 times faster than attempting to use the GIS-based hydraulic analysis software package.

Figure 2 shows the extent of the CoCT_2018 hydraulic model for reference.

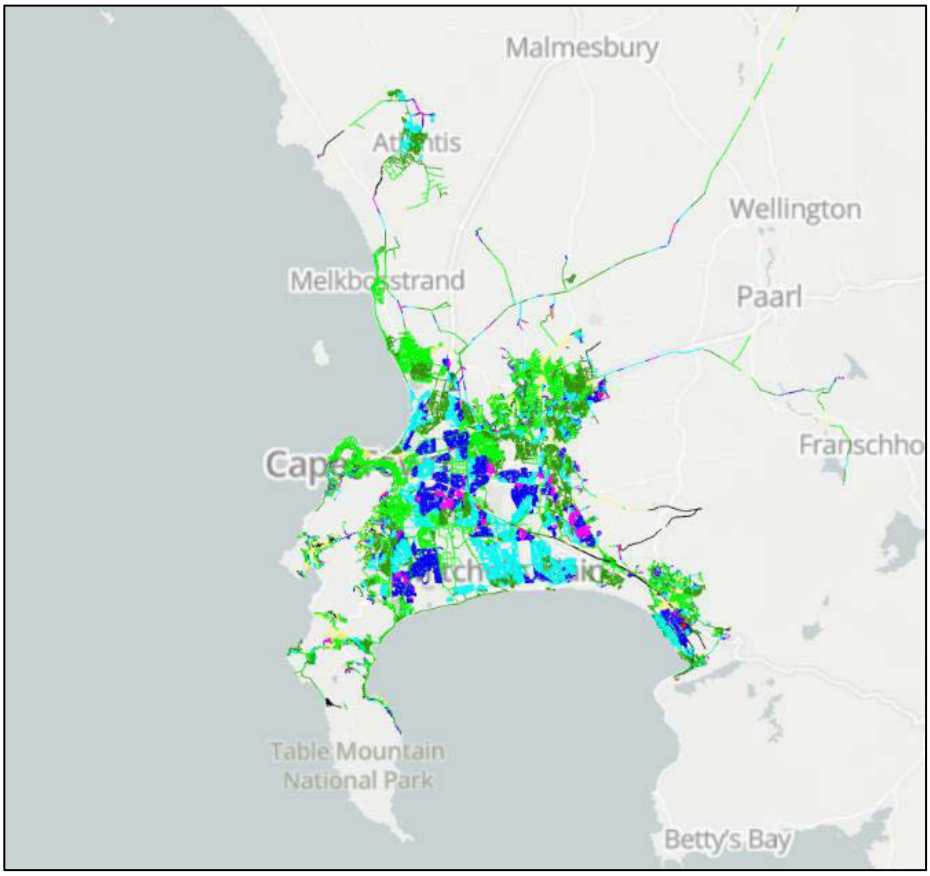

Figure 2. Extent of the CoCT_2018 hydraulic model as visualised in Wadiso.

3 MODEL PREPARATION

3.1 Model Creation

The model needs to be created and verified. The model can be populated with theoretical demands per land use or in our case study the Average Annual Daily Demand (AADD). A model should generally be well calibrated before performing a fire flow study. An extended period time simulation could be run, but the instantaneous nature of the fire event allows for a steady-state analysis. In a fire flow scenario tank levels are not looked at in detail.

Another important factor for using a steady-state analysis rather than a time simulation, is time. When analysing a system for example with 60 000 stands. Every second of computation time adds more than 16 hours to the analysis time if running on a single thread. This can be mitigated by using machines with multiple cores (as discussed earlier), breaking models into smaller discrete zones, or finding unique fire events to reduce the number of simulations required (discussed below).

3.2 Stand Categorisation

In our case study, stands are categorised according to local standards, such as the South African Bureau of Standards (SANS) code [7]. The code defines the fire flow requirements to be delivered to a stand in the event of a fire. This will vary according to each nation's or region's own standards.

The requirements in the SANS code are generally the minimum number of hydrants to be within a distance from the fire, the minimum flow that needs to be delivered and the minimum allowable pressure at the hydrant. Normally the base analysis for a fire event is simulated at two times the Annual Average Daily Demand to simulate a relative high demand of water in the area.

Below is an extract of the SANS codes for fire flow events.

Table 1. SANS Codes [7]

Code	Hydrant count	Distance (m)	Flow (L/min)	Min. Pressure (m)	Description
SANS D1	2	300	1 900	15	SANS 10090 Category D1: Houses > 30 m apart
SANS D2	2	200	2 850	15	SANS 10090 Category D2: Houses 10,1 to 30 m apart
SANS D3	3	200	3 800	15	SANS 10090 Category D3: Houses 3 – 10 m apart
SANS D4	3	200	5 700	15	SANS 10090 Category D4: Houses < 3 m apart
SANS C	3	200	6 000	15	SANS 10090 Category C: Non-residential buildings with divisions not greater than 1250 m^2
SANS B	5	120	9 000	15	SANS 10090 Category B: Non-residential buildings having divisions not greater than 2 500 m^2
SANS A	7	85	13 000	15	SANS 10090 Category A: Non-residential buildings with divisions not greater than 5000 m^2

3.3 Hydrants

Hydrants can either form part of the model by flagging nodes as hydrants or they can be placed as points on a different model layer, known as model appurtenances. The advantage of having the hydrants physically part of the model is accuracy. On larger systems it might be preferable to have fewer nodes and rather allocate the hydrant's demand to the nearest node. This approach would also be acceptable when looking at the bulk system's capacity for handling fires, while having detail up to the node level would be preferable when looking at the local system's ability to deliver adequate water during a fire.

This process can also be done in two different ways. The first is to find the closest hydrant "as the crow flies". This is the easiest but can often lead to a hydrant being chosen that would not necessarily be used for fire fighting. The second option would be to find the closest pipe to the fire and then traversing the network to find the closest hydrants along the route. This often leads to more accurate results as pipes tend to follow roads and as such the path is generally the shortest road path to the hydrants. A more accurate method would be to get actual road layouts, but this information is not always available and would not necessarily increase the accuracy by much.

3.4 Finding Unique Fires

When analysing larger systems it becomes advantageous to recognise unique fire events. A number of stands in the same area often share the same land use category as well. This means that they have the same fire flow requirements. If the closest hydrants also happen to be the same hydrants, then the fire event can be classified as the same event. As a result a number of stands can be analysed only once.

For example on the CoCT system with 587 000 stands, the number of unique fires can be reduced to only 82 112 individual events that need to be analysed. Using the metrics from previous sections this will reduce the analysis time on a laptop doing 250 analyses per minute from 39 hours to less than 6 hours. When using the cloud computing server doing 700 analyses per minute the time will decrease from 14 hours to under 2 hours.

Figure 3 shows the distribution of unique fire events in a residential area where hydrants were selected using the basic "as the crow flies" method.

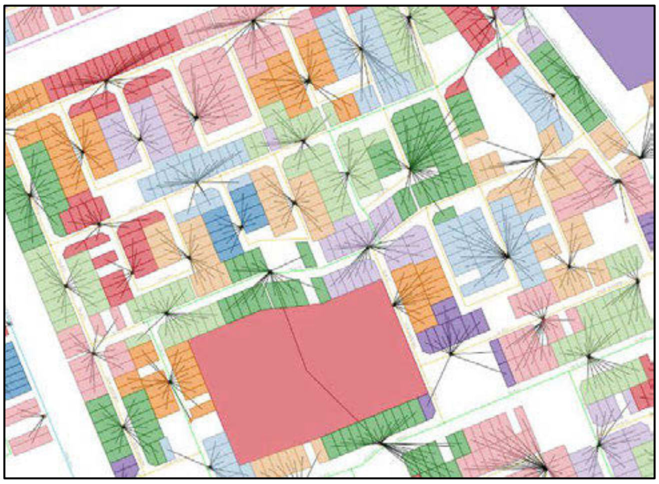

Figure 3. Example of unique fire events

4 RESULT PRESENTATION

4.1 Post Analysis

For result presentation a smaller coastal municipality near the City of Cape Town was used as a test case mainly due the larger variation of property land use, and thus risk categorisation, as well as greater elevation changes in close proximity, to better illustrate differing FRCS results.

Analysis results are imported for each fire event and applied to the relevant property. This allows for a spatial visualisation for levels of compliance in terms of the categorisation table. Critical areas can be identified where intervention will be required.

Table 2 shows a small extract example of the result table after results are imported and assigned to the properties that are linked to each unique fire event. A status message is provided that indicates which requirements have not been met in cases where the FRCS is less than 100% (imported as a ratio). A comment is provided in cases where an insufficient number of hydrants (hydrant shortage) are within the required distance from the fire event.

Table 2 Example of Result table

ID	Status	FRCS	Comments	Category	Description
HIND 02362	Not achieved: Fire demand	0.71	The nearest hydrant is beyond the required distance away	BUS_COMM	SANS 10090 Category C
HMP 06183	All requirements achieved	1.00		RES[2000]	SANS 10090 Category D1
HSB 00250	All requirements achieved	1.00		RES[1500]	SANS 10090 Category D1
HSB 01239	Not achieved: Fire demand	0.97		RES[1000]	SANS 10090 Category D2
HSB 01378			Excluded from analysis	NO FIRE	
HZW 00658	Not achieved: Fire demand & minimum pressure at a node/hydrant	0.61		RES[500]	SANS 10090 Category D3

Hydrant compliance is important to ensure redundancy for fire fighting capability. Areas may have insufficient hydrant distribution regardless of network capabilities. Figure 4 provides and example where no hydrants are found within the required 200 m distance for a property classified as SANS 10090 Category D2: Houses 10.1 to 30 m apart.

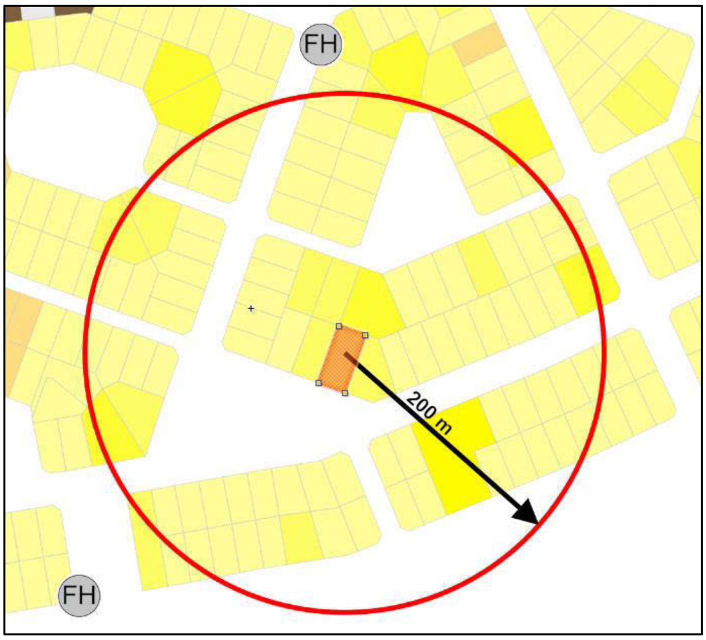

Figure 4. Example of hydrant shortage (non-compliance)

Only part of the larger test case area is displayed in Figures 5, 6 and 7 for clearer illustration of the analysis results. Properties that have a hydrant shortage based on their risk categorisation have a dark red border.

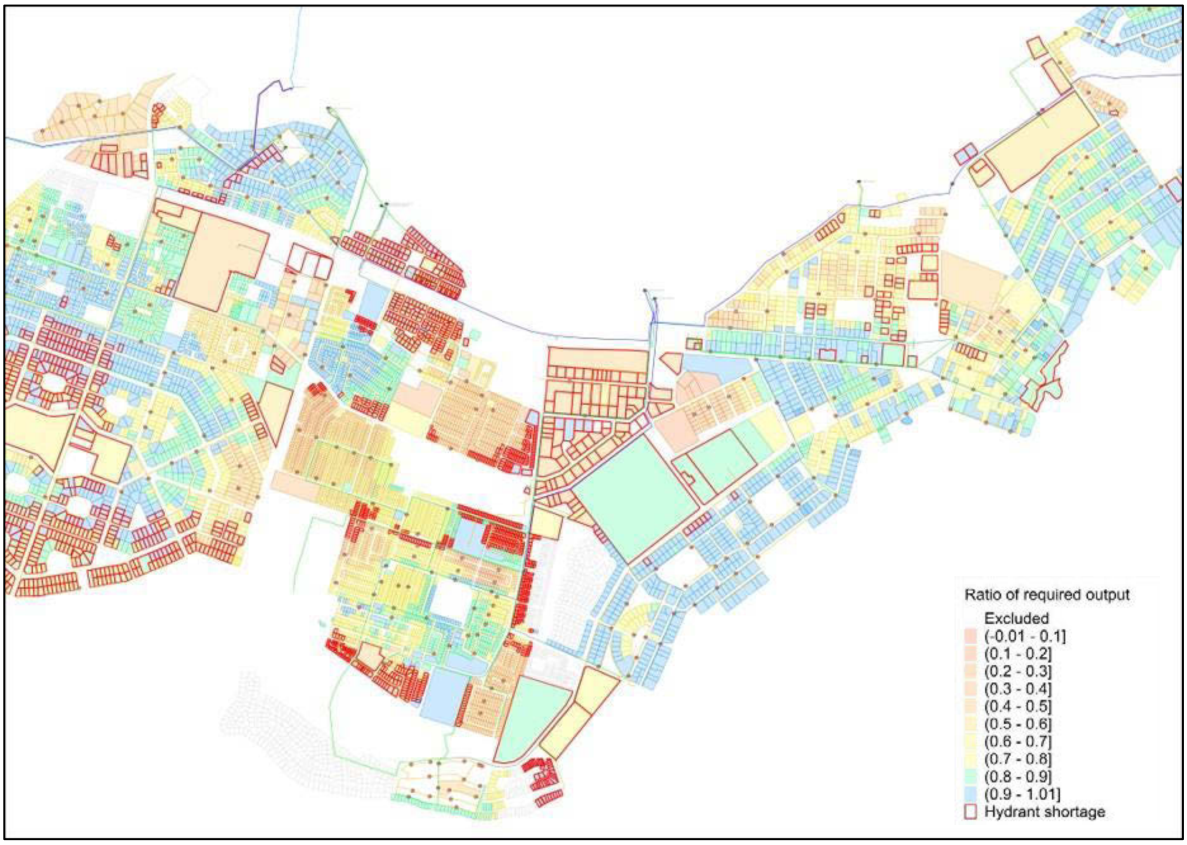

Figure 5. Test Case fire compliance visualisation before network reinforcements

Interpretation of the flow and pressure results are dependent on the analysis method used. With a PDA, achieved fire flow is considered along with the pressure, as demands in the model are reduced based on simulation settings for the PDA analysis. With a DDA, the achievable fire flow at the prescribed pressure is provided where the FRCS is below 100%.

If the network cannot deliver the required fire flow at the prescribed pressure, then intervention is required to augment the network to allow for fire fighting compliance. The augmented model is then analysed to determine if adequate compliance is achieved. For quicker turn-around time a subset or even a single fire event can be analysed for the augmented model, to determine if adequate compliance is achieved when considering localised improvements/changes to the network.

Figure 6 shows the required network reinforcements required for fire fighting compliance, over and above standard MP upgrades that are required for sufficient nodal pressure and flow velocity limitation within the system, that would be required regardless of the fire flow analysis.

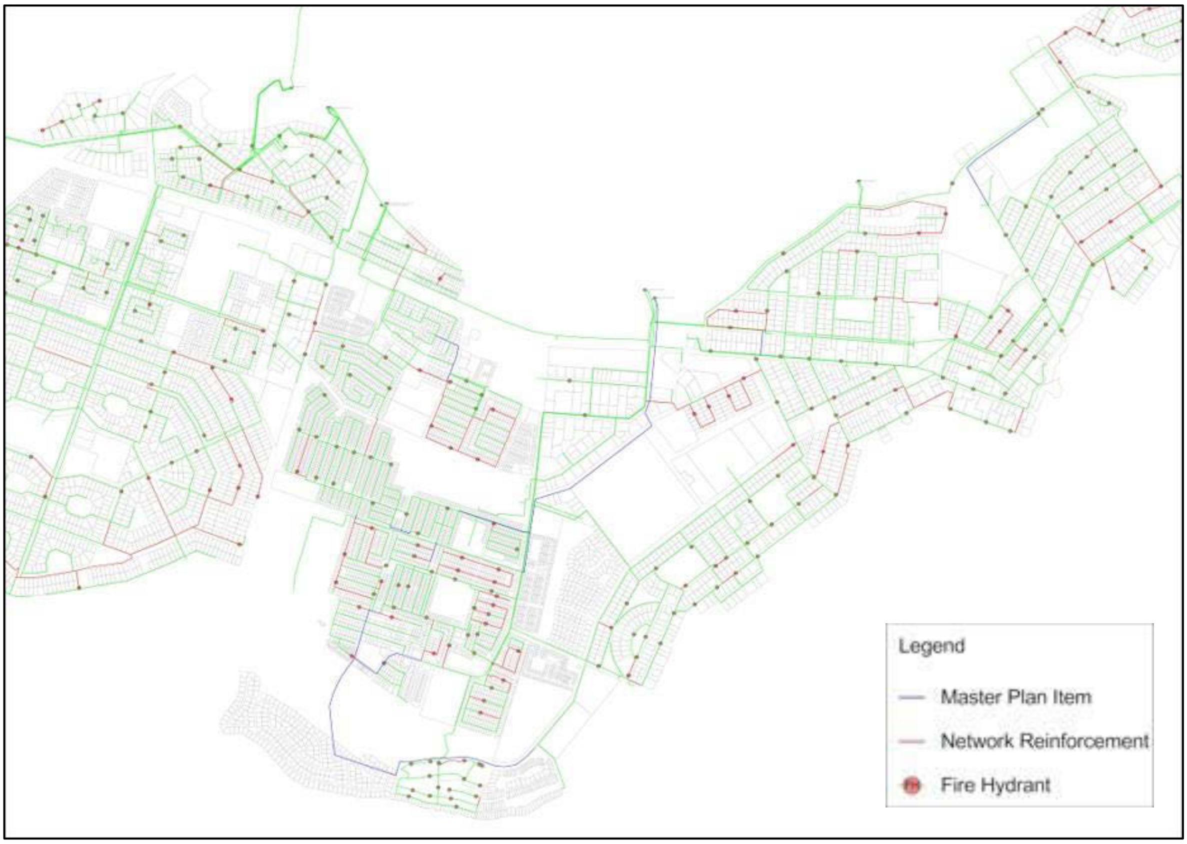

Figure 6. Test Case Network upgrades

After implementation of the proposed improvements the fire risk is dramatically improved as shown in Figure 7, with the majority of the properties now indicating full to only slight non-compliance, when compared to Figure 5.

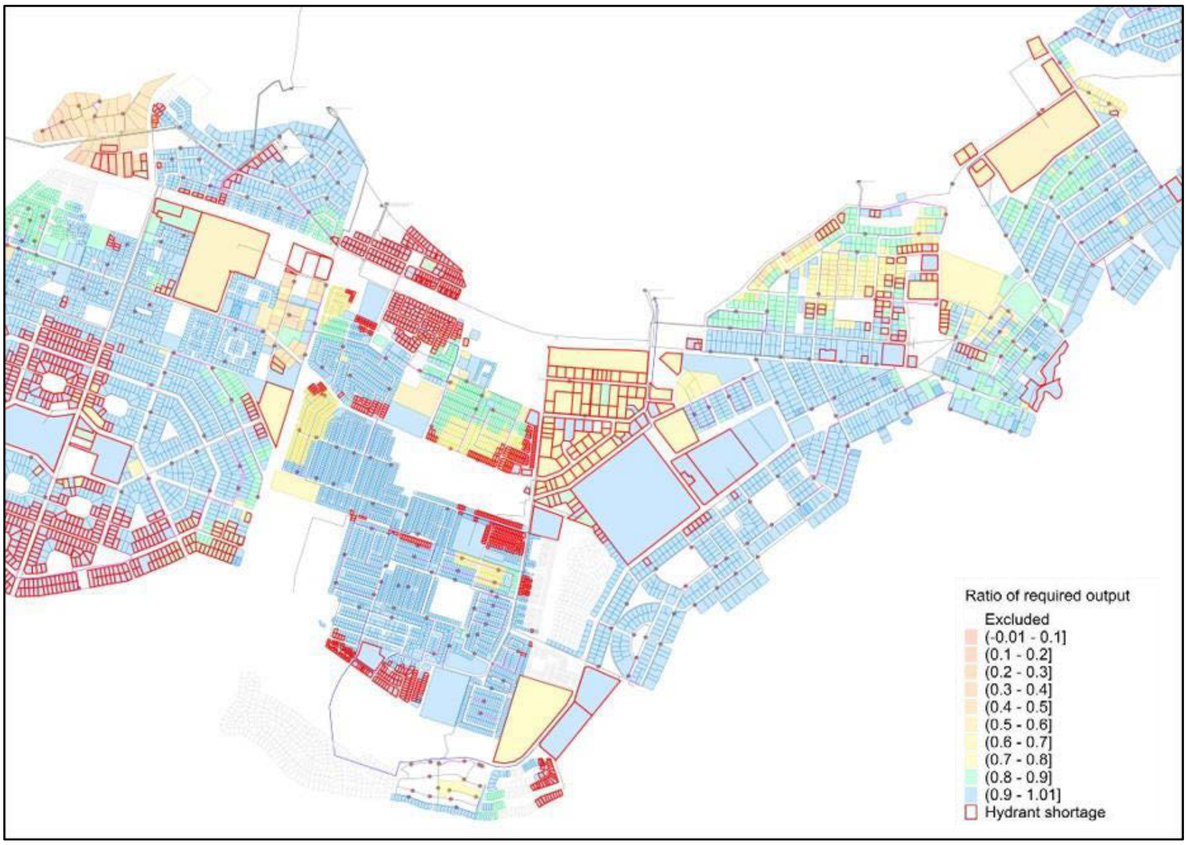

Figure 7. Test Case fire compliance visualisation after network improvements

Besides proposing network reinforcements for pipes with high velocity and headloss, it is important to apply engineering judgement and consider existing pressure reduction zones, and investigate if any pressure reduction settings can be increased to improve the results of the fire flow analysis before other reinforcements are proposed. Consider Figures 8 and 9 below which shows the FRCS before and after a PRV bypass is implemented.

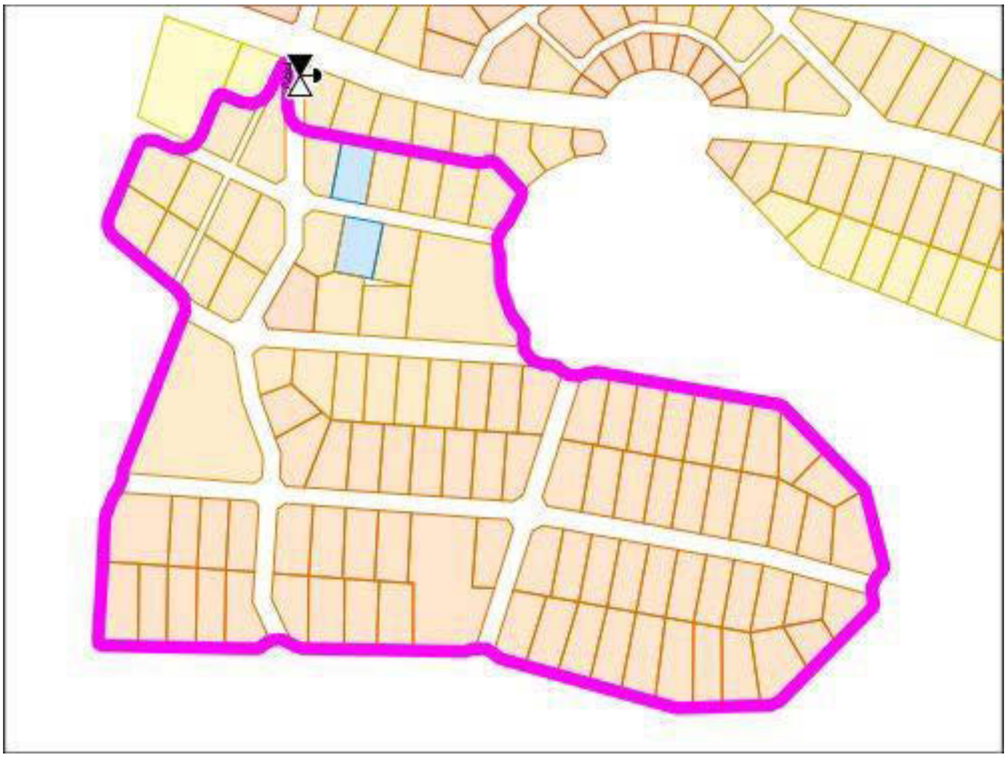

Figure 8. PRV zone FRCS before intervention

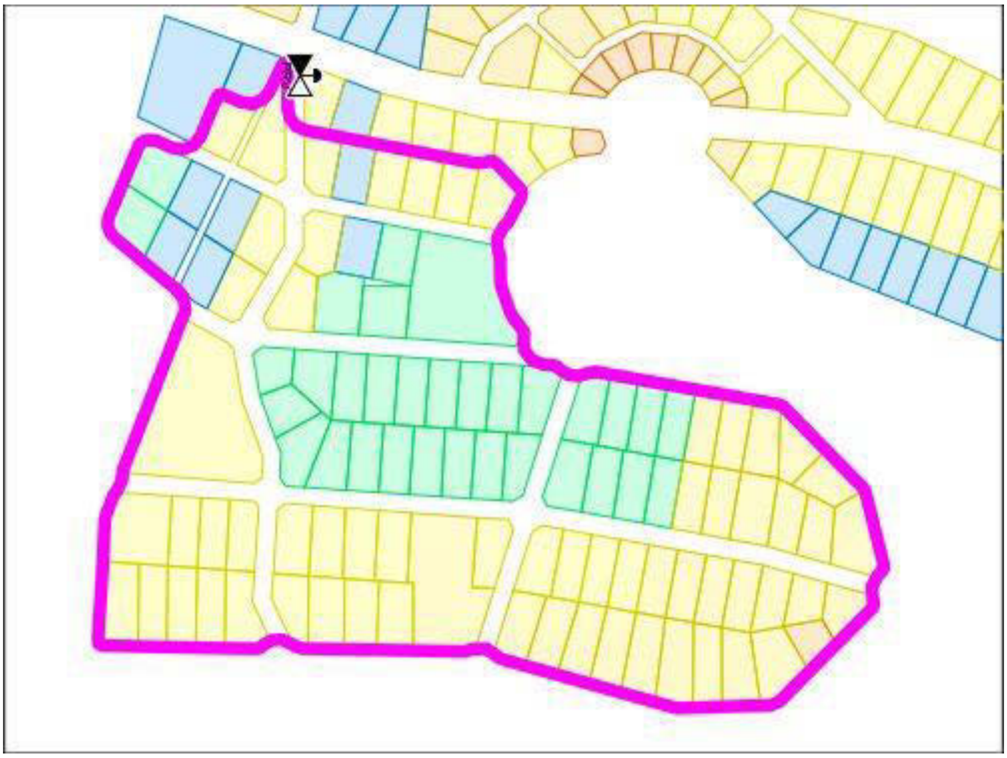

Figure 9. PRV zone FRCS after intervention (PRV bypassed)

5 CONCLUSIONS

The development of a multi-threaded client server software application, based on the latest open source EPANET 2.2 hydraulic analysis engine, in partnership with a GIS-based water analysis software enables city wide fire flow risk analysis on a property-by-property basis.

A Fire Risk Compliance Score is assigned for each property and produces a heat map of fire flow requirement compliance based on required flow, pressure and number of feeder hydrants within a minimum distance. This provides an invaluable view of the state of the water network to determine where the system is inadequate to deliver fire flows at the required pressure. Critical areas can be identified on a broader scale and allows for a rational approach to decide where to focus on network augmentation, or alternatively to provide on-site fire fighting capabilities.

The ease of setup via the *Wadiso* front-end allows for quick creation of various fire flow risk analysis scenarios to compare severity of fire category assignment.

Future work includes moving the server to the cloud to eliminate Local Area Computer Network dependence and to improve the display of results by adding more meta data to the node sets supporting filtering based on criteria.

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