# Applications of Intelligent Data Analysis in Urban Water Systems

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# Agent-based Division of Water Distribution Systems into District Metered Areas*

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## INTRODUCTION

Water supply is one of the more recognizable and important public services contributing to quality of life. It exhibits a number of characteristics that are quite different from those of other public services. Its distribution is irregular, both in temporal and spatial terms. In addition, its operation can be analyzed from very different perspectives. As water is for consumption, aspects related to health need to be considered: water quality and the appropriate control measures to maintain quality during residence time in the network. However, water systems suffer a number of operational and environmental conditions, which lead to progressive and insidious deterioration. There are a variety of factors involved: loss of pressure, due to increasing inner roughness of pipes; breakage or cracking of pipes, caused by corrosion and mechanical and thermal charges; and loss of water (leaks), due to pipe breaks and cracks, with their corresponding economic loss, and third party damage. All these factors can create a risk of contamination. Because of the complexity of water systems, mainly due to the interconnected nature of sources and consumption points, it is extremely difficult to balance production and distribution, that

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is to say, to control the water supplied and consumed. Division of the network into DMAs follows a divide-and-conquer strategy that splits a large and highly interconnected distribution network into smaller and virtually independent networks – each supplied by a pre-fixed number of sources.

Independence can be physically achieved in a number of ways: by closing valves in existing pipes, by sectioning existing pipes, by introducing new pipes that redistribute the flow, etc.

Manageable DMAs will enable action to be taken to improve the control and management of important aspects of water distribution, such as water quality and the intensity and spatial and temporal distribution of leaks. DMAs will help reduce unaccounted-for water loss and improve the water-tightness of the system – thereby saving huge amounts of water and preserving water quality. Substantial water savings can be forecasted if sectorization is enforced systematically.

Real water distribution systems may consist of thousands of consumption nodes interconnected by thousands of lines, as well as the necessary elements to feed the network. These networks are not usually the result of a unique process of design, but the consequence of years of anarchic response to continually rising demands. As a consequence, their layouts lack a clear structure from a topological point of view. This fact renders these networks difficult to understand, control, and manage. In the case of small networks, simple techniques, sometimes of a visual character, enable division into a few DMAs. But this task is unthinkable for very large networks because their complexity renders the problem virtually unfeasible. As a consequence, new algorithmic capabilities, not implicitly contained in the hydraulic model, would be of great interest.

The main objective of creating DMAs (or sectorization) is to obtain the distributed and manageably scaled information necessary to perform key actions in each sector (AVSA, 2009). These actions include:

- audit the hydraulic efficiency or NRW (non-revenue water),
- characterize the demand curve, especially the night flow,
- quickly detect possible leaks by analyzing the evolution of the night minimum flow,
- check the results of search campaigns and repair leaks quickly,
- detect fraud, under-registration, or diverse errors of measurement,
- reduce maintenance costs,
- plan investments when guiding supply to the sectors with more NRW.

The procedure to define the hydraulic sectors implies (Tzatchkov et al., 2006):

- Obtaining the number of independent sectors in a network layout. A sector of the network is said to be independent when it is supplied exclusively from its own water sources, and is not connected to other sectors in the network.
- Obtaining the set of network nodes belonging to each individual sector.
- Revising proposed sectorization actions, such as valve closing or pipe sectioning, in case such actions may cut the water supply for some parts of the network.
- Defining the area served by each water source, and the contribution of each source to the consumption of each network node.

The first and third of these four tasks are crucial for detecting errors in the network layout and in proposed sectorization decisions. The second task is essential for water audits, and the fourth task is important for defining and visualizing any proposed sectorization.

A District Metered Area (DMA) is a part of the water distribution network that is hydraulically isolated, temporally or permanently, and ideally has just one supply node equipped with a flow meter. DMAs are small zones of the system and usually contain between 500 and 3000 service connections.

The concept of DMA management was first introduced to the UK water industry in the early 1980s (Morrison, 2004), and it has been used as an instrument to monitor and reduce the level of leaks in water supply systems. The technique was mainly developed in Europe, and has been used in Latin America from the 1990s, while it is less often used in the United States and Canada. The development of DMAs has been strongly empirical, being based on technical experience and with very few scientific contributions. It is necessary to highlight the contributions in UKWIR (1999) and IWA (2007). Recently, some proposals have been presented for a conceptual and scientific framework – such as Hunaidi (2005) relative to the periodic acoustic surveys in a DMA; or Tzatchkov et al. (2006), in applying graph theory to establish the division of DMAs.

In this paper, we explore the division of a water supply system into DMAs by using a multi-agent approach. Multi-agent techniques have proven to be highly efficient in the solution of very complex problems of a distributed nature – an example of which is shown below. In the water field, in particular, there has been a tendency in recent years to include multi-agent techniques as an interesting alternative for solving complex problems that differ from the problem addressed in this article. See, for example, (Izquierdo et al. 2008) on multi-agent applications in urban hydraulics; (Maturana et al. 2006) on water and waste water control system architecture; (Kotina et al. 2006) on control systems for municipal water; (Nichita and Oprea 2007) on water pollution diagnosis; (Feuillette et al. 2003) on water demand management for a free access water table; (Hai-bo et al. 2005) on water quality; (Becu et al. 2001) on water management at catchment scale; (Cao et al. 2007) on optimization of water networks; (Mikulecký et al. 2008) on water management at river basin scale; and (Hailu and Thoyer 2005) on allocation of scarce water, among others.

Complex problems, such as the problem considered in this article, can be resolved using distributed agents because the agents can handle combinatorial complexity in a real-time suboptimal approach (Maturana et al., 2004).

The structure of this paper is as follows. Firstly, we introduce the agent-based ingredients, then describe the used implementation, and finally, present the main results. A conclusions section closes the paper.

## MULTI-AGENT METAPHOR

In the study of complex systems, computer programs have played an important role. However, the actual process of writing software is a complicated technical task with much room for error. Multi-agent philosophy adopts a modelling formalism based on a collection of independent agents interacting through discrete events. Simulation of discrete interactions between agents stands in contrast to continuous system simulations, where simulated phenomena are quantities in a system of coupled equations.

An agent is any actor in a system: any entity that can generate events that affect itself and other agents. In the problem we consider below, agents are consumption nodes, connecting pipes, supply sources, ground and underground patches containing the network; as well as district metered areas, which are set of nodes, pipes, sources, and patches. Even the whole network is an agent following specific scheduled actions. In these last two cases, agent behaviour is defined by the emergent actions of the agents they contain.

Agents define the basic objects in the system – the simulated components. The simulation occurs in the modelled world itself, and it is frequent to speak of agents as living in an environment, which, in its turn, can be an agent itself.

Once agents have been defined and their relationships established, a schedule of discrete events for these objects defines a process occurring over time. Individual actions take place at some specific time; and time only advances alongside events scheduled at successive times. A schedule is a data structure that combines actions in the specific order in which they should execute. The passage of time is modelled by the execution of the events in some sequence. Instructions are given to hundreds or thousands of independently operating agents. This makes it possible to explore the connection between the micro-level behaviour of individuals; and the macro-level patterns that emerge from the interaction of many individuals.

A final step consists in observing the model and recording what is happening. Observers perform these actions. In most platforms there are also agents with specific tasks, such as plotting, storing data, monitoring and displaying certain variables, etc.

Agents should possess the following properties: autonomy, mobility, reactivity, pro-activity, adaptability, communicativeness, robustness, learning ability, task-based orientation, and goal-based orientation (Lee, 2006).

The agent-based approach is worthwhile (Wooldridge and Jennings, 1995), (Wooldridge, 2002) when facing:

- open, highly dynamic, variable, poorly structured, uncertain situations
- where the environment can be seen as a system of autonomous, cooperative, or competitive entities
- data, control, or expertise is distributed
- the system can be divided into independent components.

## IMPLEMENTATION

NetLogo (NetLogo, 2007) is an environment for developing complex, multi-agent models that evolve over time. It is possible to create populations of changing agents in a suitable grid of stable agents. The evolution of agents can take different forms. Agents can be created, move, change their properties, change their behaviour, change their nature or breed, and even die.

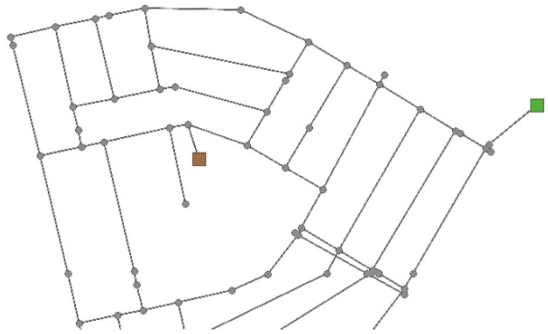

Figure 1. Detail of the network in NetLogo environment

Our model is created from GIS data defining the physical and topological network characteristics. The experimental data was obtained from a GIS model of a real moderately-sized network that has been studied by the authors within a joint research project with an international water company. This network is a part of a water distribution system in a Latin American capital.

The area is divided into squares (patches), which gives some raster format to the environment. Patches represent the ground (underground) where pipes and nodes are buried. Figure 1 shows a section of the network. Patches are used to define areas occupied by the different divisions that will be created. As a consequence, this raster structure cannot be observed in Figure 1. Consumption nodes (small circles) are agents (turtles) of a certain breed with a number of associated variables. Among the user-defined variables, elevation and demand are the most important. During the process, colour is used to define the DMA that the agents belong to. Pipes (grey lines) are links (in the problem under consideration they are undirected links). Each pipe connects two different nodes and also has some associated variables. The main user-defined variables are diameter and length. Source points (coloured squares) are another breed of turtles, whose variables are the average of the demand they supply and the DMAs they feed. Patches, sources, nodes, and pipes are spatially fixed agents in the sense that, obviously, they do not change their position with time. Instead, they change their properties, especially colour, and as a result they eventually belong to one DMA or another. Initially, the sources, nodes, and pipes are presented in light grey, since no district structure is available at the setup.

In this model, the user decides the number of DMAs to be built. Then, randomly the same number of source points are selected to be the seeds for the corresponding districts. Upon setup, these turtles start a process of probing their neighbouring nodes and checking the likelihood of their neighbours being assimilated into the same would-be DMA as themselves. This likelihood is derived from a number of tests, which are performed on the basis of sources, nodes, and pipe properties:

- the total length of the current DMA must be bounded by minimum and maximum values for the total length of the set of its members,
- the elevation of a new candidate must be in a certain range around the average elevation of the current DMA,
- the total demand of the sector must be between certain pre-fixed limits,
- the associated sources must be able to meet that demand,
- the geometrical properties of the area occupied by a DMA must exhibit certain basic requirements (connectivity, convexity, etc.),
- other properties.

Nodes and pipes passing these tests are assimilated to the winning DMA, and the process is repeated again. The process is able to find good solutions for the connectivity between DMAs. As a consequence, the number and location of the closure valves is optimized for a given layout. In addition, nodes are assigned to sectors in a remarkably stable way that further stabilizes during the evolution of the process. Also, the best partitions can be found with frequency during different runs of the process. As a result, by repeating the process a certain number of times, the engineer can make a final decision that may, or may not, coincide with any of the obtained partitions – these being used as a basis for the decision.

Neighbouring nodes for every hydraulic sector or division are explored in each step of the algorithm. These nodes are given a certain probability of belonging to a given district. This probability reflects the difference between the elevation of the node and the average elevation of the district; and the difference between its demand and the average demand of the sector. In this way, the simple greedy competition based on minimum distance among the districts is improved, and this adds increased probabilistic richness to the process. As a result, the model agents, performing a mixture of individual and collective actions, can explore good network sectorization layouts.

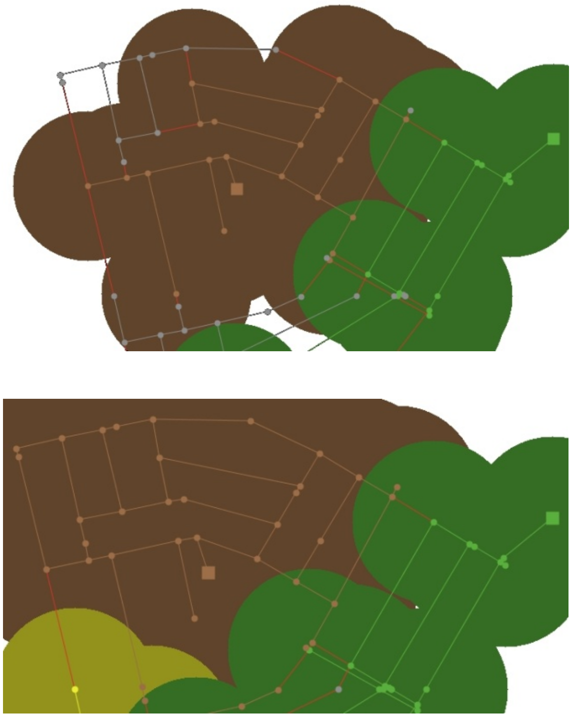

Figure 2. Two stages of the sectorization process

From the point of view of Logo programming, the functions *self* and *myself* are essential to define the list of inputs of the agent (set of agents) to be interrogated, and the agent (set of agents) making the enquiry. In other words, nodes are assigned to a given sector after some dialectic process of neighbouring enquiries among different sectors competing for the node (see Figure 2 showing two stages of the process). In the upper part of the figure, a number of nodes (coloured) have already been assigned to specific sectors, while others (grey) are still unassigned. Regarding pipes, grey means unassigned, and red is used to identify pipes connecting two different sectors.

Figure 3 shows the assignment procedure that decides the assignment of nodes for a calling sector. Firstly, neighbouring nodes for the calling sector are scanned. Then a decision is made about the colour to be assigned to a neighbouring node. This decision is performed by weighting the difference between the node's elevation and demand with regard to the average elevation and demand of the calling sector (bold line in Figure 1). This weighted difference provides a resistance degree (*resist*) in terms of the probability of making a decision about joining the calling hydraulic sector. The weights influencing this difference are selected by the user through the slider called 'weight-demand' (see

Figure 4). Once a new configuration has been built, other requisites (sector size, connectivity, etc.) are checked before validating the configuration. Borders between sectors – which can be fuzzy – are identified by red pipes, showing the location of cut-off valves, which are used to isolate the sectors during operation.

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```
to add-to-cluster


ifelse any? link-neighbors with [color != [color] of myself and shape != "square"]
[ask one-of link-neighbors with [color != [color] of myself and shape != "square"][
  let color1 color
  set color [color] of myself
  if zoning [splotch]
  ask my-links [set color [color] of myself]
  let elevation-cluster mean[elevation] of turtles with [color = [color] of myself]
  let demand-cluster mean[demand] of turtles with [color = [color] of myself]
  let resist  weight-elevation * ([elevation] of self - elevation-cluster) + weight-demand
      * ([demand] of self - demand-cluster)
  if random 100 < resist [
  set color color1
  ask my-links [set color color1]
  if zoning [splotch]
  build-cluster]
]
]
[stop ]


end
```

---

Figure 3. Assignment procedure

The natural consequence of this process is that different DMAs are built and minimal sets of sectioning lines are identified. Nevertheless, some nodes may end up disconnected and borders between sectors may be poorly defined. The main objective is the identification of DMAs and sectioning lines. The information about disconnected nodes and overlaps between nodes and pipes of certain colours with sectors of a different colour (lower part of Figure 2) can also be used by the network manager. These circumstances, which show that the desired balance is still undergoing some debate regarding assignations, can be used to detect errors in network data, propose candidate areas for sensitivity analyses, and encourage various actions aimed at improving the layout and/or the topology of the network.

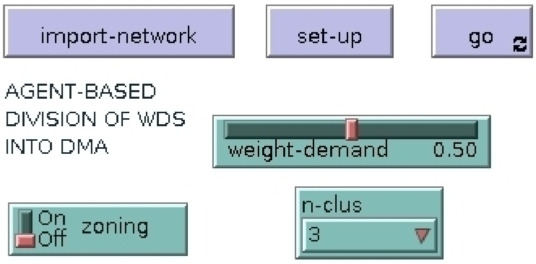
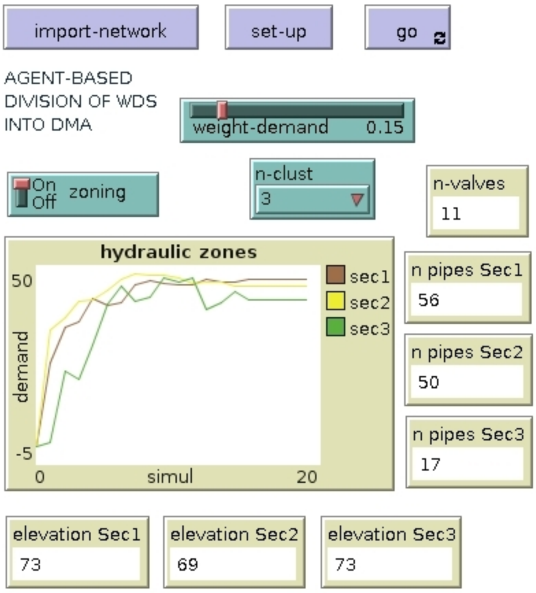


Figure 4. The interface elements

Through additional interface elements, the user can manage the course of the simulation by changing different parameters (see Figure 4). The membership probability measurements of a node with respect to a district depend on elevation and demand. As stated earlier, the user can modify the weight of these elements by using the slider labelled ‘weight-demand’. The default for this value is 0.5, and the sum of the weights corresponding to elevation and demand is 1.

The user can decide *a priori* the number of hydraulic sectors to be built by selecting an option from the chooser labelled ‘n-clus’. By using switch ‘zoning’ the user can also ask the program to colour the patches occupied by the different hydraulic sectors. This option, as well as offering an interesting visual value, enables the user to decide if the built districts exhibit good topological properties. Certain convexity and/or compactness properties are desirable for the districts. By default (option off), the different colours for the pipes and nodes make clear the division of the hydraulic network into districts. By flipping the switch to ‘on’, patches are coloured according to the colour of the nodes and pipes they contain. This option is useful for revealing overlaps between sectors which, as explained before, can be used to produce suitable sensitivity analyses. Finally, those pipes that enable isolation/communication between two sectors are represented in red, and provide the engineer with useful information about the candidate pipes for sectioning and where to install cut-off valves to isolate the districts.

The simulation results can be visualized on screens, plots, and graphs; and data can be stored for further processing in hydraulic simulation software and for decision-making support.



weight-demand 0.15

n-clust 3

n-valves 11

n pipes Sec1 56

n pipes Sec2 50

n pipes Sec3 17

elevation Sec1 73

elevation Sec2 69

elevation Sec3 73

Figure 5. Interface including monitors

Figure 5 presents several displays showing some of the used parameters, such as the average elevation of the different sectors and the number of pipes in the sectors. Of special importance is the display labelled ‘n-valves’ which shows the number of sectioning links connecting different sectors; and corresponds to closing valves for the given partition. Engineers must take important decisions about the need to install closing valves in existing pipes, and about sectioning those pipes, and/or introducing new pipes that redistribute the flow in more a reasonable manner.

Our simulation model helps managers communicate with domain experts, because they can perform their reasoning by solving modelled situations. The model is based on simple physical principles, but its large-scale modification is straightforward.

## RESULTS

To show the performance of the presented process, we present the results for a network (see Figure 6) fed by three reservoirs and made of 132 lines and 104 consumption nodes; its total length being 9.055km, and the total consumed flowrate amounting to 47.09l/s.

After 20 runs of the model simulating the partition of this network into hydraulic sectors, the configuration shown in Figure 7 was obtained in 80% of the cases. As a result, three sectors have been obtained that are isolated through 11 cut-off valves (links shown in red). These sectors have 56, 50, and 17 pipes, respectively. All of these sectors satisfy the requirements for becoming valid hydraulic sectors in terms of maximum and minimum total pipe lengths.

The average elevations for these sectors are 73m for the brown sector, 69m for the yellow sector, and again 73m for the green sector. As shown by the plots in Figure 5, the architecture of the sectors stabilizes during the simulation. In this case, it is the evolution of the average sector demand that is represented. We have chosen this graph since it shows the main reason why the green sector appears as a genuine sector, despite the fact that its average elevation coincides with that of the brown sector.

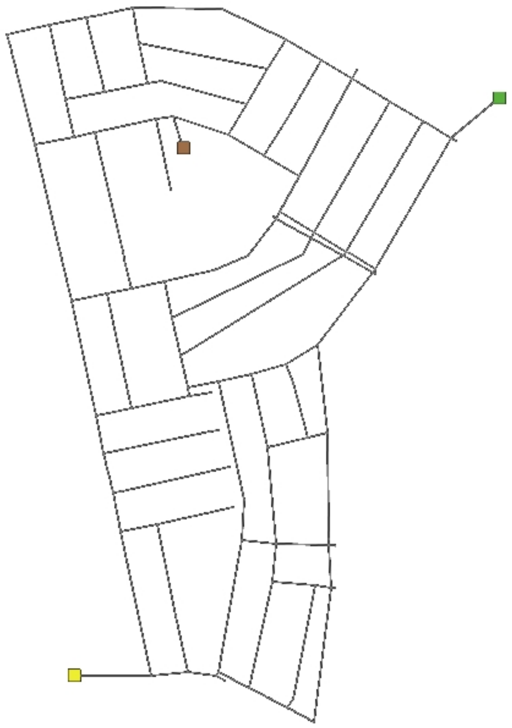


Figure 6. Layout of the studied network

Finally, it is noteworthy that the validity of the district division has been checked using EPANET2. The analyses performed show that the proposed division effectively cuts the water supply for the desired parts of the network. Also, the entire network and individual sectors maintain all their design requirements. As a consequence, the proposed division into DMAs is perfectly feasible and reliable.

## CONCLUSIONS

The multi-agent metaphor has been used with success in different areas and is reasonably applicable in the water management field. In addition to the traditional centralized architecture of a single reasoning agent (the computing counterpart of human decision support), it is possible to use systems of reasoning agents, or to apply multi-agent simulations to verify hypotheses about the various processes in water distribution. Partial implementations of multi-agent applications are expected to simplify communication with domain experts during the process of modelling the expert knowledge, identifying needs, and summarizing requirements for final application operation. Among the various scenarios using multi-agent systems in the scope of decision support for a water management company, we have focused on the division of a network into district metered areas. Division into DMAs helps the decision-making process, as well as the implementation of suitable actions to improve the control of a network and give solutions for important aspects of water distribution management – such as leaks and water quality.

Figure 7. Final distribution of hydraulic sectors

We will be researching various lines of research in the future. One line of action will be addressed to exploiting the presented model in a number of ways: adding new conditions to cluster building; refining the implemented clusters; and generally improving the performance of the model. An interesting improvement would consider starting the process automatically, instead of waiting for the user to define *a priori* the number of sectors, thus performing the division into an optimum number of sectors. The model must also be applied to larger networks. Nevertheless, taking into account that the considered network is medium-sized and running times are slow (ranging between 10 and 20 seconds on a PC with an Intel Core 2 Duo T5500 (1.66 GHz) processor for the case considered), no added difficulties are foreseen. Another line of research will focus on the development of other scenarios for multi-agent applications in the water supply field, including aspects related to water quality and other managerial issues.

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