OPERATIONAL AND STRATEGIC PLANNING FOR A DYNAMIC WATER SUPPLY SYSTEM

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ABSTRACT

Wellington Water Ltd manages a dynamic water supply system that relies on water drawn from two surface water collection schemes and an aquifer. This presents unique challenges when assessing the long term ability of the system to withstand drought or the operational risk of supply shortfall during summer. Wellington Water uses a strategic planning tool called the Sustainable Yield Model (SYM) to support its decision making. The SYM simulates the entire water supply system including resource consents and infrastructure constraints. The SYM has recently been comprehensively upgraded through a project completed by the National Institute of Water and Atmospheric Research (NIWA). The project is future-proofing the SYM by streamlining the assessment process and incorporating the latest water demand and climate change information. Wellington Water uses the SYM to assess the future upgrades needed to maintain the Wellington Region's drought level of service in the context of increasing demand, changing climate and rising sea level. The SYM is also used in an operational capacity during summer to support a risk based assessment of the likelihood of supply shortfall and the need for watering restrictions. This paper outlines how the SYM is used for strategic and operational planning at Wellington Water.

KEYWORDS

Water supply infrastructure planning, supply and demand assessment, climate change, sea level rise, water restrictions, Sustainable Yield Model (SYM), WATHNET.

1 INTRODUCTION

Water utility organisations have to deal with both short term and long term issues affecting supply and demand. In the short term they have to deal with changes in day-to-day supply caused by weather dependent demands, planned outages for scheduled maintenance, and emergency situations. Over the longer term, there are issues related to gradual changes in demand, both temporal and spatial, changes in supply caused potential changes to the climate, the introduction of new sources of supply and the discontinuation of old facilities. Some of the long term changes are multi-faceted. For example, changes consequent on climate change may involve allowing for increased demand because of higher temperatures, changes in supply availability where sea-level rise impacts on aquifers, and changes in the seasonal distribution of rainfall affecting the availability of river sources.

Temporal issues affecting the supply system can be short term in nature lasting only a few days, or can take years or decades to work through. At the intermediate timescale there are also seasonal challenges that occur between this short and long term view. In an ideal world, a water supply system would know ahead of time exactly how much water was required, and could then operate to meet demand. Ideally for this to occur, perfect fore-knowledge of demand and supply availability is required.

To compensate for imperfect fore-knowledge, supplies are typically “buffered” through the use of reservoirs. Small service reservoirs deal with day-to-day variations in demand, while large storage reservoirs cope with longer term variation in supply. For supply systems without large amounts of controllable storage, such as the Wellington Water potable water network, guidance on the likelihood of future conditions is critical. Up to a week in advance, meteorological forecasts can be converted into useful demand forecasts. For guidance over decades, climate change predictions provide the best available information. However, there is a problem for seasonal forecasting since the time period to be covered is too long for standard meteorological forecasts to provide reliable information, and too short for climate studies to provide useful information.

To address these challenges, Greater Wellington Regional Council (GWRC) worked with the National Institute of Water and Atmospheric Research Limited (NIWA) to develop a WATHNET based tool nearly 20 years ago. The tool, now called the Sustainable Yield Model (SYM), has been updated a number of times to maintain model credibility and increase functionality. A significant update in 2004 included creating a procedure to use the SYM for seasonal prediction, called the Karaka model (Ibbitt, 2004) and Ibbitt and Woolley (2008). The procedure extracts guidance information from the Seasonal Climate Outlook published each month by NIWA. The Karaka model procedure involved a number of manual steps and utility programs dictated by the need to combine results from different software packages.

Responsibility for managing the Wellington metropolitan water supply transferred to Wellington Water Ltd in 2014. In 2015 Wellington Water initiated a project with NIWA to upgrade the SYM to the latest version of WATHNET and streamline the modelling process. With the introduction of WATHNET v5, (Kuczera et al., 2010) and its new scripting facility, there have been significant improvements that can now meet a host of different needs.

Subsequent sections of this paper:

1. Give a brief outline of WATHNET, focusing on such things as the elements it provides to model a water supply system;
2. Briefly describe the structure of the Wellington Water potable water network;
3. Indicate how the SYM is used to support strategic, i.e. long term, decisions;
4. Outline the Karaka model process;
5. Conclude with comments about how the Wellington Water potable water network, which has successfully used the SYM based on earlier versions of WATHNET for nearly 20 years, is now set up for the future.

2 OUTLINE OF WATHNET

WATHNET (Kuczera et al., 2009) is a multi-functional objective based water resources system network linear programming model. It can simulate, optimize and calibrate simple to very complex water resources. WATHNET is a generalised simulation model that departs from a more traditional “headroom” based approach to assessing system capacity such as outlined in the UK Water Industry Research (UKWIR) publication ‘*An Improved Methodology for Assessing Headroom – Final Report*’(UKWIR, 2002). WATHNET uses a network linear programme to simulate the operation of a wide range of water supply network configurations. It uses information about the current state of the system as well as forecasts of flow and demand to formulate a network linear programme problem. For each simulation time step WATHNET determines the water allocation for given streamflows and demands in accordance with following hierarchy of objectives (Cui et al., 2011):

- Satisfy demand at all demand centres

- Satisfy all instream flow requirements and constraints
- Ensure that reservoirs are at their target volumes
- Minimise delivery costs
- Avoid any unnecessary spill from the system

WATHNET represents a water resources system by a network of nodes and arcs and provides a good graphical presentation of the system being modelled. It incorporates a multi-objective genetic algorithm for optimisation to efficiently search through the multitude of possible solutions so as to identify a set of solutions that optimally trade-off expected performance against robustness or sensitivity of performance over the range of future climates (Mortazavi-Naeini et al., 2013). WATHNET uses network linear programming with constraints to allocate water within the system. It also uses a scripting language which enables the user to specify complex runtime functions to assign arc capacities and costs and constraints to the network linear program (Mortazavi et al., 2012).

Using WATHNET, NIWA developed the Sustainable Yield model for Wellington Water. Figure 1 shows a schematic of the SYM. Nodes represent network components such as reservoirs, pipe junctions and demand centres, and arcs represent pipes and stream channels. One of the innovative aspects of the SYM is the use of a series of reservoir nodes and streamflow channels to simulate the behaviour of the Hutt aquifer system that is subject to pumped abstraction. The SYM has been set up to simulate the operational and environmental controls that affect running of the actual supply network, e.g., minimum flows in rivers. Owing to the nature of the resource consents many of the environmental rules are complex and the system is able to easily handle these.

The SYM uses daily demand, rainfall, evaporation, temperature, and river flow data to model water supply under specific operating procedures. The network can be altered easily to add new components, such as reservoirs, or to change the properties of existing components, such as pipe capacity. This allows assessment of the response of the water supply system to changes in infrastructure and/or changes in operating practices, such as changes in environmental constraints. The input data can be altered to assess the sensitivity of the system to changes in climate, and the demand data can be altered to assess changes in water use under different climate scenarios, new stresses imposed by population growth, or the potential effects of demand restriction scenarios. The SYM can also be used to assess the effect of sea level rise or aquifer subsidence from movement of the Wellington Fault by implementing an alternative calibration for the aquifer sub-component that reflects the results of detailed studies.

The scripting language of WATHNET enables the SYM to attach complex consent conditions to conduits in straightforward ways. An example of a script is illustrated in Figure 2. This script checks the turbidity in the Orongorongo River. If the flow is above a set value water is not abstracted so as to ensure water treatment is not compromised by poor water quality. In this case flow rate is being used as a model approximation for water quality. The script also determines how much water can be abstracted from various sources within the Orongorongo catchment subject to pipe capacities and legal resource consent requirements.

Figure 1: Schematic of the SYM network (green lines represent the conduits, while blue lines represent streams. Small red squares represent storage units. Small yellow squares represent the demand centres. Small blue and green squares represent the stream and conduits nodal points such as pumping stations, pipe junctions etc.)

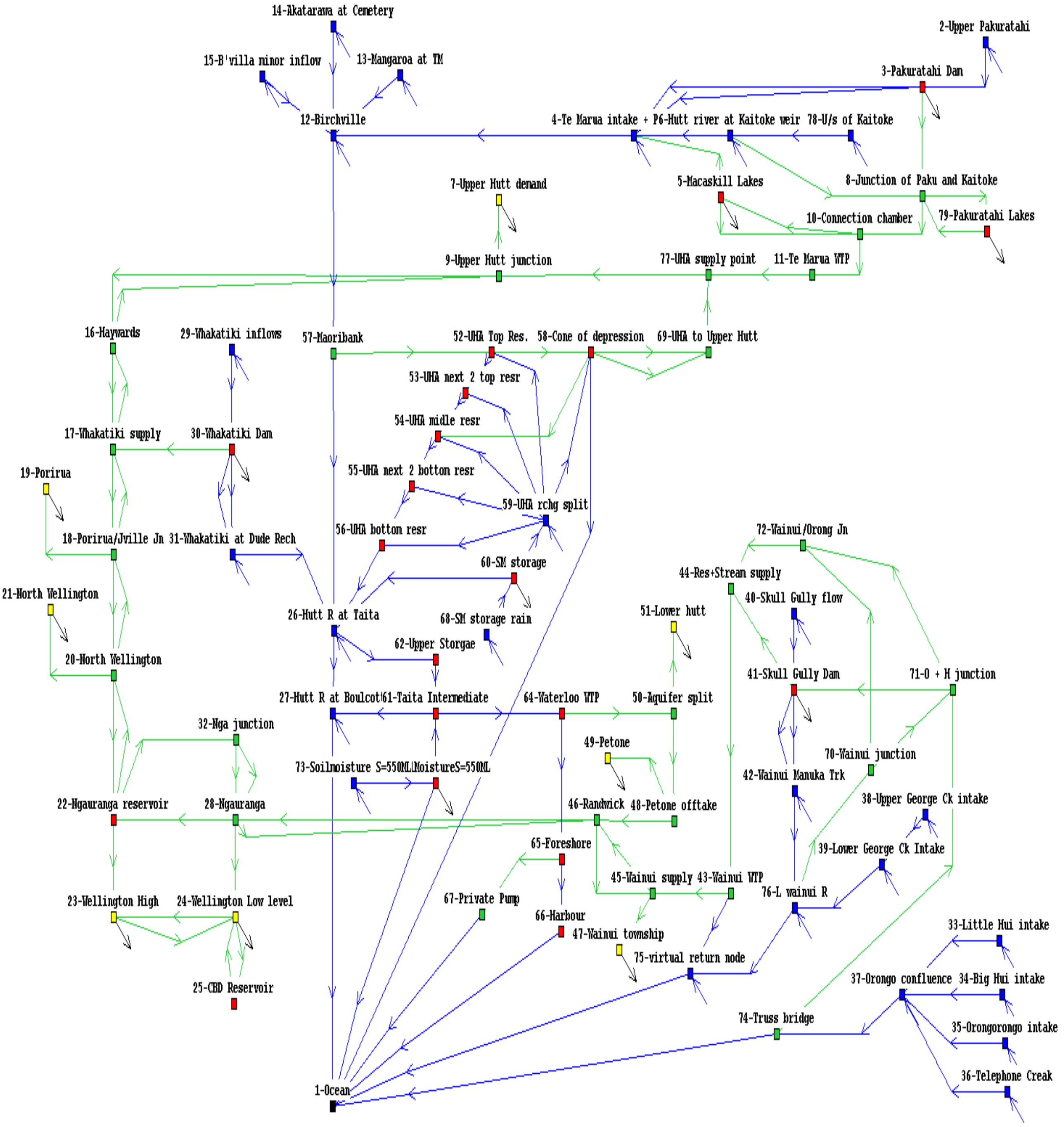
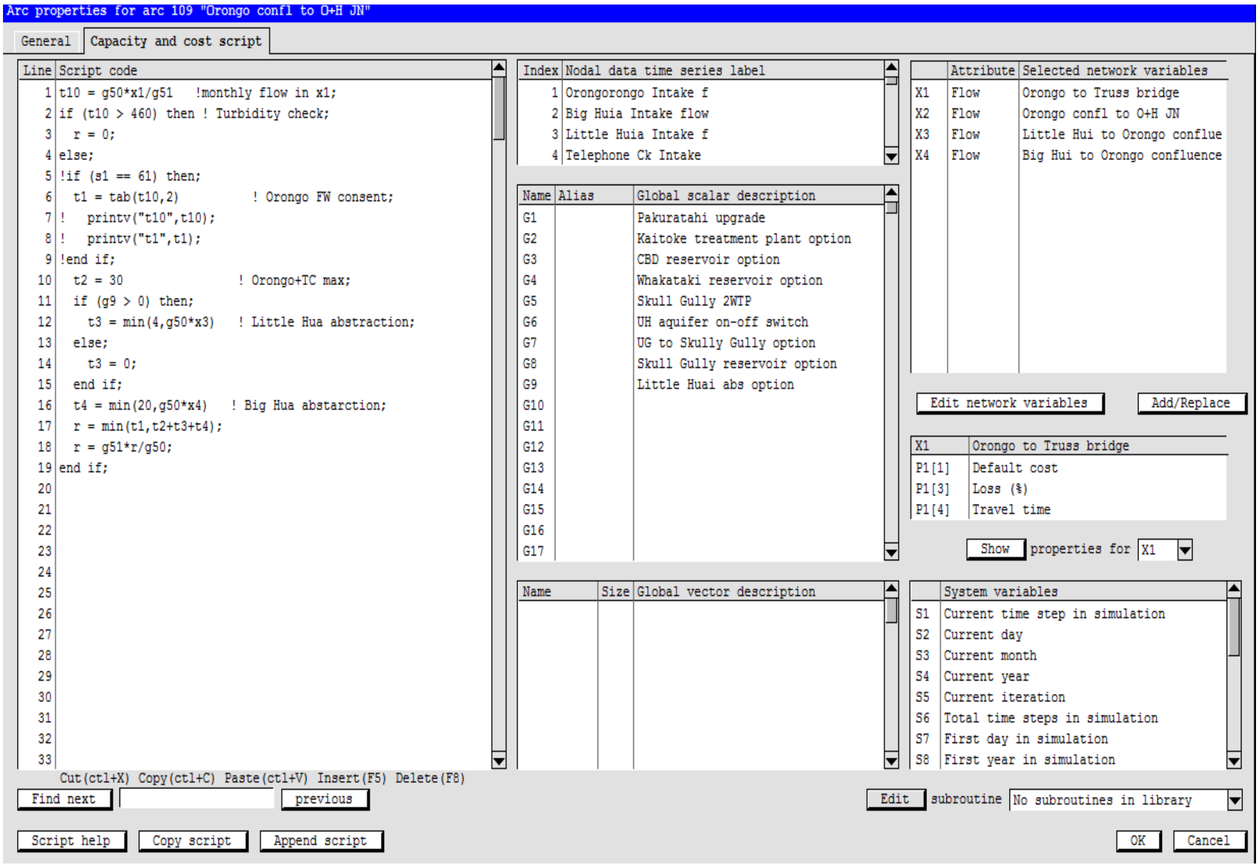


Figure 2: An illustration of WATHNET's scripting facility in the SYM. The left hand panel shows the script instructions while the other two panels show the definitions of the variables used in the script.



```
t10 = g50*x1/g51   !monthly flow in x1;
if (t10 > 460) then ! Turbidity check;
  r = 0;
else;
!if (s1 == 61) then;
  t1 = tab(t10,2)          ! Orongo FW consent;
!   printv("t10",t10);
!   printv("t1",t1);
!end if;
  t2 = 30                ! Orongo+TC max;
  if (g9 > 0) then;
    t3 = min(4,g50*x3)   ! Little Hua abstraction;
  else;
    t3 = 0;
  end if;
  t4 = min(20,g50*x4)   ! Big Hua abstarction;
  r = min(t1,t2+t3+t4);
  r = g51*r/g50;
end if;
```

Index	Nodal data time series label
1	Orongorongo Intake f
2	Big Huia Intake flow
3	Little Huia Intake f
4	Telephone Ck Intake

Name	Alias	Global scalar description
G1		Pakuratahi upgrade
G2		Kaitoke treatment plant option
G3		CBD reservoir option
G4		Whakataki reservoir option
G5		Skull Gully 2WTP
G6		UH aquifer on-off switch
G7		UG to Skully Gully option
G8		Skull Gully reservoir option
G9		Little Huai abs option
G10		
G11		
G12		
G13		
G14		
G15		
G16		
G17		

Name	Size	Global vector description

	Attribute	Selected network variables
X1	Flow	Orongo to Truss bridge
X2	Flow	Orongo confl to O+H JN
X3	Flow	Little Hui to Orongo conflue
X4	Flow	Big Hui to Orongo confluence

X1	Orongo to Truss bridge
P1[1]	Default cost
P1[3]	Loss (%)
P1[4]	Travel time

	System variables
S1	Current time step in simulation
S2	Current day
S3	Current month
S4	Current year
S5	Current iteration
S6	Total time steps in simulation
S7	First day in simulation
S8	First year in simulation

3 STRUCTURE OF THE WELLINGTON WATER POTABLE WATER NETWORK

The Wellington Water managed potable water network takes water from a combination of river and aquifer sources and delivers treated water through an integrated network of pipes to the cities of Hutt, Upper Hutt, Porirua and Wellington. Figure 3 shows the main physical features of the potable water network. The surface water sources are the Hutt, Wainuiomata and Orongorongo Rivers and their tributaries. The main ground water source is the Waiwhetu artesian aquifer which is recharged from the Hutt River once it enters the Lower Hutt flood plan. To enhance the quality, surface water from the rivers is treated at two treatment plants, one at Te Marua and the other in the Wainuiomata catchment. Orongorongo River water is piped to the Wainuiomata treatment plant for processing before entering the distribution system. The main source of ground water is pumped from the Waiwhetu aquifer at Waterloo treatment plant. The overall system is notable for the relatively small amount of surface reservoir storage capacity. Surface storage is augmented by aquifer water during summer months or when river sources are shut down for water quality reasons during rainfall events. While the Waiwhetu aquifer is the largest available source of stored water in the region, use of the water is restricted by environmental constraints to protect the resource from intrusion of saline water from the Wellington harbour.

Rivers can rise and fall quickly and demand variations have a significant weather related component. The SYM operates on a daily time scale to cope with the dynamic nature of the system. A significant challenge for the water supply system is its reliance on regular and sufficient rainfall to ensure adequate flow in the rivers to meet customer demands. This makes the system dynamic and particularly vulnerable to drought during abnormally dry conditions or where long term changes are likely to affect catchment yield characteristics.

The key to assessing how vulnerable the system is to drought is through a comprehensive and holistic understanding of how system supply and demand can change, and how these changes can affect the ability of the system to meet demand. The SYM provides the means to address this fundamental planning issue.

For more details about the Wellington Water potable water network please refer to Ibbitt and Williams (2010).

4 LONG TERM DECISIONS USING SYM

The Wellington Water drought reliability level of service standard is a system-wide annual shortfall probability of 2%, or in other words, normal demand should be met unless a drought is experienced that is more severe than a 1 in 50 year event. The network reliability is assessed using the SYM to predict the likelihood of supply shortfall for a given population, demand and climate scenario. This is completed as a Monte Carlo simulation typically using 2000 replicates, each with two years of daily data. The Monte Carlo approach significantly improves confidence in model outcomes. This is achieved by introducing statistical variability that may not be present in the historic data, but could potentially occur in the future based on our understanding of the underlying probability distributions.

Wellington is fortunate that there is historical rainfall data dating back to around 1890. There are also long temperature records as well as some flow records dating back to the 1960s. Using correlation models to extend the region’s multiple rainfall records back to 1890 provided the input to TopNet rainfall-to-runoff models for each of three river systems drawn on by the water supply system (Bandaragoda et al., 2004; Clark et al., 2008). The result of this modelling provides the river flow data for the SYM.

The SYM uses eight demand centres to represent water usage across the metropolitan region. An in-depth investigation was completed in 2010 to assess various factors affecting demand. The result was a set of statistical models of demand for each demand centre in terms of per capita demand (PCD). The demand models were fully revised as part of the upgrade in 2015. Each model has a non-linear deterministic component based on daily rainfall, temperature, sunshine hours and evaporation data, coupled with a stochastic component whose sole purpose is to allow for factors that cannot be extracted from the measured data. The deterministic components of the demand model were shown to typically explain 60% to 70% of the variance in measured validation data. The two components together provide realistic demand sequences that can be extended back to 1890 using the various meteorological inputs (Ibbitt, 2010).

Daily demand is calculated within the SYM as the product of population and per capita demand from each demand model. Statistics New Zealand population estimates and projections are used to generate current and future population scenarios

Figure 4 shows an example of results generated by the SYM. The system annual shortfall probability (ASP) for the existing system is expected to increase with population. Eventually the ASP will exceed the 2% level of service standard which represents the point at which either a network upgrade or demand reduction will be needed. The SYM is used to determine the impact of future upgrades such as increasing storage capacity to balance increasing demand, or distribution upgrades to overcome constraints affecting the ability of the network to fully utilise source capacity.

Figure 3: Wellington Water potable water network showing the location of the main surface water resources, the various demand centres, and the main components of the overall system. Adopted from (WWL, 2016).

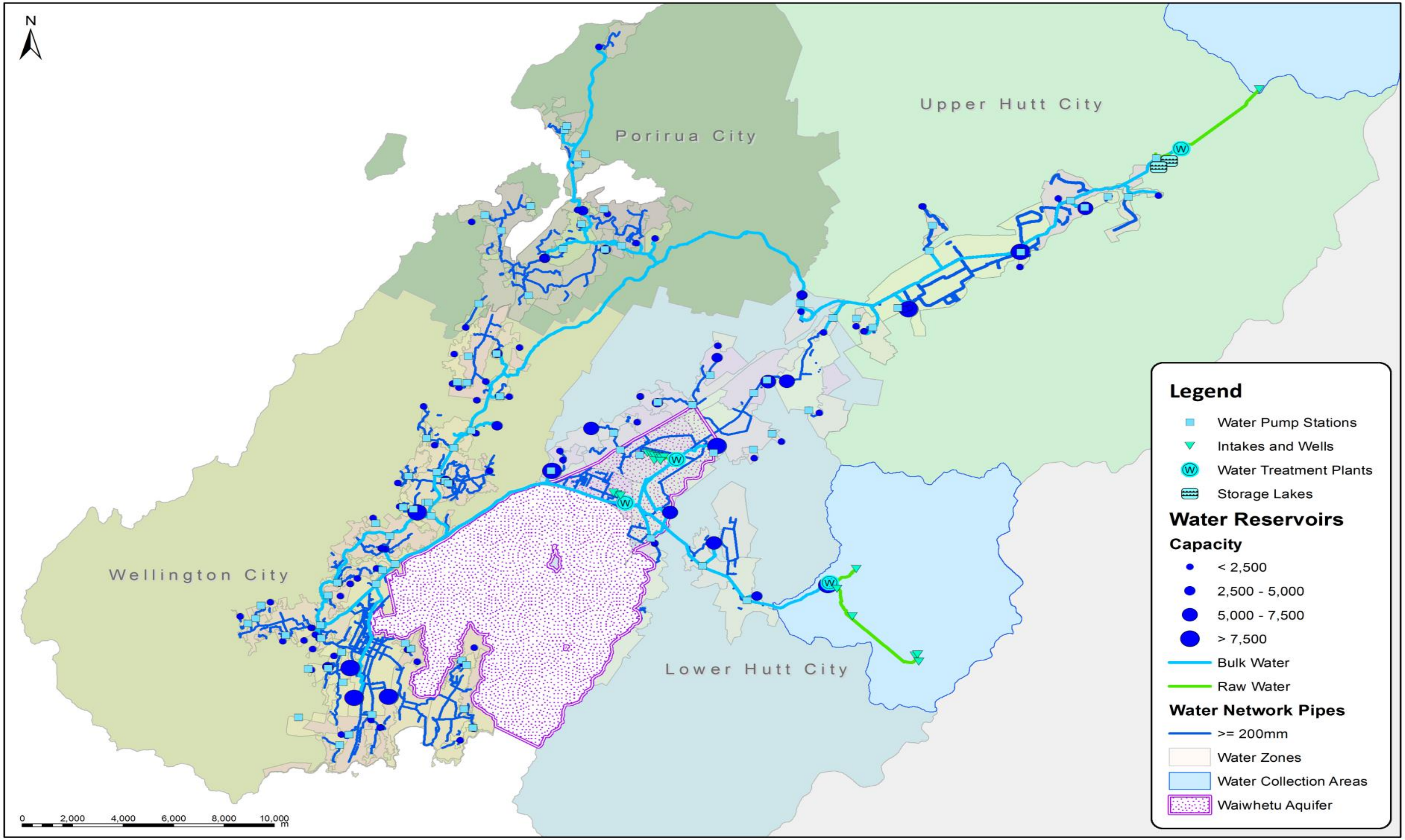
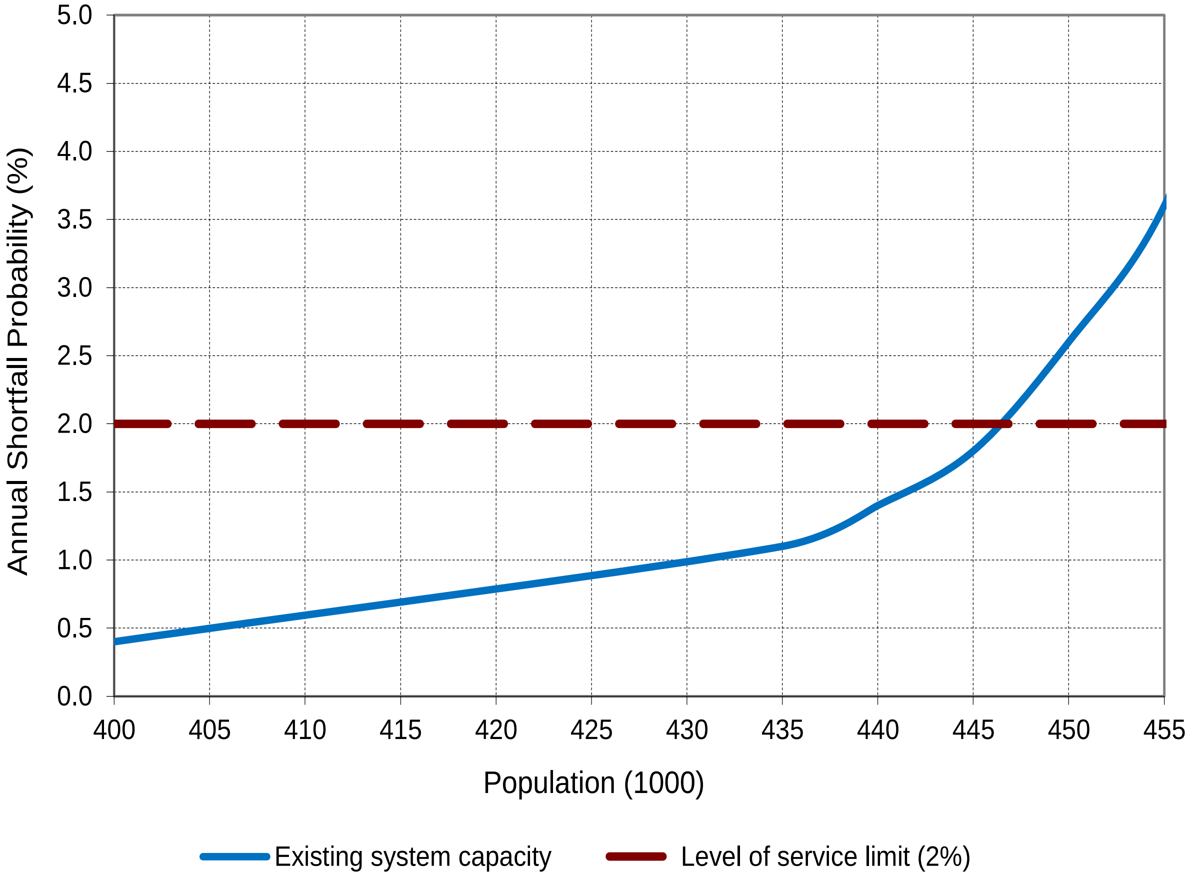


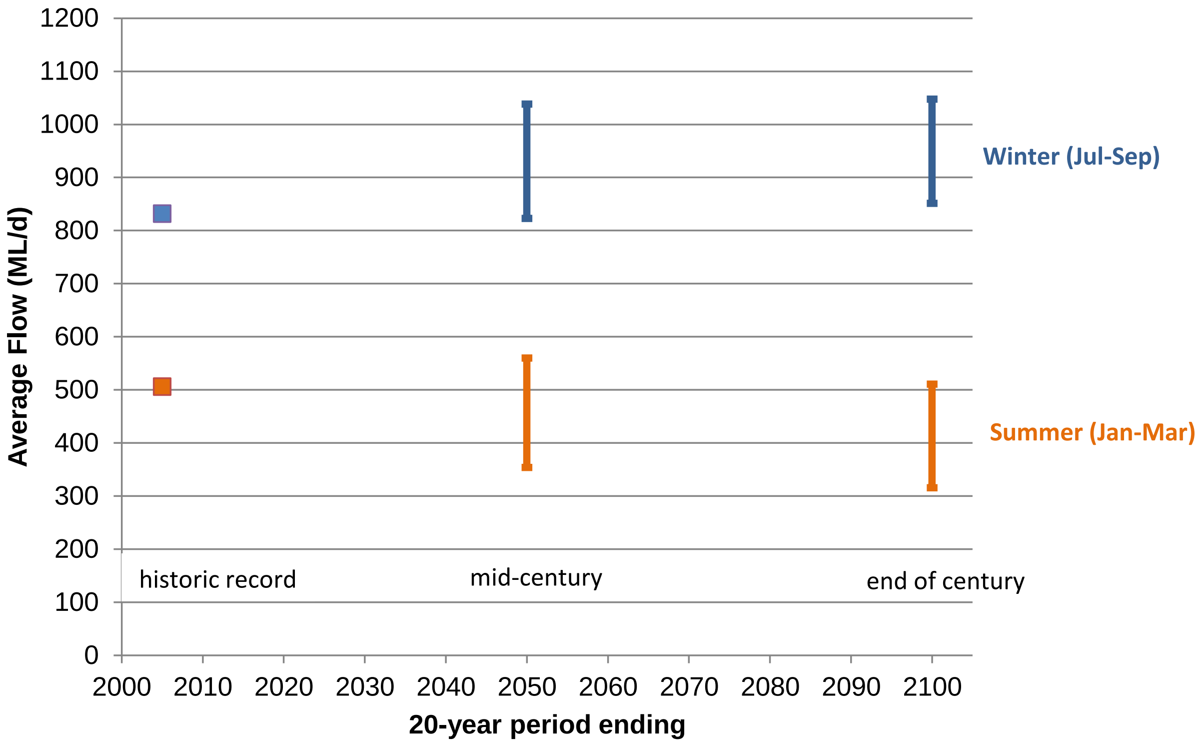
Figure 4: Annual Shortfall Probability (ASP) verses population for the existing Wellington Water potable water network, adopted from (GWRC, 2014).



The recent SYM upgrade also included creation of climate and river flow datasets consistent with the most recent findings of the Intergovernmental Panel on Climate Change (IPCC) in its Fifth Assessment report (IPCC, 2013). Six Global Climate Models (GCM) and four Representative Concentration Pathways (RCP) were selected for downscaling through NIWA’s regional climate model. This produced in total twenty four sets of daily data spanning the period 1971-2100. Further detail on the downscaling process can be found in (Mullan et al., 2016).

Analysis of the climate change adjusted river flow data for the key abstraction point on the Hutt River at Kaitoke provides an insight into the likely effect of climate change on source availability. For the purpose of assessing potential changes in source yield, the twenty four climate change datasets containing 120 years of daily data were divided into four seasons of three months duration, and three 20-year blocks representing the current climate, mid-century and the end of the century. Figure 5 shows the range in summer/winter average flows observed in the climate change adjusted datasets and the historic record taken as the period ending 2005.

Figure 5: Expected range for average flows in the Hutt River at Kaitoke during summer and winter based on NIWA downscaling of six global climate models and four RCP's.



Initial observations with respect to possible changes in source yield at Kaitoke over the remainder of the century are:

- There is a significant variation in possible outcomes.
- There is not a consistent trend of decreasing summer yield with increasing RCP across the model results.
- The range of model results for the end of the century indicate summers are likely to be the same or drier than the current climate.
- The most significant reduction in yield around the middle of the century is nearly as severe as the most extreme scenario for the end of the century.
- It is possible there will be an increase or no reduction in summer yield.

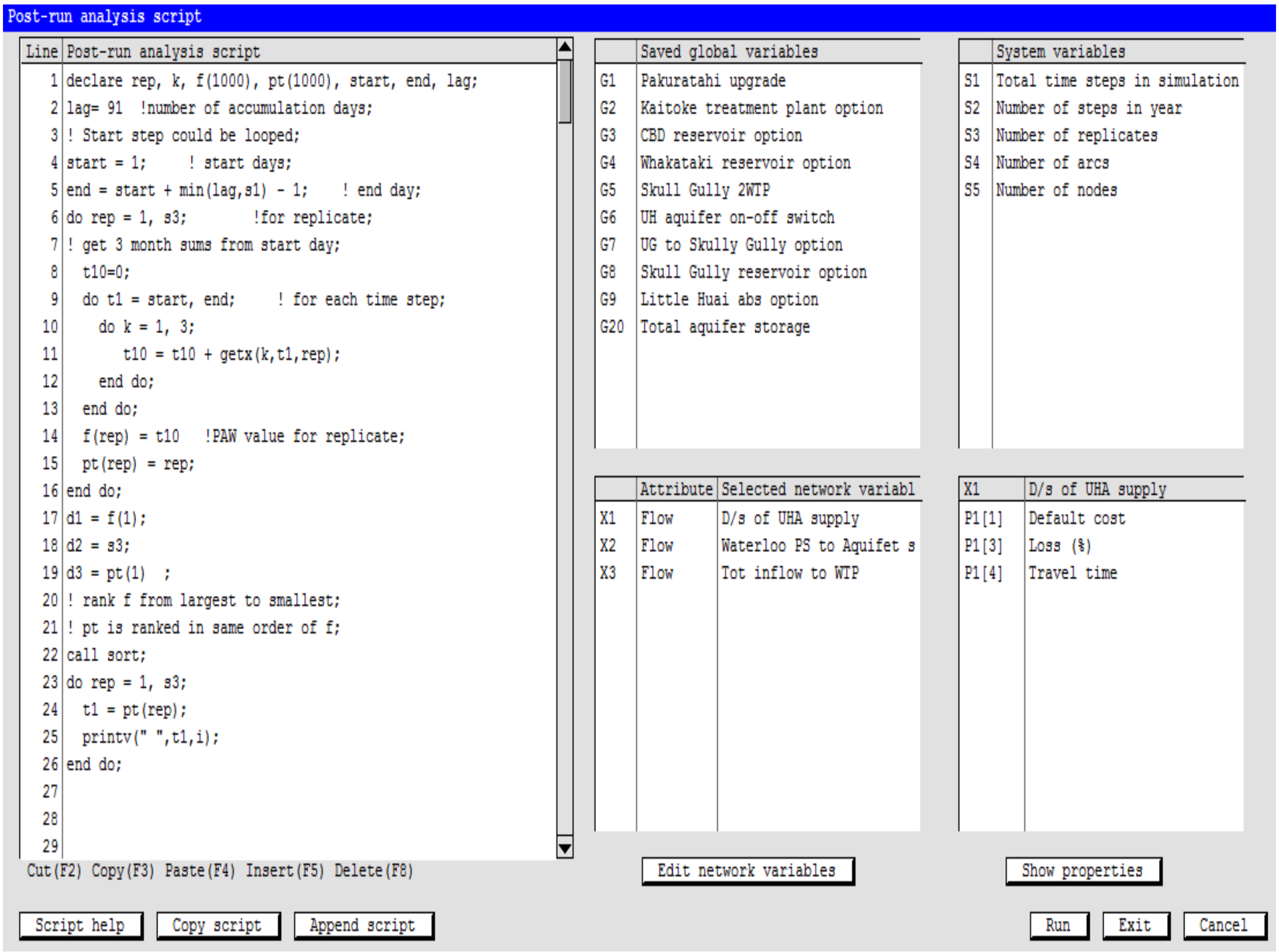
Further work is planned to select a sample of the climate change adjusted datasets and assess the likely impact on drought resilience using the SYM process including Monte Carlo simulation. The key message for the Wellington Water potable water network at this stage is that the expected significant variation in possible outcomes will likely require a flexible and adaptive approach to address future climate change challenges.

5 KARAKA MODEL AND ITS APPLICATION

The Karaka model process uses a probabilistic climate prediction to take in to account what may happen to the temperature, rainfall and river flows over an outlook period of three months. The main purpose of the Karaka model is to provide Wellington Water with a way of assessing the risk of water supply shortfall in the coming months. Similar to the SYM, the Karaka model also uses a Monte Carlo simulation approach to define a set of input conditions (river flows and aquifer levels) and demands. The key feature of the Karaka model is that it incorporates initial reservoir storage volumes matching current values and uses a replicate dataset consistent with the predicted climate over the coming three months. The latter is achieved using NIWA's National Climate Centre Seasonal Climate Outlook to put potential bias into the input climate and river flow data. Detail about KARAKA model can be found in Ibbitt (2004) and Ibbitt and Woolley (2008)

During the recent upgrade of the SYM to WATHNET v5, the Karaka model, which had previously been a set of standalone procedures, was made an integral part of WATHNET using the advanced scripting capability and a new embedded utility. Figures 6 and 7 illustrate the scripting capability and inbuilt utility used in WATHNET v5 to bias input data files consistent with climate outlook projections.

Figure 6 Advanced scripting example. The left hand panel shows the script instructions while the other two panels show the definitions of the variables used in the script.



```
declare rep, k, f(1000), pt(1000), start, end, lag;
lag= 91  !number of accumulation days;
! Start step could be looped;
start = 1;      ! start days;
end = start + min(lag,s1) - 1;     ! end day;
do rep = 1, s3;         !for replicate;
! get 3 month sums from start day;
  t10=0;
  do t1 = start, end;     ! for each time step;
    do k = 1, 3;
       t10 = t10 + getx(k,t1,rep);
    end do;
  end do;
  f(rep) = t10   !PAW value for replicate;
  pt(rep) = rep;
end do;
d1 = f(1);
d2 = s3;
d3 = pt(1)   ;
! rank f from largest to smallest;
! pt is ranked in same order of f;
call sort;
do rep = 1, s3;
  t1 = pt(rep);
  printv(" ",t1,i);
end do;
```

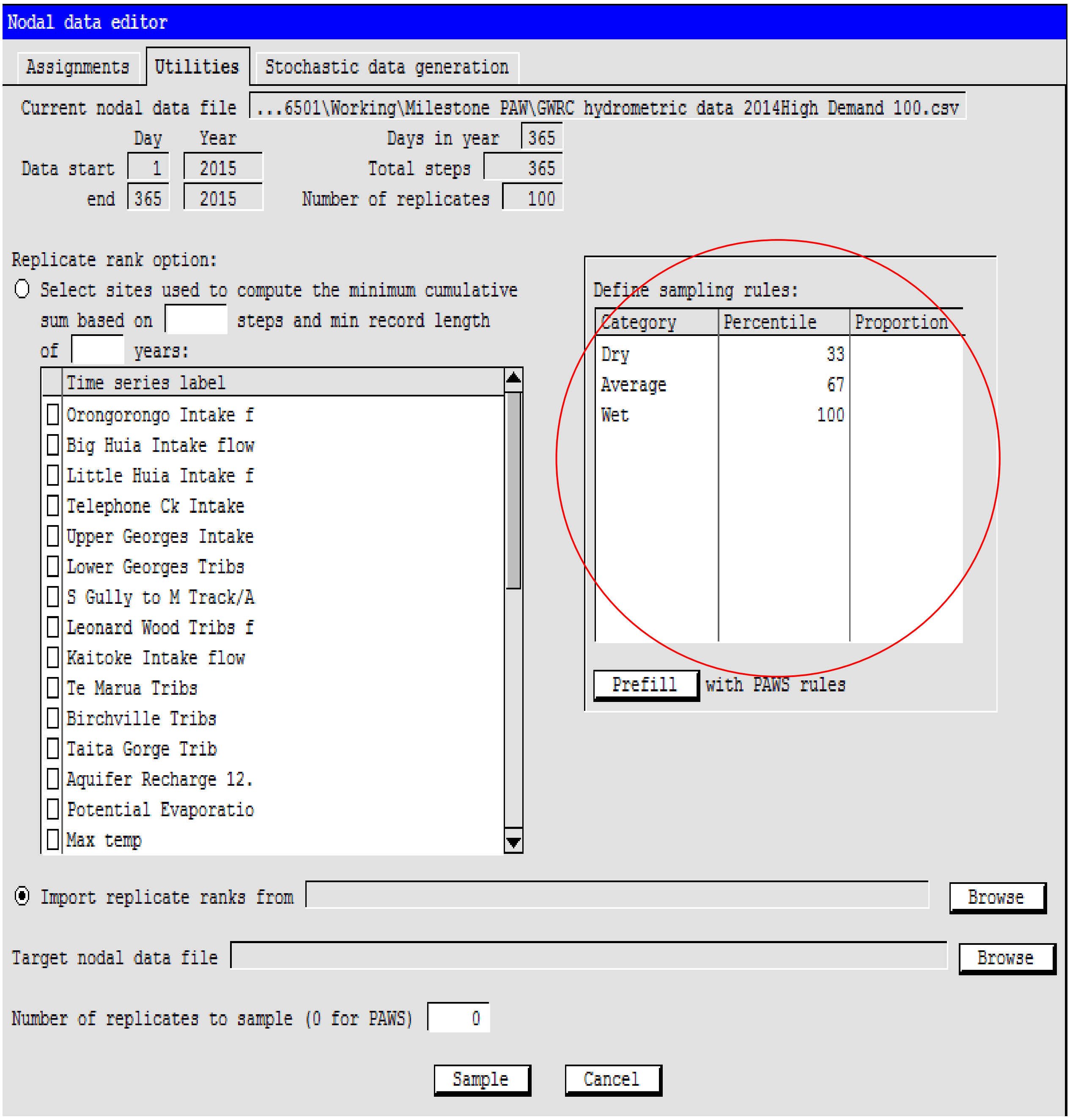
	Saved global variables
G1	Pakuratahi upgrade
G2	Kaitoke treatment plant option
G3	CBD reservoir option
G4	Whakataki reservoir option
G5	Skull Gully 2WTP
G6	UH aquifer on-off switch
G7	UG to Skully Gully option
G8	Skull Gully reservoir option
G9	Little Huai abs option
G20	Total aquifer storage

	System variables
S1	Total time steps in simulation
S2	Number of steps in year
S3	Number of replicates
S4	Number of arcs
S5	Number of nodes

	Attribute	Selected network variabl
X1	Flow	D/s of UHA supply
X2	Flow	Waterloo PS to Aquifet s
X3	Flow	Tot inflow to WTP

X1	D/s of UHA supply
P1[1]	Default cost
P1[3]	Loss (%)
P1[4]	Travel time

Figure 7 Example of the new inbuilt feature in WATHNET used to bias input data files consistent with NIWA climate outlook projections



Current nodal data file ...6501\Working\Milestone PAW\GWRC hydrometric data 2014High Demand 100.csv

	Day	Year
Data start	1	2015
end	365	2015

Days in year 365
Total steps 365
Number of replicates 100

Replicate rank option:

○ Select sites used to compute the minimum cumulative sum based on ____ steps and min record length of ____ years:

	Time series label
☐	Orongorongo Intake f
☐	Big Huia Intake flow
☐	Little Huia Intake f
☐	Telephone Ck Intake
☐	Upper Georges Intake
☐	Lower Georges Tribs
☐	S Gully to M Track/A
☐	Leonard Wood Tribs f
☐	Kaitoke Intake flow
☐	Te Marua Tribs
☐	Birchville Tribs
☐	Taita Gorge Trib
☐	Aquifer Recharge 12.
☐	Potential Evaporatio
☐	Max temp

Define sampling rules:

Category	Percentile	Proportion
Dry	33	
Average	67	
Wet	100	

Prefill with PAWS rules

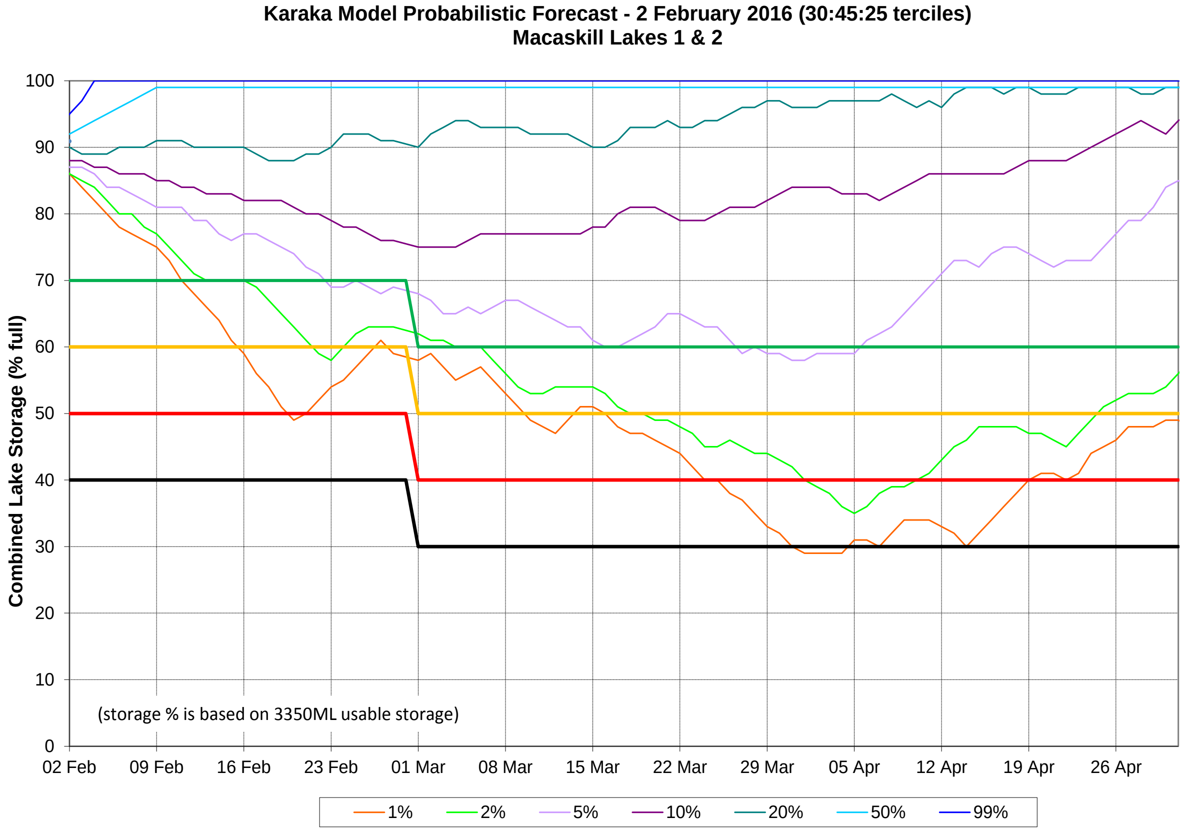
● Import replicate ranks from

Target nodal data file

Number of replicates to sample (0 for PAWS) 0

Figure 8 shows a typical example of Karaka model output for the Macaskill storage lakes. The plot shows the probability that the reservoir storage will not exceed particular values on a particular day in the future. Through use of the Karaka model, Wellington Water can assess the likelihood of changes to the risk of supply shortfall in the coming three month period. This is used to support operational decision-making including adjusting the source operating strategy to preserve surface water storage, and implementing watering restrictions at an appropriate time.

Figure 8 Example of Karaka model results for the Macaskill Lakes showing different storage exceedance percentiles and risk management limits for guidance purposes (green, yellow, red and black lines).



6 CONCLUSION

The SYM, based on earlier versions of WATHNET, has been successfully used as a planning tool for the Wellington Water potable water network for nearly 20 years. Recently the SYM has been upgraded to provide Wellington Water with a tool appropriate for the challenges ahead. The new SYM has more flexibility to adopt complex constraint conditions and now incorporates the latest climate change information. It also brings together a diverse range of planning tools under one software product to assess the impact of seasonal and long term issues affecting water supply and demand.

7 ACKNOWLEDGEMENTS

NIWA and Wellington Water Ltd acknowledge support and associated funding from Greater Wellington Regional Council that allowed the SYM upgrade project to proceed.

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