

## WatSup model: a high resolution water supply modelling system

M. G. Murray and P. M. Murray

### ABSTRACT

The WatSup<sup>®</sup> (Watsup Model Systems Ltd) model is a high resolution model of dendritic water supply networks formed by interconnected modules. Each module, e.g. a house, office, etc, can have multiple users using elemental demands, which can be stochastic or deterministic, to produce representative flows. Elemental demands represent water using devices, e.g. a toilet, and are modelled as flow against time. Stochastic elemental demands have modeller defined variability and can include queuing. Deterministic elemental demands occur at fixed times. Modules, which can include local storage, are interconnected to form networks with the flows being aggregated at each node. Network and system faults can be introduced as stochastic processes, flow limits and hydraulic constraints are observed and queued demands carried forward until satisfied. A novel double sweep algorithm is used to distribute flows within the model. The WatSup model uses an advanced object-oriented numerical engine to provide a robust, fast modelling system with a time step of one second.

**Key words** | Disaggregated model, elemental demands, Poisson process, residential water demands, water demand, water supply

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### NOTATION

$D$	Diurnal factor	$T$	Internal elemental demands time index (seconds)
$dm$	Elemental demands mains flow profile ( $m^3$ )	$Ta$	Time of arrival (seconds)
$dt$	Elemental demands tank flow profile ( $m^3$ )	$Ta\ Span$	Mean time of arrival spread (seconds)
$Fi$	Failure interval (seconds)	$Ts$	Service time (seconds)
$Fn$	Random function	$Ts\ Span$	Service time spread (seconds)
$F\ Span$	Failure interval spread (seconds)	$U$	Usage scaling factor
$i$	Elemental demand index	$U\ Span$	Usage scaling factor variation
$j$	Connected mains module index	$Us_n$	Users $Ta$ factors
$Id$	Identification time (seconds)	$Vm$	Main volume ( $m^3$ )
$Id\ Span$	Identification span (seconds)	$Vv$	Valve volume ( $m^3$ )
$m$	Module index	$Vt$	Tank volume ( $m^3$ )
$M$	Monthly factor	$W$	Weekly factor
$Mr$	Connected mains volume required ( $m^3$ )		
$n$	Number of active elemental demands		
$Prob$	Probability of use		
$R$	Repair time (seconds)		
$R\ Span$	Repair time spread (seconds)		
$Q$	Required volume ( $m^3$ )		

### ACRONYMS

HAM	Human Activity Model
OON	Object-Oriented Numerics
PRP	Poisson Rectangular Pulse

## INTRODUCTION

The stochastic nature of water supply system operation is caused by the ever changing pattern of consumption. Methods for estimating water usage vary greatly, from the use of metering and surveys (Edwards & Martin 1995) to the examination and monitoring of a water supply system operation and the fitting of distribution functions and parameters to produce stochastic consumption methods (Verbitsky 1993).

Verbitsky (1993) describes a stochastic water demand model used to build demand distribution functions for any duration (year, day and hour) of maximum water consumption in a cyclic network. The work is based upon analysis of existing network records and their statistical properties.

Buchberger & Wu (1995) describe a stochastic model of indoor residential water demands based upon a non-homogeneous Poisson rectangular process (PRP), where residential water use can be characterised by three variables: intensity, duration and frequency. The concept of elementary queuing theory was employed with the random arrival of customers (users) following a Poisson process and servers (appliances) engaged for random or fixed lengths of time along a dead-end supply network (cul-de-sac, high-rise apartments). Expressions were derived for the mean variance and probability distribution of the flow rate and corresponding pipe Reynolds number at any time and point in the system. It was found that the PRP queuing model provided a reasonable description of the temporal and spatial variability of flow in dead-end supply networks, whilst requiring few parameters.

Buchberger & Wells (1996) extended the work of Buchberger & Wu (1995) by testing the model for instantaneous water demands against four data logged single dwellings. Each dwelling provided a full year's inflow data logged at one second intervals. Using this data, individual rectangular flow pulses were created using signal smoothing and pulse separation techniques and compared with the PRP model. They concluded that water demands for internal domestic use could be characterised by equivalent rectangular pulses and that a PRP was a good representation for dead-end supply networks, although the variation in daily routine did sometimes go beyond the bounds of a Poisson process.

Following on from this work, Buchberger & Lee (1999) enlarged the case study to 21 houses, 18 of which they monitored for internal flows only using data loggers. Using the assumptions that the server engaged two customers at the same starting time, but allowed overlapping flows to occur, single Poisson rectangular pulses could be extracted. Diurnal cycles were dealt with by breaking a day into 24 one-hour intervals, each of which was considered homogeneous. The results showed a strong correlation between modelled hourly cumulative flows and measured flows.

## WATSUP MODEL CONCEPT

The WatSup model concept is the generation of a disaggregated model by combining an analogue of each elemental water-using unit (elemental demand), each water user (user), the groupings of water users into modules and the network connections, including leakage and component failures. This model is evaluated using a one second time step and can be run for a lengthy simulation period (e.g. years) or for multiple runs of a specified period.

Analysis of the elemental water-using units shows that two types of model, stochastic and deterministic, can represent the entire range of water-using devices. Furthermore, each elemental water-using unit can be associated with a number of users. Users can be grouped into modules/nodes which represent supplied units, e.g. a dwelling, office or factory unit, etc. In this way a model can be built to represent the analogue of the physical system and can model the characteristics of water-using devices taking into account the habits of users. Multiple, mixed or similar units (modules) can be included in a model, as can component and network failure characteristics, thus leading to a comprehensive model of a given network.

## THEORY

Component water use falls into two categories: stochastic and deterministic. Stochastic demands can be defined by probability of use. However, the probability of use is not constant over time; it can vary with the time of day, the day of the week and with the seasons. For example, the

probability of toilet use is higher during waking hours than during sleeping hours, the probability of using an office toilet is higher during a weekday than at a weekend and the probability of watering a garden is higher during the summer months than during the winter months. All of these factors can be taken into account when building a model so that the model output is representative of reality over extended time periods.

Deterministic demands can be defined as water usage at fixed intervals or at set times. For example, a process plant running through a production cycle, or a dishwasher running off a time clock to use cheap rate electricity.

To give a realistic simulation of typical water usage, usage is broken down into its fundamental components. For example, washing machines, baths, showers, toilets, production and process cycles, etc., collectively referred to as elemental demands. The elemental water usage of each active elemental demand is defined as a time series to give typical instantaneous and total flow demands with defined variability from use to use where appropriate.

The WatSup model is a rigorous application of multiple processes at the elemental demand level with full control of probabilistic variables for each user of each stochastic elemental demand. Typically, for stochastic elemental demands, water use can be visualised as a customer-server interaction in which customers arrive according to a non-homogeneous Poisson process and engage a water server for a variable period of time and a variable flow rate. This is the basis of the technique used in the WatSup model to aggregate multiple stochastic elemental demands for each time step at sample points to produce typical flow patterns for a given network with a given combination of elemental demands and users assigned to each node of the network.

In addition deterministic elemental demands can be modelled where demands occur at fixed times or intervals, the effect of these demands being aggregated each time step in the same way as stochastic elemental demands. In this way a very complex water supply system can be modelled using either stochastic or deterministic elemental demands or a combination of both. There are no restrictions on the type of demand modelled and the WatSup model can produce integrated flow information for any mix of demands such as housing, office, agricultural and industrial usage.

The WatSup model simulates a dendritic water supply network, single-pipe or multiple branches, with provision for both flow and local storage at each node. The WatSup model algorithm consists of five parts: the physical system, elemental demands, users, system reliability and internal analysis. The physical system represents the limitations and connections within the model. Elemental demands describe the resources available, e.g. baths, toilets, etc., within each module and users are defined to link the elemental demands to the physical system. The system reliability introduces failure modes and characteristics and the internal analysis provides in-depth analysis of the internal flow patterns, elemental demand usage, user interactions and the states of local storage within the WatSup model.

## PHYSICAL SYSTEM

The physical system describes the physical limitations of the system such as flow constraints, tank/reservoir capacities, pump or valve performance and the connections between the component parts of the system. Tanks/reservoirs are described by their shape (rectangular or circular tanks), or by using an elevation-volume relationship (irregularly shaped tanks). Valves and pumps describe the method of filling of the local supply tank. Modelled valve types can range from simple ball valves to complex electric valves and pumps with hysteresis. Ball valves and pumps are modelled using tabulated lookup data describing opening/elevation flow relationships. Electric valves are on or off, giving the maximum flow as limited by the valve or network constraints or zero flow.

Modules, see [Figure 1](#), incorporate a supply pipe, an optional tank, a mains delivery pipe, an optional tank delivery pipe and users with their sets of demands. The WatSup model uses modules connected together to form a dendritic network.

The supply pipe can be constrained physically to reflect pipe sizes and maximum flow rates and between the supply pipe and the tank is a valve or pump which characterises the flow into the tank. Although pressure heads are not calculated throughout the model the physical system acts within hydraulic constraints to produce a flow-limited

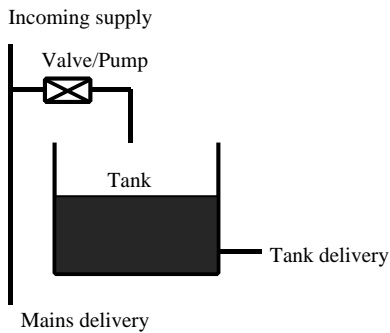


Figure 1 | Configuration of a module.

model capable of representing both fully pressurised and non-pressurised systems.

The modules can be coupled together so that each module can be connected to either the mains or the tank delivery pipe of any preceding module to form a dendritic system. The module can be used in many ways. It can represent a single housing unit with local storage, such as is commonly used in the UK. By ignoring the tank and valves the module becomes a node and by ignoring the mains delivery the module becomes a service reservoir.

## ELEMENTAL DEMANDS

Elemental demands provide the patterns of water usage within the model and can be thought of as a series of flow time events which are called upon when certain actions are carried out – typically a user arrives and activates an elemental demand which has a service time. There are two main parts to elemental demands: the trigger method, which specifies when and how an elemental demand is triggered by a user, and a flow time profile which is used when the elemental demand is triggered. The trigger method depends upon whether the elemental demand type represents a stochastic or a deterministic process, whereas the use of a flow time profile is common to both elemental demand types.

An elemental demand flow profile consists of two series of time flow points. One series typifies flow time requirements from the mains supply source of the module and the second series typifies flow time requirements from the tank/reservoir within the module. In this way a demand can

represent mains-only flow such as drinking water, a hot water supply fed from the tank or a mixed process such as a washing machine or running a bath. In addition a usage scaling factor,  $U$ , can apply a scaling factor to the flow values of each series, thus allowing scaling of the flow rates without altering the time points. The service time,  $T_s$ , is the length of time of the demand flow profile. It is fixed in deterministic elemental demands but may be randomly varied over a preset range for each use of a stochastic elemental demand.

Both stochastic and deterministic elemental demands are specified globally within the model. Association with a user within a module produces an instance of the specified elemental demand which operates independently of all other instances of the same elemental demand: thus, many modules can have the use of the same elemental demand, each acting independently. However, only one instance of that elemental demand may be in use at any one time in each module. In modules in which a multiple of the same elemental demand is required elemental demands can be added in parallel by declaring multiple copies of the elemental demand with different names (e.g. Toilet 1, Toilet 2, etc.).

The trigger method for a stochastic elemental demand is based on a Poisson process. The Poisson process for a stochastic elemental demand is based on a user arriving at random intervals, with a mean time of arrival, i.e. the mean interval between use,  $T_a$  (seconds).

The most basic form of probability,  $Prob$ , of a stochastic elemental demand being used in any given time step is given by:

$$Prob = \frac{1}{T_a} \quad (1)$$

The  $T_a$  of a stochastic elemental demand may be altered by  $T_a$  Span (seconds), the mean time of arrival spread, that may adjust the spread of  $T_a$  within a range of  $T_a \pm 1/2 T_a$  Span when it is calculated at each time step. Additionally,  $Us_n$ , the user numbers' factor, can be used to alter the likelihood of a stochastic elemental demand's use with the number of users in the module it is linked to, according to a lookup table entry. This allows for a non-linear relationship to the number of users within the module that the stochastic elemental demand is linked into.  $Us_n$  factors greater than

1 increase the likelihood of use whilst those less than 1 decrease the likelihood of use. An example when this factor may be used is a washing machine, where one user typically uses it for all the household, but the total number of users within the household alters the interval between use and therefore the probability of use in any time step interval.

The probability of a demand being used in any given time step with variation due to the number of users and a spread in the average  $Ta$  is given by:

$$Prob = \frac{Us_n}{Ta + Fn(Ta Span/2)} \quad (2)$$

where  $Fn$  is a random number in the range  $\pm 1/2 Ta Span$ . Furthermore, the Poisson process can be selected to include seasonal variation by the use of three factors: a diurnal factor,  $D$ , that describes variations within a 24-hour period, a weekly factor,  $W$ , that describes variations within a week, and a monthly factor,  $M$ , that describes variations from month to month where  $D$ ,  $W$  and  $M$  average 1 over the appropriate interval. The seasonal factors are each described using lookup tables that use linear interpolation between the factor points. Diurnal factors are described using hourly data starting at midnight, weekly factors use daily factors from midnight running Monday to Sunday and monthly factors are specified at the change of each month using a synthetic year of 365 days and standard year month length values.

The probability of an elemental demand being used in any one time step when including seasonal factors is:

$$Prob = \frac{DWMUs_n}{Ta + Fn(Ta Span/2)} \quad (3)$$

Seasonal factors allow for the mean  $Ta$  of a stochastic elemental demand to be adjusted in each time step without altering the given general  $Ta$ . Seasonal factors greater than one increase the likelihood of use whilst those less than one decrease the likelihood of use. Seasonal factors may be used, for example, to specify preferred times for stochastic elemental demands to occur. For example, agricultural irrigation systems are unlikely to be used in the winter and early spring, but are used in the summer and early autumn. In addition, the preferred time to irrigate is early evening. It should be noted, however, that if the average value of the seasonal factors does not equal one then the average  $Ta$  over the period covered by the seasonal factors will be modified.

The elemental demand flow profiles may be adjusted once a stochastic elemental demand is selected for use. The adjustment of the service time,  $Ts$ , uses  $Ts Span$  which randomizes the effective  $Ts$  in the range  $Ts \pm 1/2 (Ts Span)$  where  $Ts$  is given in seconds. This is used to adjust all the time points within each flow time series. An example of the effect of  $Ta Span$  on a time series is shown in Figure 2.

Scaling of the flow values of the points is carried out using the usage span,  $U Span$ , which randomizes the usage factor in the range  $U \pm 1/2 (U Span)$ . Usage span is given as a percentage of the usage factor. The same factor value is applied to each value in the time flow series to maintain consistency (see Figure 3).

Deterministic elemental demands are used when the elemental demand is known to occur at a fixed interval, or at predetermined times. Water-using machines or equipment may, for example, go through a fixed period wash cycle or have predetermined times at which a resource is required. Deterministic elemental demands can be specified in two ways: the first is with a fixed interval  $Ta$  and an initial offset for the beginning of the model run, while the second is for the elemental demand to occur at exact times. Additionally, the fixed times may be repeated using a daily or weekly cycle. Deterministic elemental demands have fixed demand rate profiles which are not altered by any stochastic sizing factors.

Elemental demand queuing caters for the occurrence of an elemental demand that is already in use which is required again. Two options are possible when this occurs. The first option is for the user to wait for the elemental demand to become available and then use it. An example of

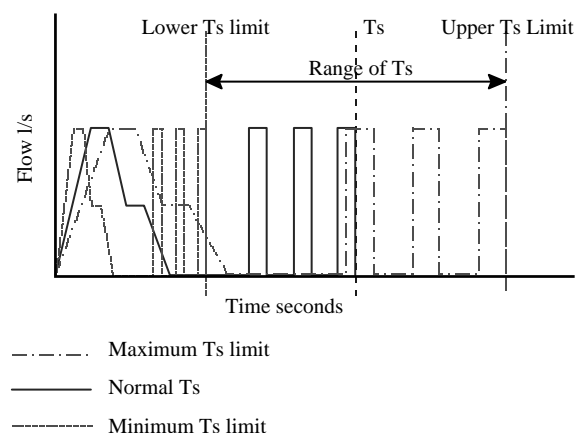
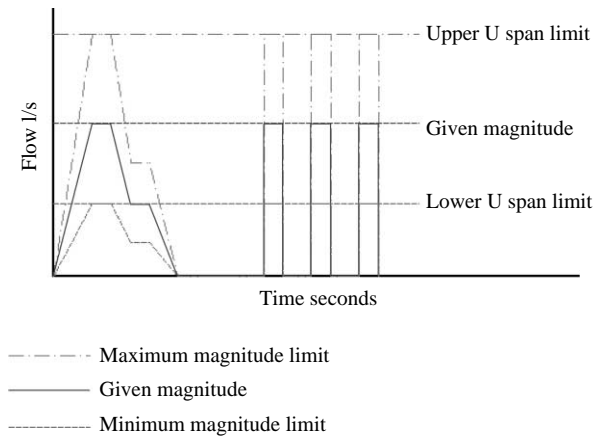


Figure 2 | Description of the effect of a service time span on the service time.



**Figure 3** | Description of the effect of usage span on the magnitude of the elemental demand flows.

this may be a family all wanting to use a bathroom in the morning when each member of the family uses the bathroom one after another. The second option is to skip usage when an elemental demand is in use. An example of this could be using a car wash at a petrol station. Use is desirable but not essential and if the car wash is in use its use can wait until another time. Elemental demand queuing may be switched off independently within each elemental demand or globally throughout the entire model.

## USERS

Users link the elemental demands within a model to the different modules. Users should be thought of as people using water devices or as individual machines running through a series of operations requiring water as a resource. An example in the case of a person could be a tap, toilet or washing machine or, in the case of a machine, a cleaning or production cycle. Users are assigned to individual modules and elemental demands which are available globally within a model are assigned to users. A user can have any number of elemental demands linked to them, thus creating an individual demand profile using a series of predetermined stochastic and deterministic elemental demand events. For some elemental demands, for example a washing machine, the elemental demand may always be used by one user, but the frequency of use may be related to the number of users in the module. In this way the number of users in a module

may modify a stochastic elemental demand's frequency of use when the stochastic elemental demand's user  $Ta$  factors are set to values other than one.

## SYSTEM RELIABILITY

The system reliability describes the reliability of various parts of the system and how failures of parts of the system will manifest themselves. There are two types of system reliability: network and equipment. Network reliability describes the reliability of the pipe network whilst equipment reliability deals with valve and pump reliability. Network reliability, which refers to leaks, is modelled by additional stochastic demands. The models of reliability incorporate the ability to respond to failures and repair them, again as stochastic processes, so that after a suitable time period the failed part of the system can be brought back into operation. Both types of reliability use a non-homogeneous Poisson process to describe failures using time intervals and variation spans that alter the intervals within a range; both the intervals and spans have the unit of time (seconds).

The general form of the probability equation used to find failure intervals using an interval,  $I$ , and span,  $S$ , where  $F_n(S)$  is a random function  $F_n$  in the range  $\pm 1/2 S$  is:

$$Prob = \frac{1}{I + F_n(S)} \quad (4)$$

Network reliability describes how failures within the pipe supply network manifest themselves. The entire dendritic network is treated in the same way with no allowance made for different pipe types, size, pressure, length, age, condition, etc. Network reliability is described using three time intervals: failure interval ( $F_i$ ) that describes the average interval between failures, identification time that describes how long it takes from the start of the failure to the beginning of the start of the repairs and repair time that describes how long it takes to repair the failure. The three time variation spans are: failure span ( $F_i$  Span), identification span and repair span; each span varies the corresponding time interval by  $\pm 1/2$  Span. The identification time is calculated using a pseudo random number to generate a mean identification time,  $I_d$ , and a span of  $I_d$  Span within the range of  $I_d \pm 1/2 (I_d$  Span). The repair

time is calculated using a pseudo random number to generate a mean identification time,  $R$ , and a span of  $R$  *Span* within the range of  $R \pm 1/2 (R \text{ Span})$ .

Network reliability for the entire network is divided into non-overlapping percentage intervals of the maximum capacity of the supply pipe, with each interval having any width. In this way a pipe can be described by many percentage intervals, each with a different probability of occurrence. Percentage intervals describe the likelihood of a failure occurring in any one time step; each pipe within the network is tested for failure within each percentage interval at each time step. If a failure occurs then the percentage failure of the selected pipe is calculated by a random function within the percentage interval multiplied by the selected pipe's maximum capacity. The losses due to leakage take precedence over elemental demands further down the supply chain. In effect, a network failure places an additional demand on the supply pipe that is satisfied before any elemental demands or tank requirements in any downstream module.

## INTERNAL ANALYSIS

Internal analysis within the WatSup model is divided into two parts. The first part provides in-depth analysis of the internal flow patterns and volume and the second part examines interactions between users and elemental demands. The analysis of the module internal flow patterns and volumes is carried out using operator defined class intervals. In addition, a log of cumulative flows and the instantaneous volumes throughout the module is kept. The monitoring locations are named in Figure 1.

The interactions between the users and elemental demands are monitored to locate the selection of the use of an elemental demand by a user, which may be either used immediately or, alternatively, enters the queue of the module if the elemental demand is already in use.

## ALGORITHM

The WatSup model uses a constant time step of one second to minimise aliasing and give a high resolution model. Aliasing occurs when the sampling frequency is such that

events can occur between samples. For example, to fill a drinking glass with water takes between two and three seconds. This can be modelled with a sample interval of one second. The calculation at each time step uses a novel double sweep algorithm to assess and distribute the flows within the model. The model can currently solve dendritic models with many branches and one source of supply. The algorithm is split into four basic parts: system reliability, first sweep, second sweep and internal analysis.

Firstly, system reliability is checked. Then the first sweep works from the extremities of the dendritic structure to the root. Within each module the tank level is calculated using the current volume within the tank, then the valve/pump flow is calculated. Next, the elemental demand queue is checked. This contains all the elemental demands that have previously been selected for use but have been unable to be used because they are already in use. Elemental demands are moved from the queue if the previous elemental demand of the same type has finished. Elemental demand usage is next checked. Each user's selection of elemental demands is checked using Eq. (3) to see if they are selected for use. If an elemental demand is selected and it is not in use then it goes straight into use: if, however, the elemental demand is being used already within the module then the elemental demand joins the queue.

Elemental demand flow profiles of each elemental demand currently in use are calculated next for both the mains and tank sources. Equations (5) and (6) below show the summation of the internal mains and tank elemental demands within each module. Values are linearly interpolated between given time points and, when the end of the flow profiles is reached, the elemental demand is automatically finished:

$$Vm = \sum_n^1 dm_{iT} \quad (5)$$

$$Vt = \sum_n^1 dt_{iT} \quad (6)$$

where  $dm$  is the elemental demand mains flow profile ( $m^3$ ),  $dt$  is the elemental demand tank flow profile ( $m^3$ ),  $i$  is the elemental demand index,  $n$  is the number of elemental demands active within the module,  $T$  is the internal elemental demand's time index,  $Vt$  is the total internal



tank volume required ( $m^3$ ) and  $Vm$  is the total mains volume required ( $m^3$ ).

Internal module flows are next calculated to give the required flow at the mains inflow point of the module. External mains and tank requirements are then added to external modules that are fed from the module and system reliability generated flows are added as shown in Eq. (7):

$$Q = Vm + Vv + F + \sum_m^1 Mr_j \quad (7)$$

where  $Q$  is the required volume ( $m^3$ ),  $Vv$  is the valve volume required ( $m^3$ ),  $F$  is the system reliability volume required,  $m$  is the number of connected mains modules,  $j$  is the module index and  $Mr$  is the connected mains volume required.

The second sweep works from the root of the dendritic structure to the extremities in the reverse order of the first sweep. Flow distribution takes the request received from the modules during the internal module flows and allocates the requested volumes, subject to the hydraulic constraints of the modules and supply pipes. The precedence used to fulfil the flow requirements from the available flow is network failure flows, then with each module internal mains, external mains and lastly tank inflows. If the flow requirements that are fed from the tank cannot be met, internal elemental demands are satisfied before any external modules are satisfied. Multiple modules connected to either the external or tank mains that cannot be satisfied are fed equally. Finally, the internal analysis is carried out in all modules.

## IMPLEMENTATION

The WatSup model is powered by an advanced object-oriented numerical (OON) engine. The numerics within the WatSup model are ill-suited for procedural programming but are ideal for object-oriented programming and the total use of object-oriented techniques provides a robust, fast solution for modelling the required numerics whilst simplifying the design of the system. Both the graphical user interface and the numerics have been programmed in Delphi.

## TESTING

The model has been tested from a single household model to networks of varying complexity. The initial test involved gathering and inputting data for a range of simple

household demands such as a bath, shower, toilet, dripping tap, etc. Using these simple demands, it was established that the model did indeed replicate a Poisson process for both single demands and multiple demands, with and without queuing. An example can be seen in Figure 4 which shows a single day's simulation of a toilet being replenished from a header tank and the ball valve refilling the header tank in a single module. In this example, the  $Ta$  of the toilet was set to 4.5 h and, although in this example the demand is used more frequently than its  $Ta$  would suggest, over an extended simulation a Poisson distribution is maintained.

It can also be seen in Figure 4 that at one point (18,000 s) multiple uses of the toilet occurred in quick succession, as shown in Figure 5. This is a good example of how overlapping uses of multiple demands can lead to aggregated flows within a module. However, it also shows an additional problem that can be encountered. Take, for example, a person's use of a bath. Even with seasonal factors set up so that baths are most likely to be taken in the evening or morning, it is possible for a person in the WatSup model to have three or more baths in quick succession and then none for the next three days. This is unrealistic and somehow needs to be solved. However, this shows that household water demands do not necessarily follow a non-homogeneous Poisson process and, hence, household water usage is not a non-homogeneous Poisson process (Buchberger & Wu 1995; Buchberger & Wells 1996; Buchberger & Lee 1999). Currently, the only way around such a problem is to use a deterministic demand. For demands which occur at a greater frequency the problem is not so great. One possible solution is to add a factor that links a previous demand's use to the probability of the demand's use again. Another solution is to create a composite deterministic stochastic elemental demand that, for example, would give a window in which a demand would stochastically occur and, once used, would not occur again until the next window of opportunity. This would allow, for example, a user to take a bath once every evening between 9 pm and midnight. The third alternative would be to develop a Human Activity Model (HAM) that reacts with the other users. These alterations have currently not been implemented.

An additional problem that can occur is that one demand is dependent upon another demand's activation and conclusion. For example, to always use the washbasin after using the toilet. This is currently only possible by



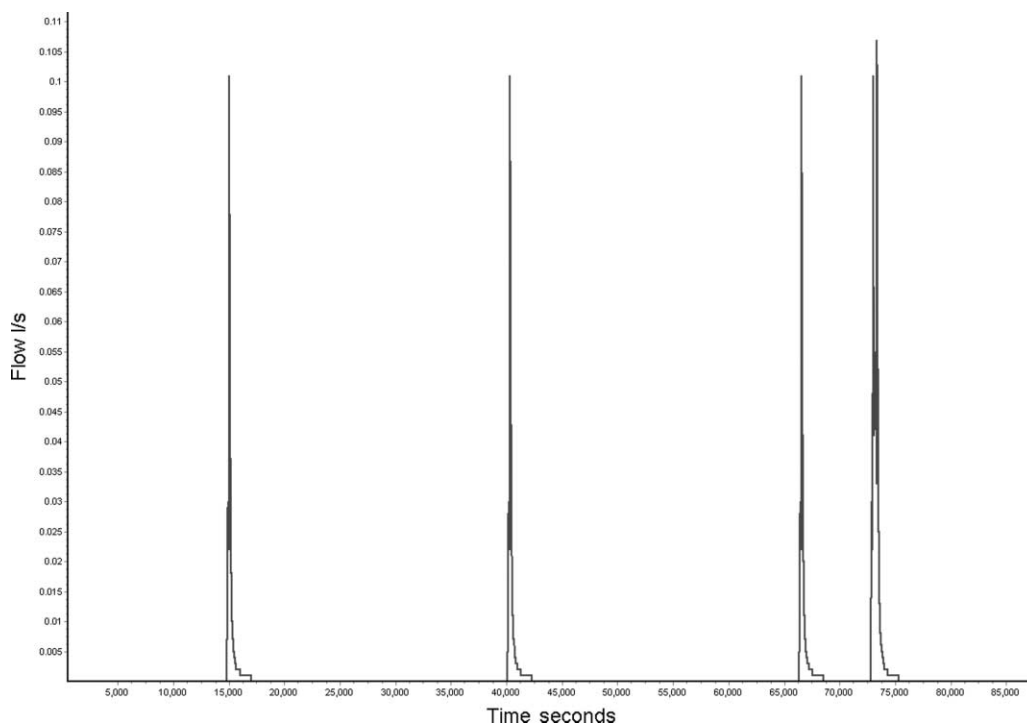


Figure 4 | An example of a single flushing toilet demand used throughout a day.

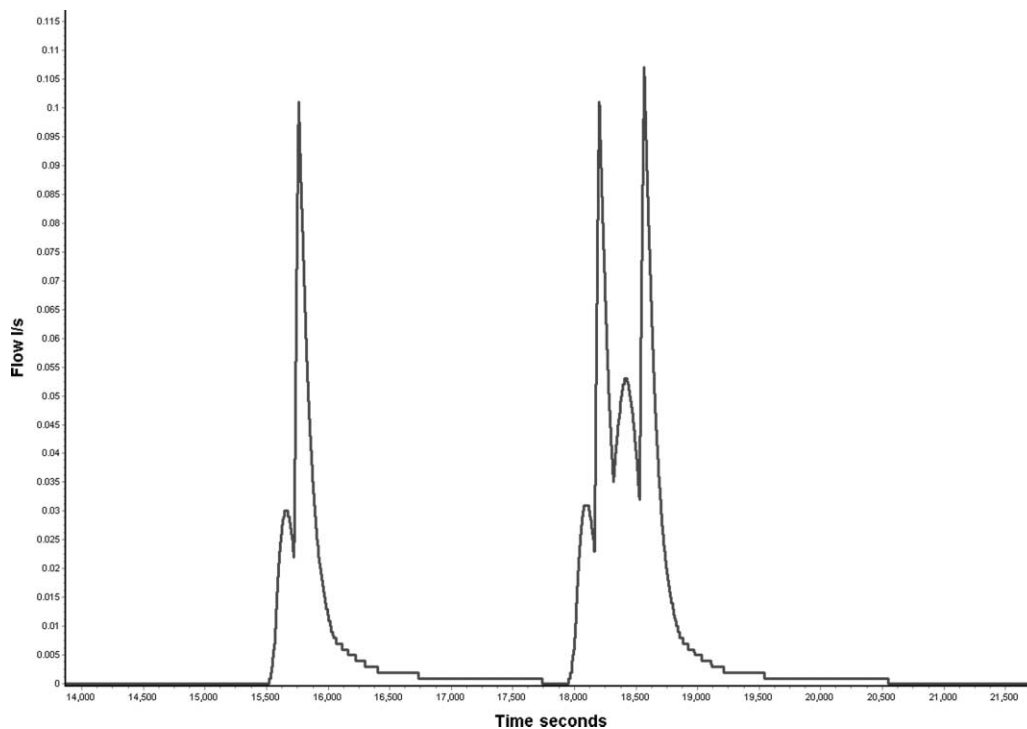


Figure 5 | Demand overlap.

including all the flow data in a composite demand time flow profile table. A better solution would be to enable a link between demand use.

The testing of one single demand has also allowed the testing of the refilling of the header tank. Tests have shown that a very accurate refill profile can be achieved. Figure 6 shows a bath being run. At first, both hot and cold taps are running and then the hot tap is turned off. It can be seen that the bath is able to take water at a faster rate than the supply because the bath is fed from the tank and not directly from the mains. The tank inflow demonstrates the opening of the ball valve to its maximum and then an extended refill period as the valve slowly closes. Following this the WatSup model was tested across large networks composed of multiple user modules with a mixture of stochastic and deterministic demands.

## DISCUSSION

At present, only dendritic networks can be modelled in the WatSup model; however, most supply networks in urban areas are cyclic in nature. The WatSup model could be

coupled up to a cyclic network model such as EPANET 2 (Rossman 2000) which would give a better representation of real systems.

Network reliability could be improved by allowing pipes to be grouped according to pipe type and then giving individual factors that allow for age, size and condition so that each part of the network can be tested separately. However, whilst this information is normally readily available, it is sometimes difficult to quantify. Additionally, calculated flows could be modified so that, when dealing with limited supply due to demands or losses caused by leakage further up the supply network, only a percentage of the actual supply passing through the pipe is removed rather than as a total of the maximum flow. However, this is not currently practical within the present flow distribution algorithm.

It has been noticed during the testing of the WatSup model that not all human/machine water using behaviour can be modelled using purely deterministic or stochastic approaches and that some linkage between the events and the users needs to be undertaken to enable more realistic behaviour to be represented. There are two possible solutions to this problem.

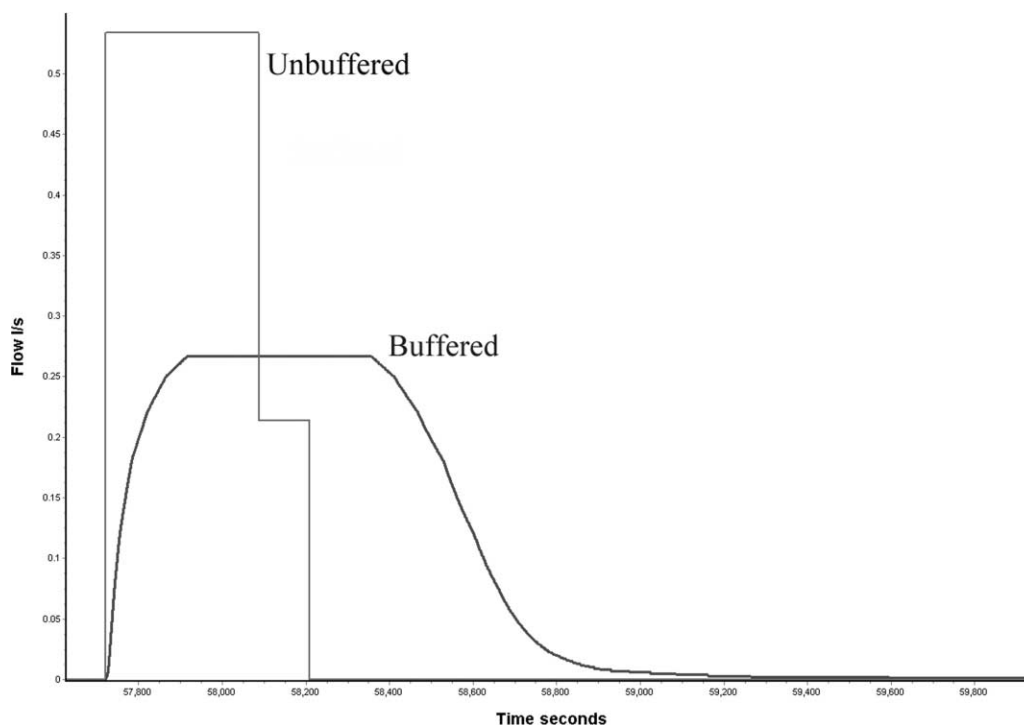


Figure 6 | Example of tank buffering.

The first solution is to alter the design of the stochastic elemental demands so that, in some cases, a demand's use can be linked to a previous demand's use and a new composite deterministic stochastic demand could be created to allow only one triggering of an elemental demand's use within a given window of time. Yet this may not solve the problem entirely because linking of the demands needs to be not only within time but to other demands within the modules: for example, going to the toilet and washing your hands afterwards. The two demands need to be not only linked together but also linked to other human habits.

The second solution takes concepts from the game and film industry. Recent advances in this field have seen thousands of computer-generated extras placed in film sequences using digital technology (Griggs 2003). Object oriented programming techniques and fuzzy logic (Verbruggen & Bakuska 1999; Nguyen & Walker 2000) are combined to create individual characters that react to their environment and each other. Effectively, each character is built from objects, has a "brain" and, when placed in an environment, "acts". One class of brain can be designed and individuals can be created as instances.

This is much like a user within the WatSup model. If you could teach a user within the model how to use water and couple that with the deterministic and stochastic concepts already used within the demands it would be possible to model the full range of water usage in households/business units.

The WatSup model is not the only area where this technique could be applied. There are many areas where human activity within models cannot be modelled completely using stochastic or deterministic techniques. This concept of generating users that react to their environment by using a mixture of stochastic, deterministic, fuzzy logic and object-oriented techniques, called HAM, is being examined within an Earth Systems Informatics Framework. Current work is being carried out to broaden and widen the concept. A general purpose model of human activity is currently under construction by the authors.

## CONCLUSION

The WatSup model is a robust, fast modelling system for the high resolution simulation of large dendritic networks of multiple occupancy modules containing a mixture of stochastic and deterministic water-using devices. The model can be run for extended periods with the flows, stored volume and events for each module being recorded or later analysis.

The Poisson process does not adequately represent all human behaviour; thus the individual detailed module flows are not always representative of real life. However, this effect is small and the aggregated flows with multiple modules are representative.

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