NIWA
Taihoro Nukurangi

Surface Hydrology in the Ruamāhanga Hill country catchment

model calibration and validation

Prepared for Greater Wellington Regional Council

May 2017

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NIWA CLIENT REPORT No:	2017140CH
Report date:	May 2017
NIWA Project:	WRC15505

Quality Assurance Statement		
	Reviewed by:	Roddy Henderson
	Formatting checked by:	Fenella Falconer
	Approved for release by:	Helen Rouse

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Executive summary

A calibrated TopNet model was constructed to provide hydrological inputs to the Ruamāhanga Groundwater Management Zone (as an upper boundary condition to a MODFLOW model). Because the overall objective at the time of model building was related to water allocation, the TopNet hydrological model was calibrated with an emphasis on low flow conditions across the Ruamāhanga catchment.

Based on the availability of flow records in the Ruamāhanga Hill country catchments, the Ruamāhanga Hill country TopNet model was subdivided into nine surface water models. The nine hydrological models were calibrated at the most downstream continuous monitoring streamflow station in each of the surface water catchments discharging to the Groundwater Management Zone. Discharges in these nine Ruamāhanga Hill country catchments are minimally impacted by water allocation activities and are thus considered to be representative of “natural conditions”.

Each model used inputs based on a combination of Virtual Climate Station Network rainfall stations and existing sub-daily precipitation information located within each surface water catchment. Spatial information representing soil and land cover conditions was based on soil information from the Fundamental Soil Layer (FSL) and the land cover database version 3 (LCDB v3).

For consistency with the groundwater model developed as part of the Whaitua Modelling Project, the TopNet model was to simulate inputs to the groundwater model over the period 2000-2012. As a result, a common calibration period for each catchment was chosen to be 2001-2003 (representing a range of hydrological conditions), with a validation period of 2001-2012. Model accuracy was represented across a range of hydrological criteria:

- Statistical measure of the goodness of fit for calibration and validation period using the Nash Sutcliffe concept for the time series of flow and the log transform of the flow. This was used as the main statistical criterion as part of the calibration process.
- Post processed hydrological statistics such as mean flow and 7-day Mean Annual Low Flow (7-day MALF).
- Analysis of time series of discharge, cumulative discharge and frequency distribution of the discharge time series.
- Analysis of monthly average discharge.

In addition, a sensitivity and uncertainty analysis was carried out as part of this project for each of the models developed.

Sensitivity and uncertainty analysis indicates that:

- The most sensitive inputs and parameters of TopNet across the nine catchments are: precipitation input, soil characterisation and depth of hydraulically active soil.
- Uncertainties are larger as catchment size increases.
- Uncertainties due to land cover are of second order compared to uncertainties associated with soil characterisation.

- Uncertainties are usually larger at high flows than low flows. This relates to: the spatial and temporal averaging of the precipitation inputs; a lack of rain gauge density in the Tararua Ranges for the development of the input rain surface; and higher uncertainty in some flood flow rating curves.

Limitations associated with the model developments carried out as part of the project are:

- Uncertainties/bias in precipitation information and interpolation driving the hydrological model. The hydrological model was calibrated in order to correct the scale of the precipitation intensity, not the spatial distribution.

- Uncertainties/bias in all other related climate information used by the hydrological model (mainly temperature).

- Uncertainties in Fundamental Soil Layer (FSL) driven soil characterisation in the Ruamāhanga Hill country catchment. This is potentially a large source of uncertainty considering that the most sensitive parameters are soil related.

Analysis of the calibration carried out at each catchment indicates:

- Spatial clustering of the performance of the model was observed between catchments on the West of the GWZ (i.e., Tauherenikau, Waiohine, Waingawa, Waipoua and Ruamāhanga) and East of the GWZ (Kopuaranga, Whangaehu, Taueru and Huangarua). Simulations for catchments located east of the GWZ tend to be better across the entire flow range, than catchments located on the west of the GWZ. This is thought to be associated with variable accuracy of the climate information used to drive the hydrological model.

- Most of the calibrated models can represent average low flow conditions at monthly time scales for most of the months during the validation period. Improvement in model performance is likely to require additional model objective functions (e.g., the number of consecutive days during a year/month below a flow threshold).

- Most of the calibrated models are not able to reproduce average flow conditions (especially for the west of the GWZ) due to potential underestimation of the winter gridded precipitation (used as part of this project) as well as the fact that the calibration process was deliberately focussed on low flows.

- Some of the models developed (i.e., Waingawa, Waiohine, Tauherenikau) require further development to better reproduce low flow conditions as required by the CHES Ruamāhanga tool (yet to be built).

- Some of the models developed (i.e., Taueru, Huangarua past 2006) could be further developed and improved once changes are implemented in flow rating curves (to improve reliability of predictions).

- Two models (i.e., Kopuaranga, Waipoua) will need to consider/conceptualise substantial groundwater input as part of further development and improvement.

Overall, the TopNet model output for these nine catchments provides a suitable basis for water allocation simulations and surface water inputs to the Ruamāhanga GWZ.

Potential TopNet developments would allow:

- Improvement in hydrological processes conceptualisation to be implemented for the Kopuaranga and Waipoua catchments.
- Validation of the current model flow predictions with spot gauging information. This should provide some assurance to GWRC about the validity of model projection within and across a calibrated catchment.
- Use of spot gauging discharge measurements in uncalibrated catchments where hydrological parameters were regionalised. This step would provide GWRC with an estimation of total model uncertainties in unmonitored catchments.
- Improvement of the spatial resolution of the climate input driving the hydrological model will result in model output improvement, as it will reduce the tendency of the calibration process to produce calibration errors at high flow.
- Review of the digital river network in the upper catchment and implications for catchment scale hydrological model conceptualisation.
- Review of the current soil parametrisation available through FSL over the Ruamāhanga Hill country catchment and comparison with S-Map derived soil parametrisation (e.g., rooting depth, plant available water, macroporosity at 60 and 90 cm, soil distribution).

1 Model objectives

A TopNet model was developed with the objective of providing time series of surface water inflow for all the reaches discharging to groundwater management zones in the Ruamāhanga catchment[1] (Figure 1-1). Those surface water inflows provide an upper boundary condition to groundwater modelling in the Groundwater Management Zone (GWZ), as carried out by Earth in Mind (Mark Gyopari) and GNS Science. There are 297 inflow streams whose locations are presented in Figure 1-2.

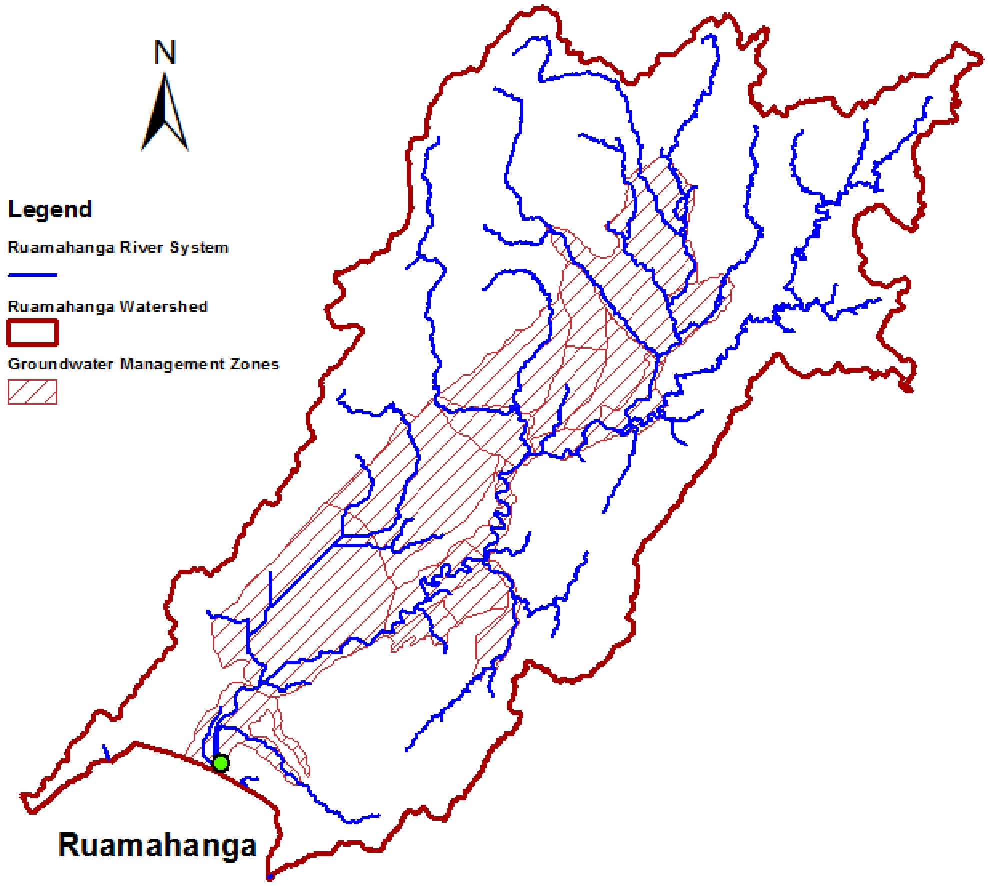

Figure 1-1: Location of GWZ in the Ruamāhanga catchment. The main river system in the Ruamāhanga (blue lines) is represented by Strahler order 4 river network.

[1] The TopNet model was initially developed to provide input to a Cumulative Hydrological Effects Simulator (CHES) simulation of the catchment for water allocation purposes. Following a recommendation of the Whaitua Modelling Technical Team, it was decided that this model would also be used for this project to provide hydrological inputs to the GWZ.

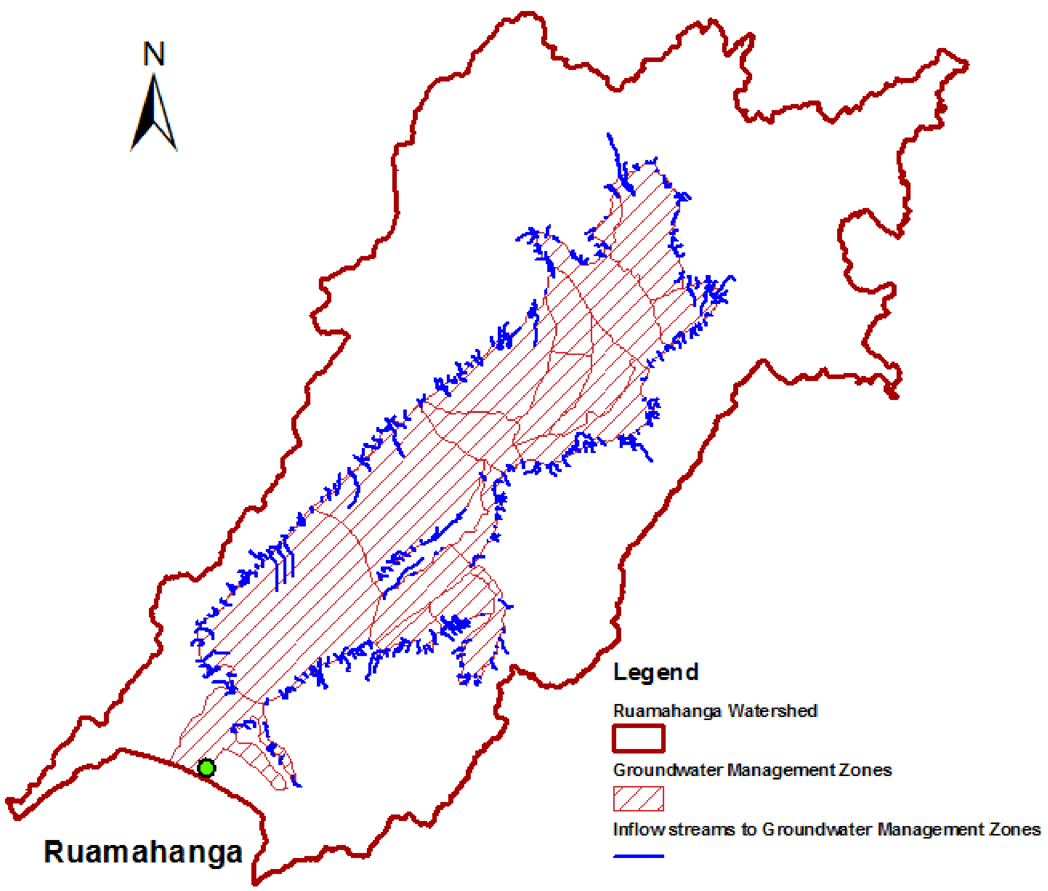

Figure 1-2: Locations of inflow streams to GWZ. Inflow streams (blue lines) are depicted at Strahler order 1.

2 Conceptualisation

The TopNet hydrological model is routinely used for hydrological modelling applications in New Zealand. It is a spatially distributed, time-stepping model of water balance. It is driven by time series of precipitation and temperature data, and of additional weather elements where available. TopNet simulates water storage in the snowpack, plant canopy, rooting zone, shallow subsurface, lakes and rivers. It produces time series of modelled river flow (under natural conditions) throughout the modelled river network, as well as evaporation. TopNet has two major components, namely a basin module and a flow routing module. The structure of the basin module is illustrated in Figure 2-1.

The model combines TOPMODEL hydrological model concepts (Beven et al. 1995) with a kinematic wave channel routing algorithm (Goring 1994; Clark et al. 2008) and a simple temperature based empirical snow model (Clark et al. 2008). As a result, TopNet can be applied across a range of temporal and spatial scales over large catchments using smaller sub-basins as model elements (Ibbitt and Woods 2002; Bandaragoda et al. 2004). Considerable effort has been made during the development of TopNet to ensure that the model has a strong physical basis and that the dominant rainfall-runoff dynamics are adequately represented in the model (McMillan et al. 2010). TopNet model equations and information requirements are provided by Clark et al. (2008) and McMillan et al. (2013).

Spatial information in TopNet is provided by national datasets on catchment topography (i.e., 30 m digital elevation model), physical (Land Cover Database version 3-LCDB3, Land Resource Inventory, Newsome et al. 2012), soil (Fundamental Soil Layer- FSL, Wilson and Giltrap 1982) and hydrological properties (River Environment Classification, Snelder and Biggs 2002). In this application, the REC hydrological network was set to REC version 2 (NIWA 2012). The method for deriving TopNet initial parameter estimates from GIS data sources in New Zealand is given in Table 1 of Clark et al. (2008).

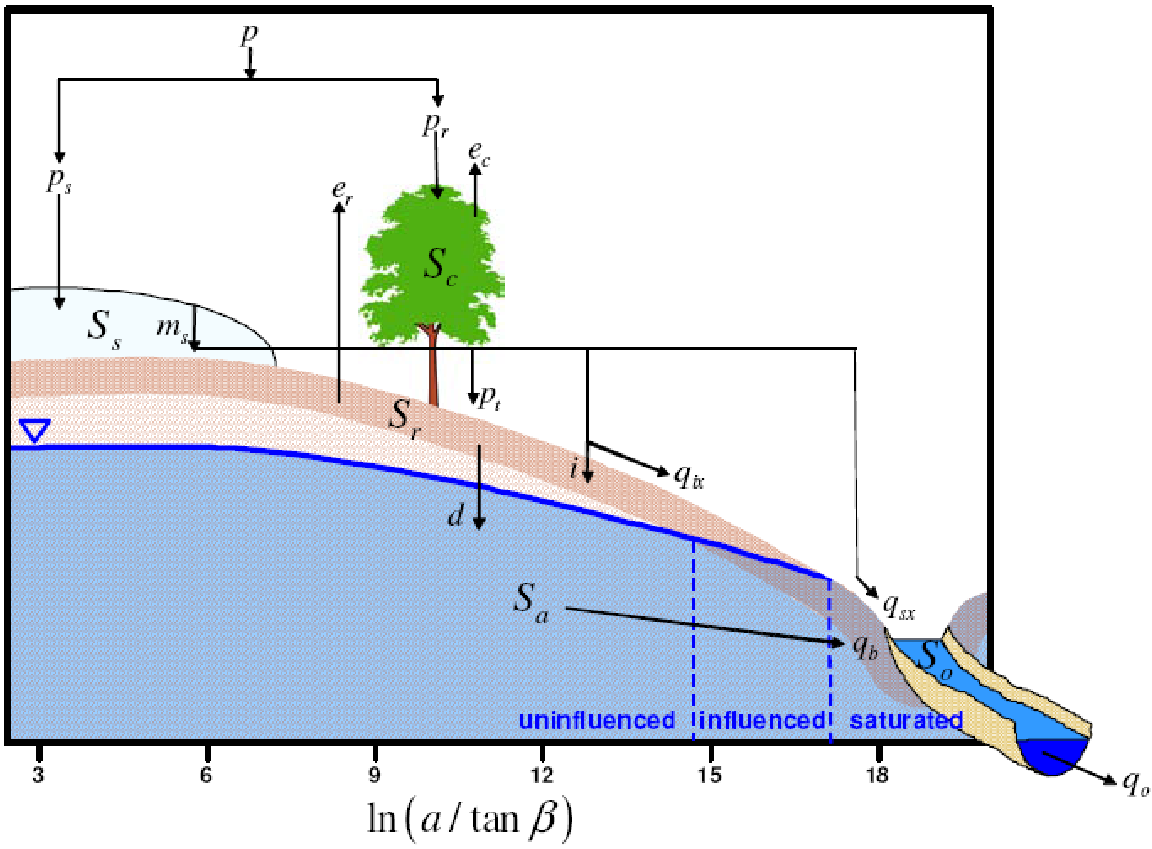

Figure 2-1: TopNet model structure within each sub-basin, showing modelled water fluxes and storages.

3 Model design

As the aim of the modelling project is to develop a hydrological model providing inflows to the Ruamāhanga GWZ, the area outside of the GWZ will be named hereafter the Ruamāhanga Hill country.

3.1 Physiographic Characteristics

The study area is the surface water catchments discharging to the sea in Palliser Bay via the Ruamāhanga River, as illustrated in Figure 3-1, while Figure 3-2 presents land use information. Land use in Ruamāhanga Hill country (i.e., outside of the GWZ zone) is predominantly pastoral (see Figure 3-2).

The digital elevation model (DEM) jointly with the location of the streamflow gauging stations were used to generate a stream network and an associated set of Strahler 1 order surface water catchments. TopNet spatially distributed parameters were established for each sub-catchment using national soil information from the Fundamental Soil Layer (FSL) and landuse/land cover information (LCDB3). A more detailed land use layer is held by GWRC but was not used for the TopNet modelling because the added detail in the GWRC layer is focussed within the groundwater model domain and not the upper parts of the Ruamāhanga catchment; the differences between the GWRC land use layer and the LCDB3 layer in the upper parts of the catchment are considered negligible with respect to the likely impact on TopNet model outputs.

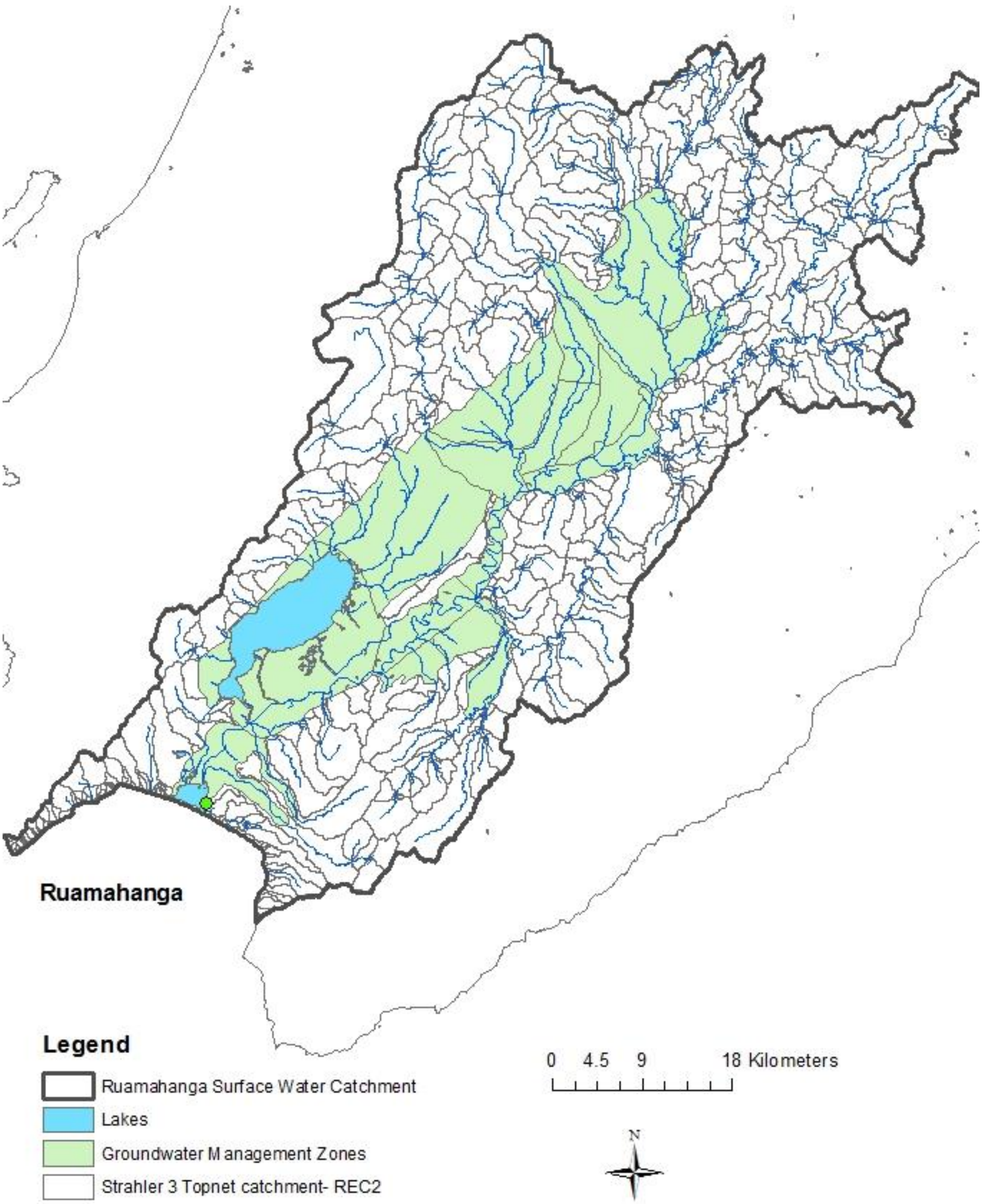

Figure 3-1: Ruamāhanga surface water catchment (blue lines represent Strahler 3 streams from the REC 2 coverage).

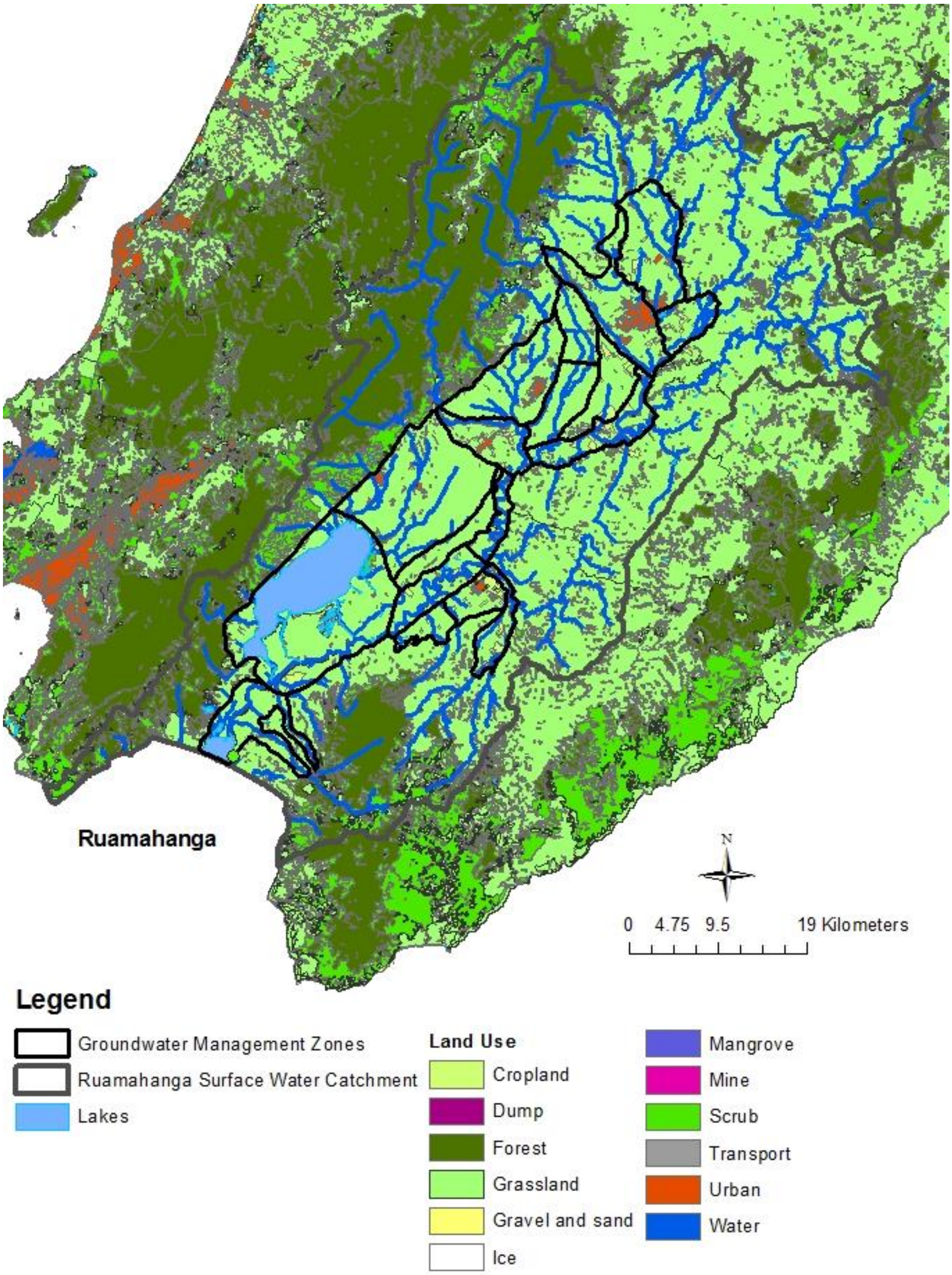

Figure 3-2: Land Use based on Land Cover DataBase version 2.0.

Land use in Ruamāhanga catchment is predominantly pastoral in the low land and forested in the Aorangi, Rimutaka and Tararua ranges (see Figure 3-2).

3.2 Climate

11 climate stations are located within the boundaries of the Ruamāhanga Hill country surface water catchment (Figure 3-3). Table 3-1 provides a summary of the precipitation time series information available for those stations.

Table 3-1: Climate station location and identification in the Ruamāhanga Hill country catchments.

Name	Tideda ID	Catchment	Elevation (masl)	Period of record
Tauherenikau at Bull Mound	59310	Tauherenikau	1034	1976-present
Waiohine at Gorge	1503191	Waiohine	140	2006-present
Waiohine at Carkeek	58411	Waiohine	1158	1974-present
Waingawa at Kaituna	58582	Waingawa	240	1994-present
Waipoua at Mikimiki	58506	Waipoua	274	1979-1997
Ruamāhanga at Bannister Basin	57511	Ruamāhanga	1006	1974-present
Ruamāhanga at Mt Bruce	57514	Ruamāhanga	300	1984-2000
Ruamāhanga at Mt Bruce river site	57559	Ruamāhanga	300	1984-present
Whangaehu at Tiki Tapu	57710	Whangaehu	198	1968-1997
Taueru at Castlehill	57958	Taueru	250	1993-present
Taueru at Te Weraiti	59795	Taueru	90	1997-present

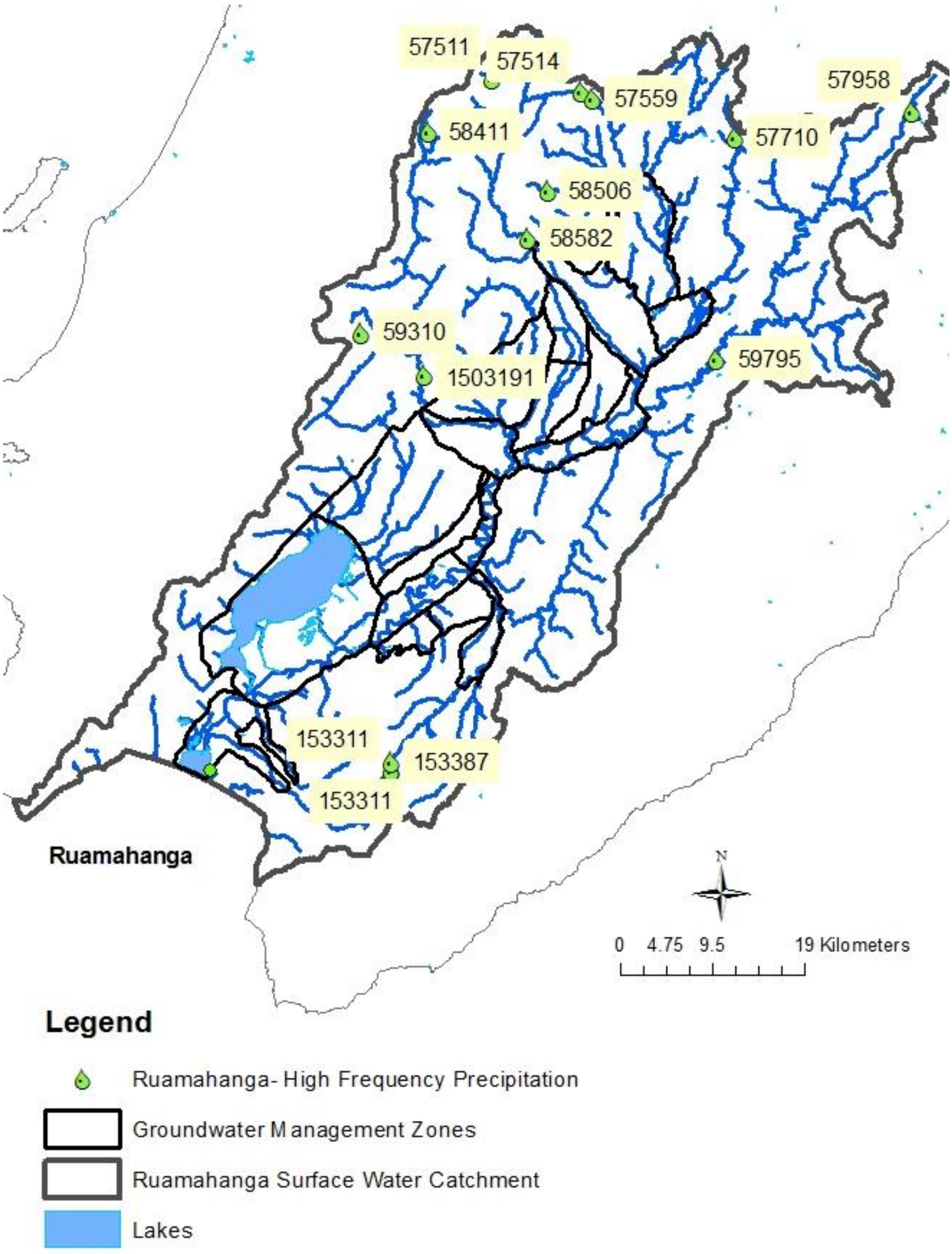

Figure 3-3: Location of the GWRC high frequency intensity in each sub-catchments and associated precipitation station sites (represented by their Tideda ID) in the Ruamāhanga catchment.

An additional source of climate information, i.e., precipitation- temperature- relative humidity (rh), solar radiation (srad)- mean sea level pressure (mslp) and wind speed, is available through NIWA's Virtual Climate Station Network (VCSN) (Tait et al. 2006). The VCSN network represents daily interpolated climate information over a regular 0.05 degrees latitude/longitude grid interpolated over nearly 500 climate stations across New Zealand with an ANU spline since 1972. Note that a precipitation station will be included in the VCSN record only if the station is included in NIWA's climate database (CliDB). Analysis of CliDB indicates that not all GWRC long term rainfall stations, present in the Ruamāhanga catchment, are included in the VCSN "dataset". Figure 3-4 presents the location of the observed precipitation gauges used to derive the daily VCSN precipitation gridded information.

Figure 3-5 and Figure 3-6 present the long-term annual average precipitation and evaporation, as estimated by NIWA. Figure 3-7 presents the median monthly catchment average precipitation and temperature simulated by TopNet for the Ruamāhanga River catchment at Mt Bruce (reach ID: 09250417), while Figure 3-8 presents a comparison between the monthly catchment scale precipitation estimated by NIWA and the monthly average precipitation measured by GWRC at Tauherenikau at Bull Mound (reach ID: 09256528) as well as the corresponding Intensity Distribution Curve (IDC).

The climate in the focus area is characterised by:

- Annual average rainfall around 6000mm/year along the Tararua Range, decreasing to 760mm/year along the Ruamāhanga River, increasing to 1200mm/year over the eastern boundary.
- Annual evaporation around 600mm/year along the Tararua Range, increasing to 700mm/year along the Ruamāhanga River and over the eastern boundary.
- Relatively low monthly accumulated rainfall during the period January to March and larger monthly accumulated rainfall during winter (over 300mm/month for Ruamāhanga at Mt Bruce).
- Monthly mean temperature ranges between 6°C in winter to 20°C in summer in the upper reaches of the Ruamāhanga surface water catchment.
- Comparison with GWRC precipitation measurements, that are not included in CliDB used by NIWA to generate the VCSN, indicates that the seasonality of the precipitation is well represented by the VCSN (Figure 3-8). However, VCSN driven precipitation is usually lower than observed precipitation, because existing VCSN observation points are not able to correctly reproduce the experienced orographic effect on the precipitation (as VCSN driven precipitation represents the average precipitation across a five by five km grid).
- Comparison of the GWRC observed precipitation intensity-distribution-curve (IDC) and the corresponding VCSN driven IDC (see Figure 3-8) indicates that the drizzle events are likely to be over-represented in the VCSN. This is due to a combination of the interpolation and temporal disaggregation methods which are likely to create a succession of small precipitation events distributed throughout the day to represent small daily precipitation events.

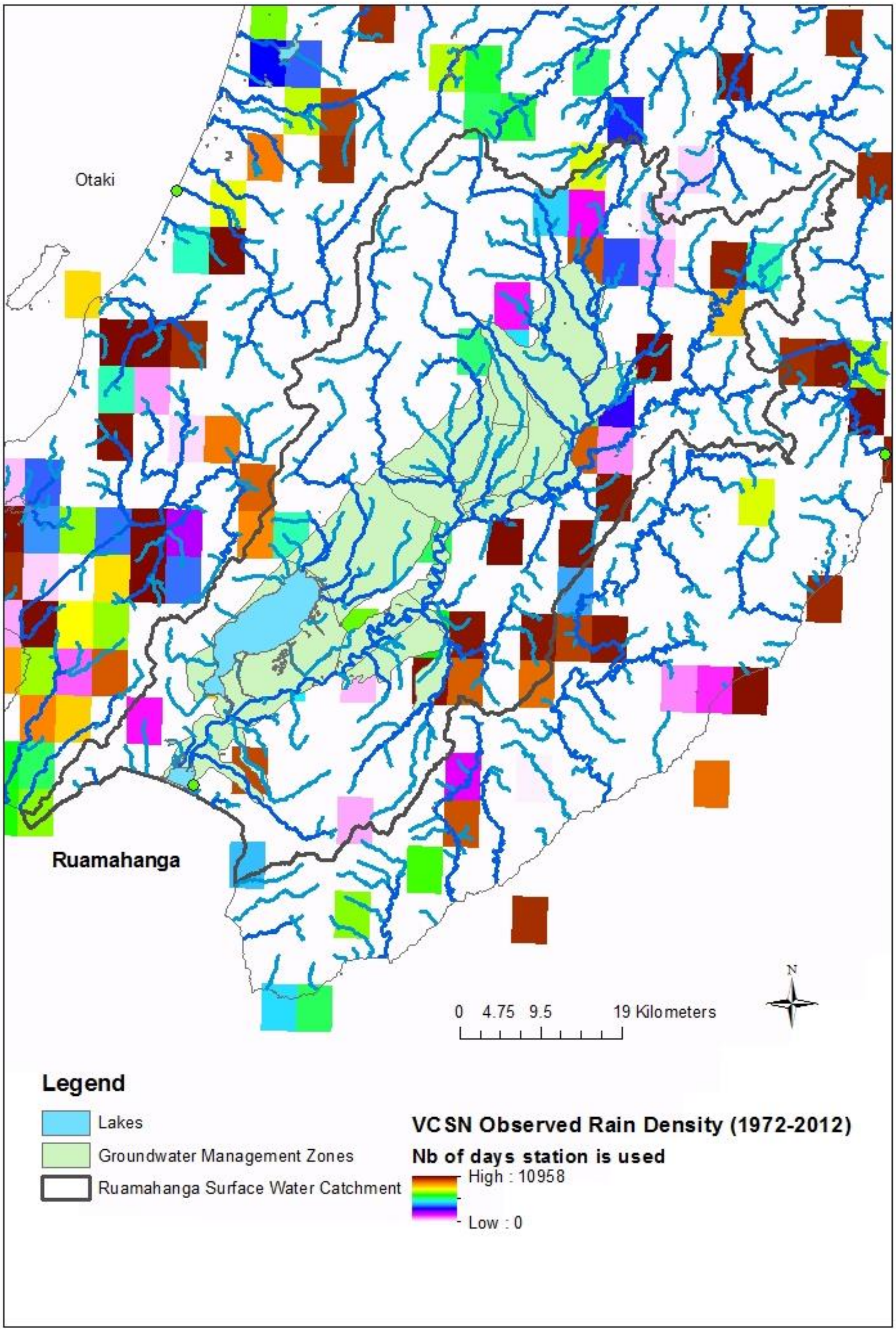

Figure 3-4: Location of the observed precipitation gauge used to derive the daily VCSN precipitation gridded information. The colour scheme represents the number of days (over a 40 year period) a particular station is used.

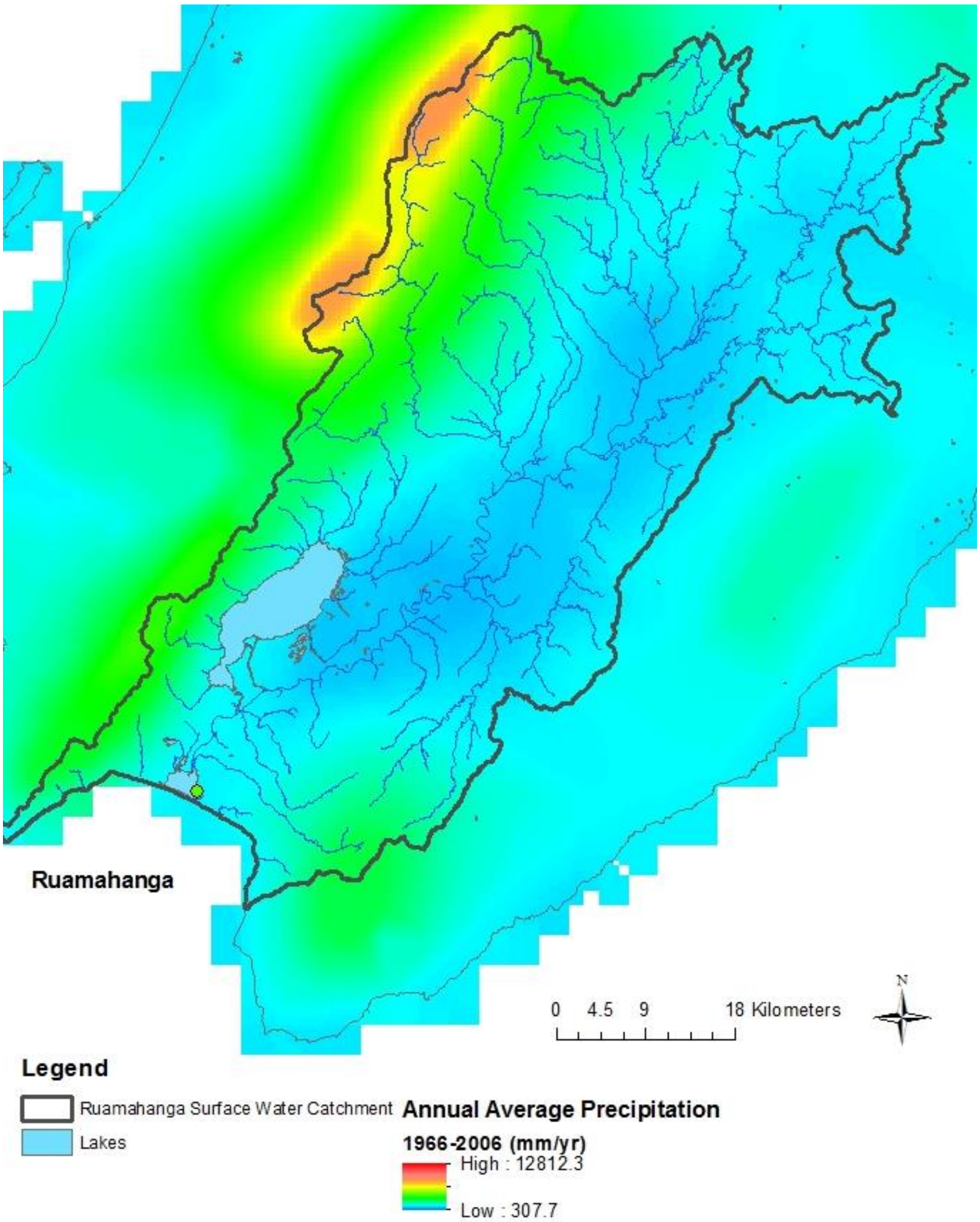

Figure 3-5: Annual precipitation for the period 1966-2006.

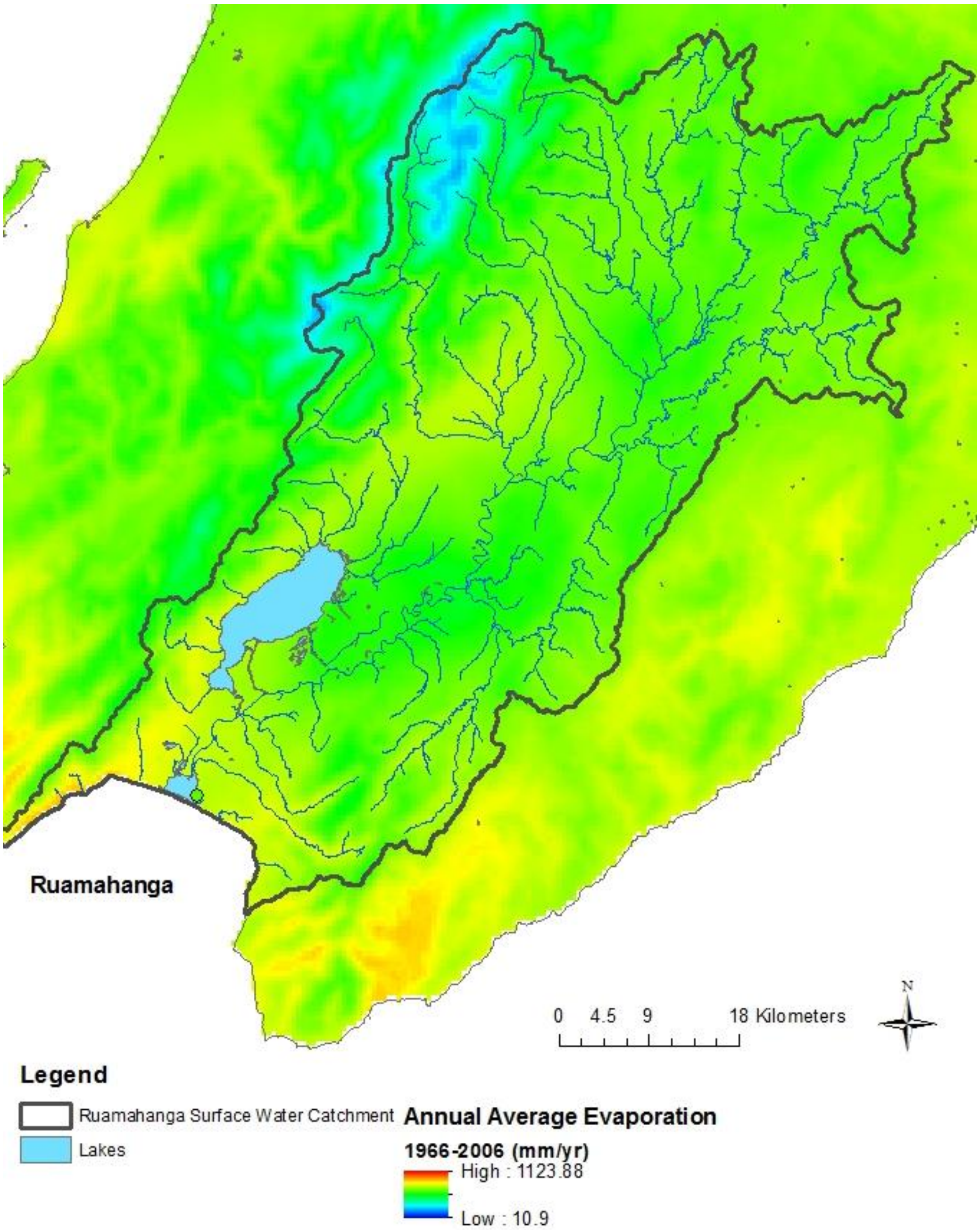

Figure 3-6: Annual evaporation for the period 1966-2006.

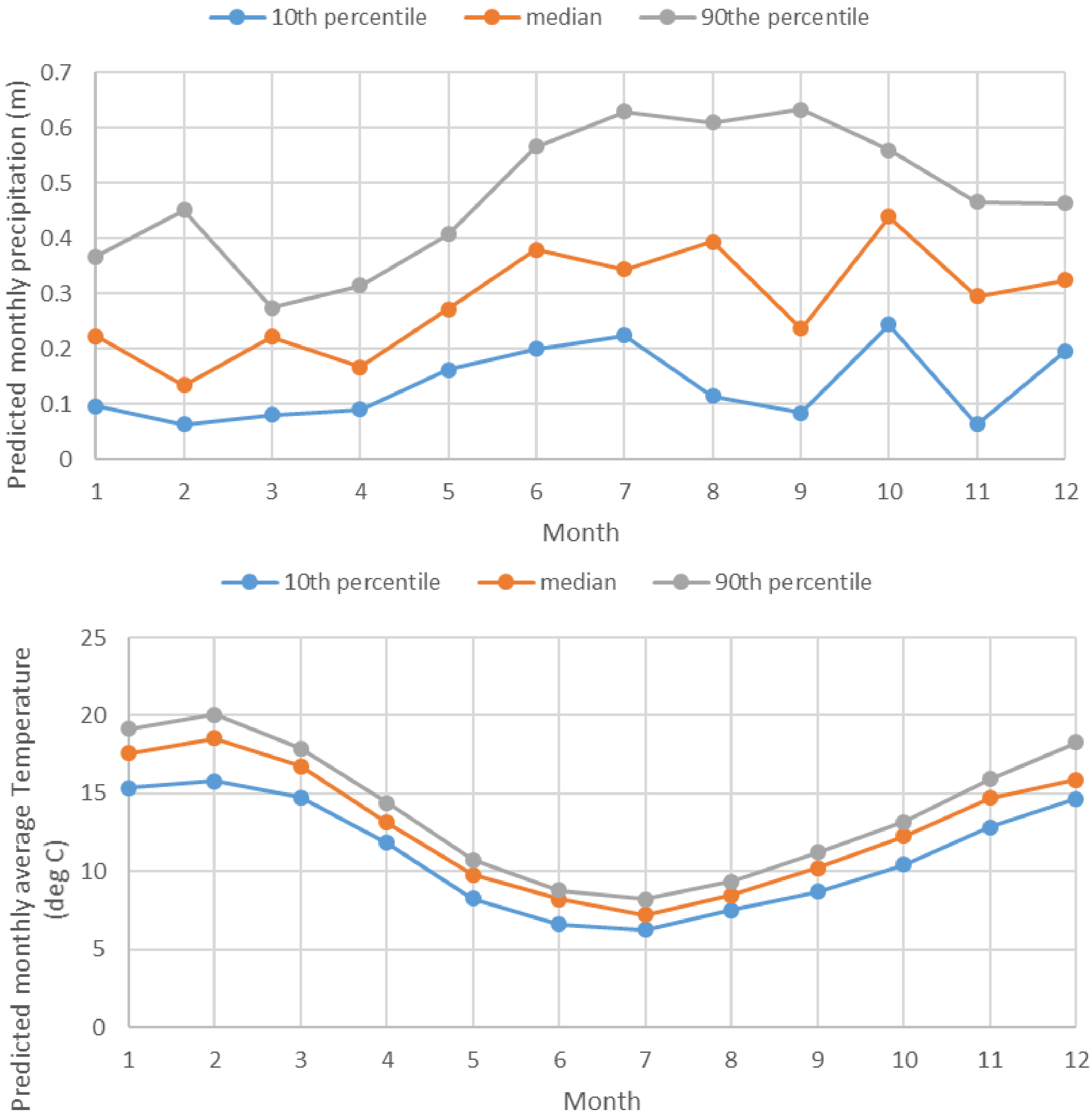

Figure 3-7: Monthly median simulated precipitation (top) and temperature (bottom) for the Ruamāhanga surface water catchment over the period 2001-2012.

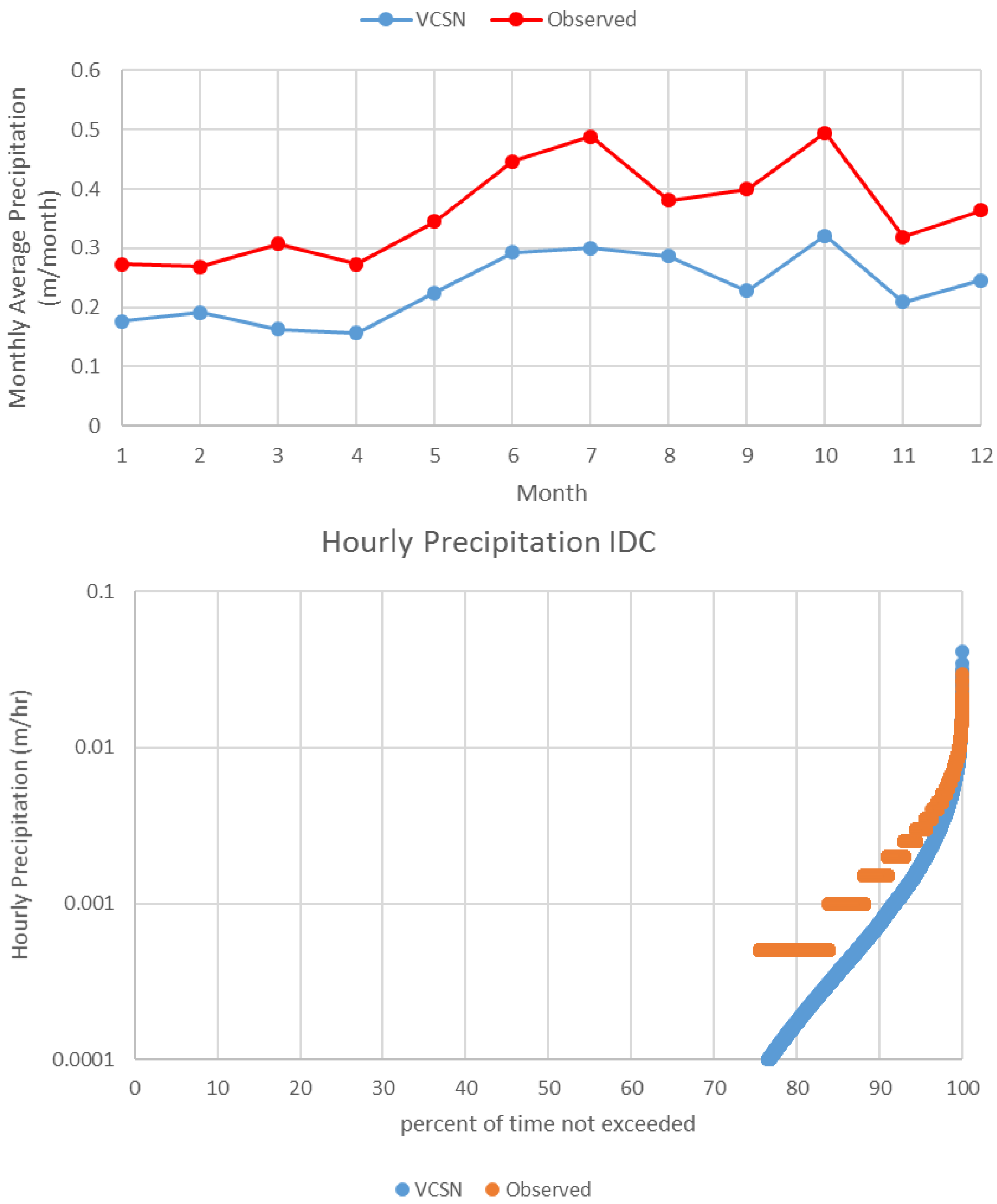

Figure 3-8: Observed monthly average precipitation at Tauherenikau at Bull Mound (Tideda ID 59310) and corresponding catchment average precipitation simulated by TopNet (reach ID 09256528) over the simulation period 2001-2012 (top). Observed and simulated precipitation intensity distribution curve at the same location over the same time period (bottom). Simulated precipitation (VCSN) truncated to 0.1mm/hr for presentation.

3.3 Water consenting

An interrogation of the GWRC consents database showed that there are no significant abstraction, damming or diversion activities upstream of the nine gauging stations. As a result observed stream flows at those sites are assumed to be in a natural state.

3.4 TopNet hydrological model

For many applications of TopNet, the estimation of model parameter values currently requires calibration, usually using measured streamflow. The parameters requiring this type of estimation are generally associated with soil hydraulic properties (hydraulic conductivity and water holding capacity of soils). However, careful review of data quality (e.g., precipitation, temperature and streamflow) is a wise first step, before calibration.

3.4.1 Observed streamflow

Review of the measured streamflow indicates that suitable discharge measurements are available at nine locations listed in Table 3-2 and mapped in Figure 3-9 together with their corresponding draining catchments.

Table 3-2: Physiographic information for the nine calibrated catchments.

Catchment	Site	Tideda ID	REC2 reach ID	Area (km2)	Useable Low Flow Date Range
Tauherenikau	Tauherenikau at Gorge	29251	9259046	114.21	All Data
Waiohine	Waiohine at Gorge (new site)	29224	9257741	177.89	May 1979 – present
Waingawa	Waingawa at Upper Kaituna	29246	9254309	76.50	All Data
Waipoua	Waipoua at Mikimiki	29257	9253108	79.84	Feb 2007 – 2011
Ruamāhanga	Ruamāhanga at Mt Bruce	29254	9250417	78.70	All Data
Kopuaranga	Kopuaranga at Palmers Bridge	29230	9252319	100.63	All Data
Whangaehu	Whangaehu at Waihi	29244	9252727	36.80	All Data
Taueru	Taueru at Te Weraiti	29231	9257216	391.19	None
Huangarua	Huangarua at Hautotara	29222	9265072	139.23	None

Five of the flow sites are fully rated (for high and low flows) from at least the mid-1970s onwards and have reliably maintained rating curves. The other four sites (Waiohine, Waipoua, Taueru and Huangarua) have for long periods in their history been maintained as flood warning sites only and low flow records during these periods are unreliable. This has been taken in to account during the model calibration/validation, except for Taueru and Huangarua that have no periods of reliable low flow data (Gordon 2013), and thus the flow data have been used as provided.

For the application presented hereafter TopNet hydrological models were built for the nine surface water catchments based on Strahler 1 catchments (typical size 0.5 km^2). The total number of TopNet catchments in the Ruamāhanga surface water catchment at Strahler 1 is 7782.

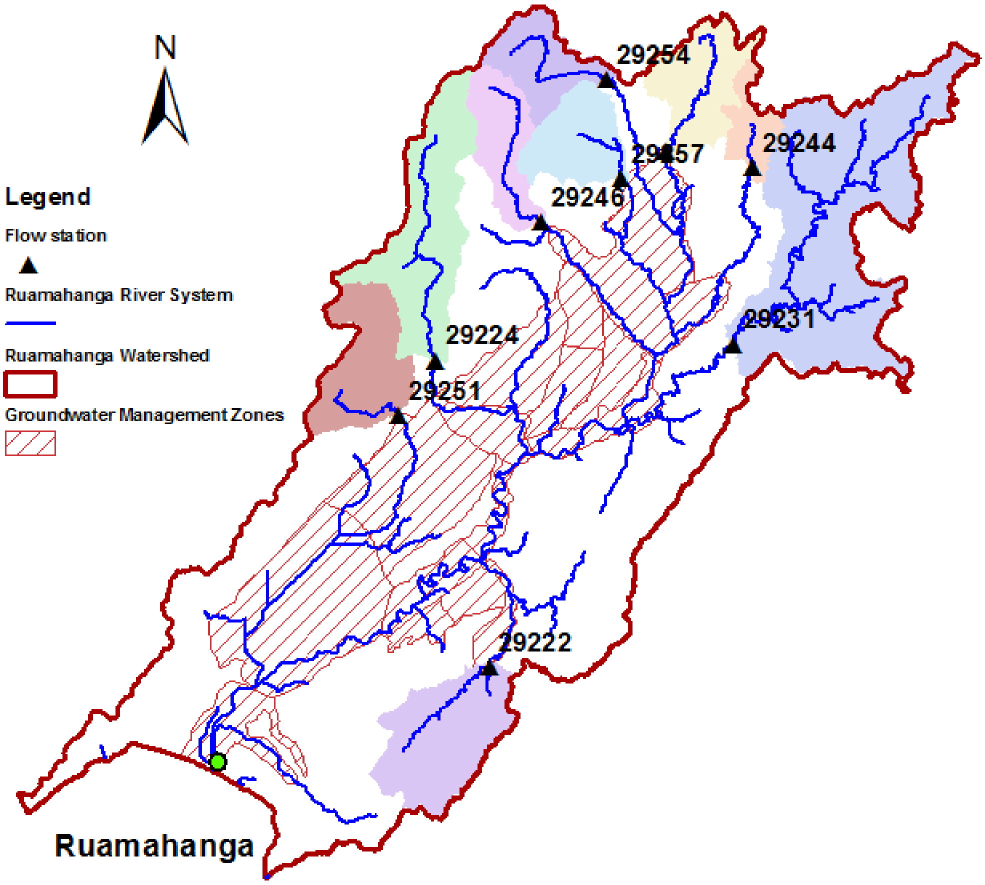

Figure 3-9: Location of the nine calibrated sub-catchments and associated flow station sites (represented by their Tideda ID) for model calibration in the Ruamāhanga catchment.

3.4.2 Precipitation

Analysis of the current network of rainfall gauges over the Ruamāhanga Hill country (Table 3-1) indicates that the current density of the network is not homogenous across the different catchments (usually only one precipitation gauge is located within the extent of each surface water catchment- see Figure 3-3). As a result it was decided to use the VCSN information as a driver of the hydrological model. For this project application, daily precipitation was temporally disaggregated to hourly time steps, using temporal precipitation information provided by the existing network of rainfall stations across the basin, in order to better represent flood generation mechanisms in each of the nine gauged catchments.

The precipitation information was bias-corrected using a water balance approach which has been described by Woods et al. (2006).

3.4.3 TopNet parametrisation

There are 31 parameters used in a TopNet model, which represent the physical characteristics of the catchment and are generally assumed not to be subject to temporal variation. These include soil properties, topography, land cover, and channel properties. The derivation of the catchment scale TopNet parameters from nationally available datasets is described in detail in Table 1 of Clark et al. (2008). These catchment scale parameters represent the default parameter values used in the subsequent sections. However due to the paucity of some spatial information at national scales the following parameters in TopNet are set to a unique default value across New Zealand:

- Surface hydraulic conductivity is set to 0.01m/s;
- Soil water characteristics (i.e., Clapp and Hornberger c exponent and Green-Ampt wetting front suction) are constant across the Ruamāhanga catchment and set to 1.0 and 0.3 respectively;
- Overland flow velocity is set to 0.1m/s.

The depth of hydraulically active soil and the surface hydraulic conductivity are two of the most sensitive and critical parameters in TopNet. The depth of hydraulically active soil is associated with the characterisation of the hydrograph recession, while the surface hydraulic conductivity is associated with recharge to the groundwater and subsurface flow characterisation. As a result, those parameters are generally calibrated based on streamflow information.

Figure 3-10 to Figure 3-14 present the spatial variation of the soil and vegetation related parameters in TopNet (estimated from nationally available datasets). These are presented to illustrate the spatial variability of the TopNet parameters across the Ruamāhanga catchment and are not further discussed in this report.

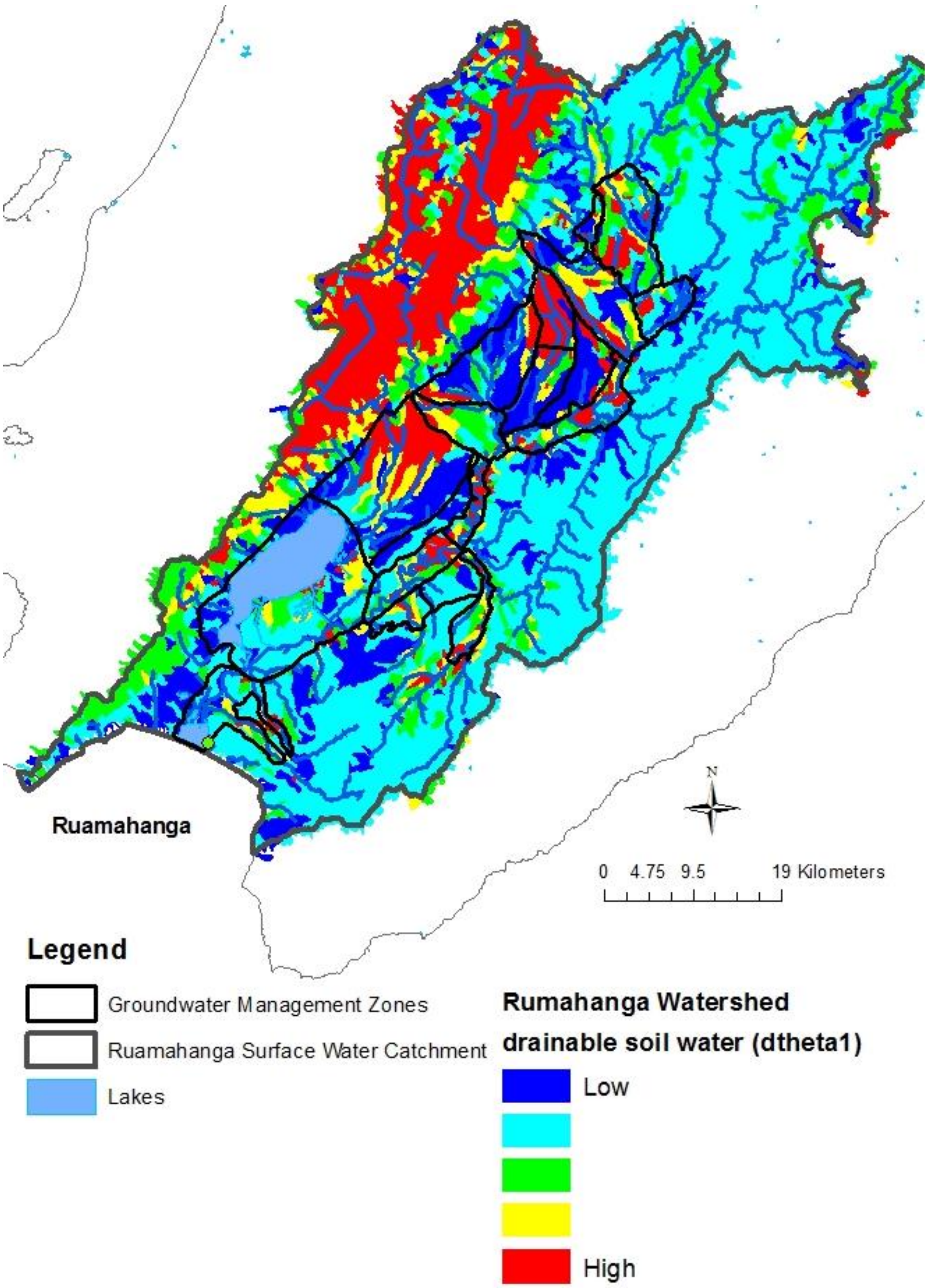

Figure 3-10: Spatial variation of the drainable water (dtheta1) TopNet parameter. Red represents high values of the parameter, while blue represents low values.

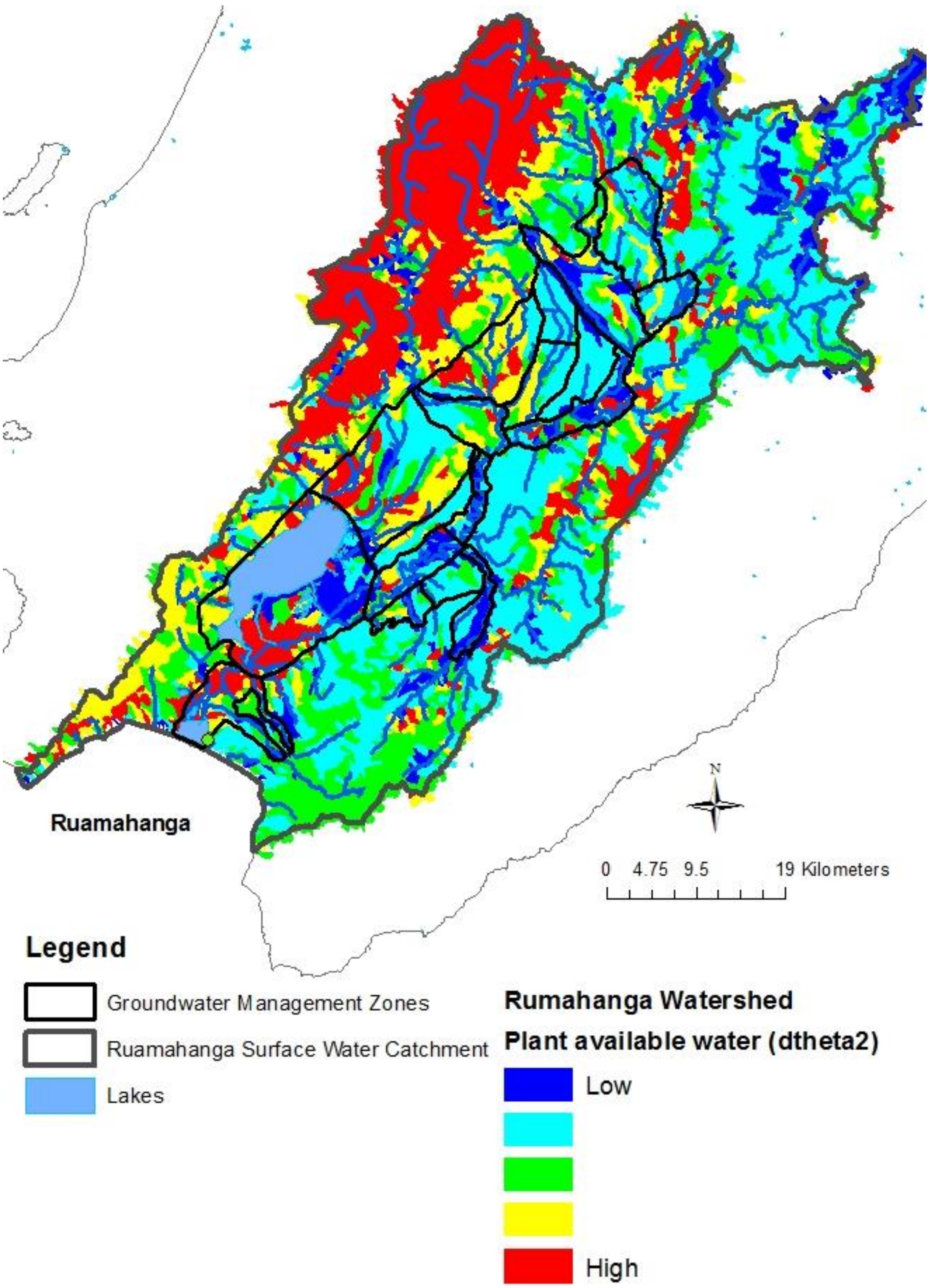

Figure 3-11: Spatial variation of the plant available water (dtheta2) TopNet parameter. Red represents high values of the parameter, while blue represents low values

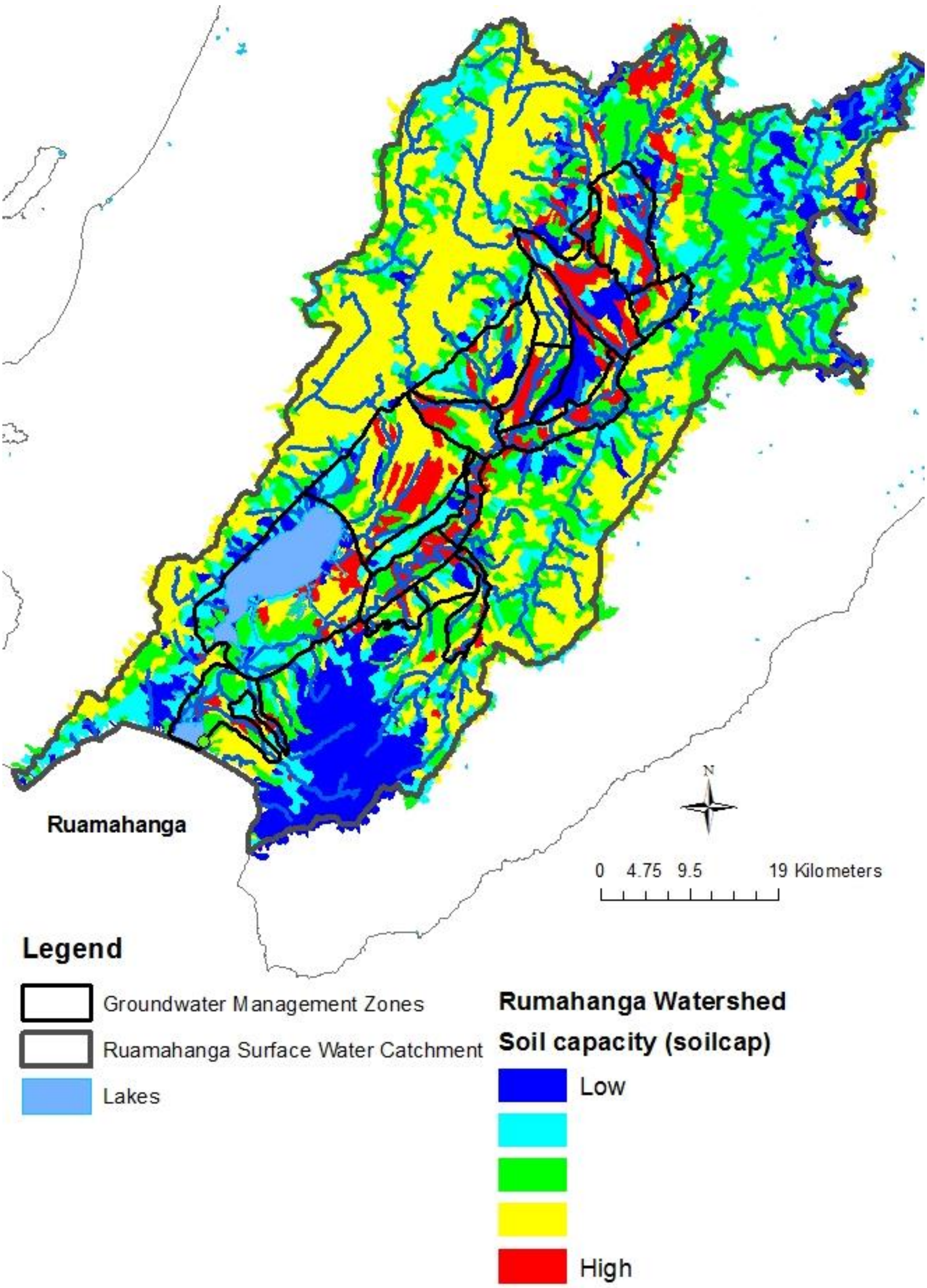

Figure 3-12: Spatial variation of the soil capacity (soilcap), used as a surrogate of the depth of hydraulically active soil in TopNet. Red represents high values of the parameter, while blue represents low values.

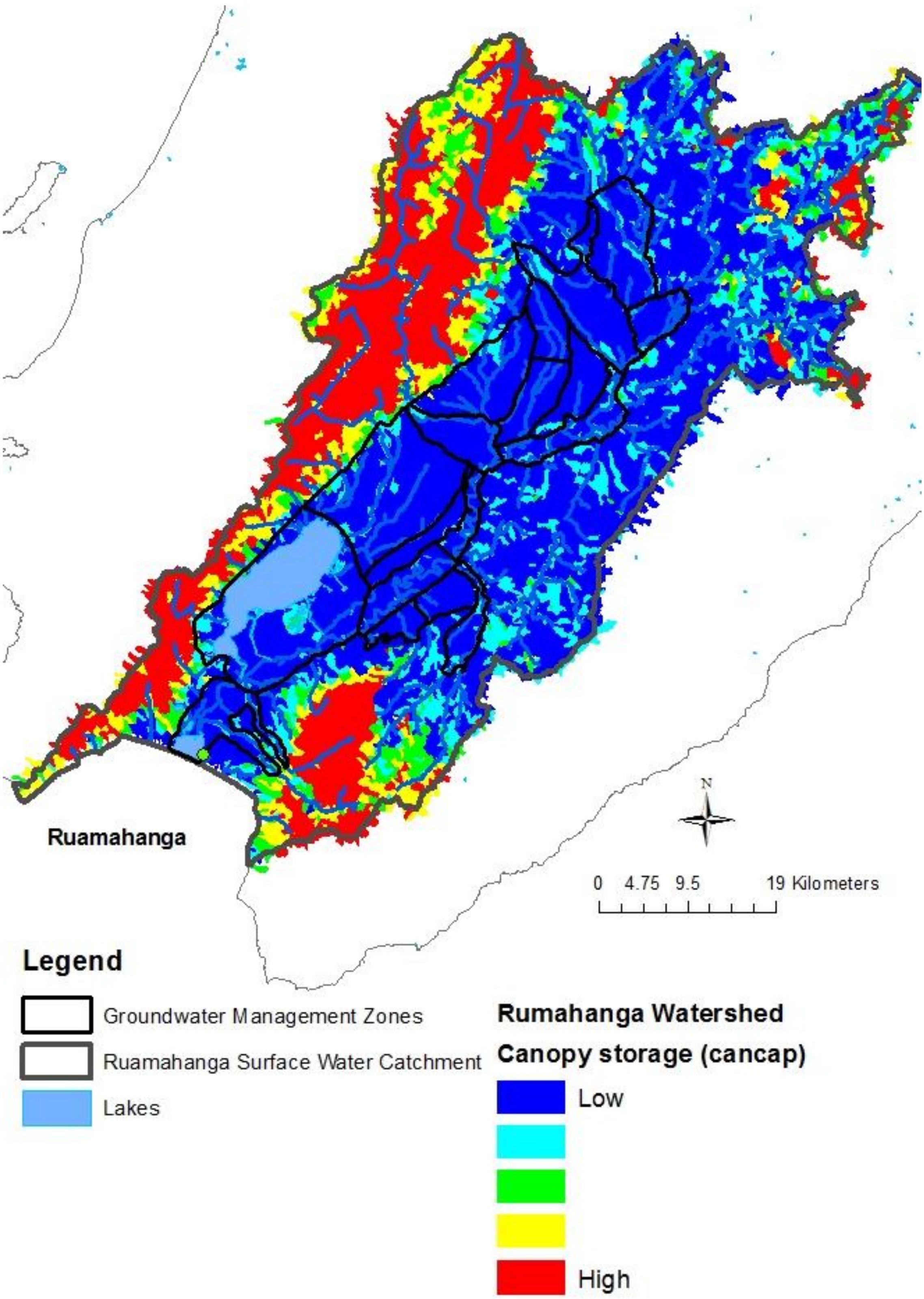

Figure 3-13: Spatial variation of the canopy storage capacity (cancap) TopNet parameter. Red represents high values of the parameter (forest), while blue represents low values (pasture).

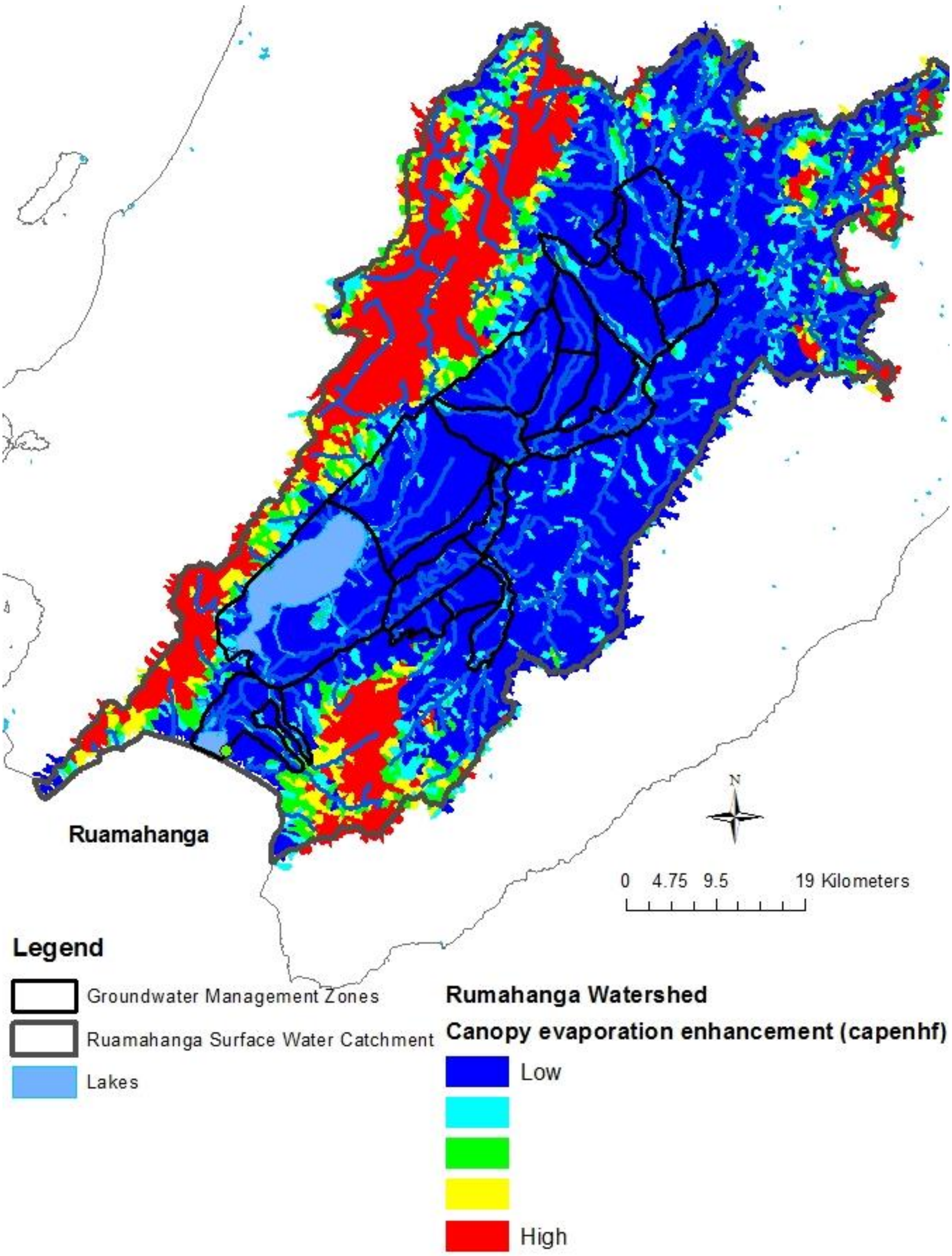

Figure 3-14: Spatial variation of the canopy evaporation enhancement factor (capenhf) TopNet parameter. Red colour represents high values of the parameter, while blue colour represents low values.

3.4.4 Parameter regionalisation

The identified nine monitored surface water catchments do not cover the entire area discharging to the GWZ. As a result, the TopNet parameters calibrated for those nine catchments, were extrapolated to the remaining ungauged surface water catchments discharging to the GWZ. In the present work, the extrapolation is based on the following criteria:

1. Soil drainage similarity based on the information provided by the FSL (Figure 3-15).
2. Soil type (Figure 3-16).
3. Climate range input (Figure 3-5).

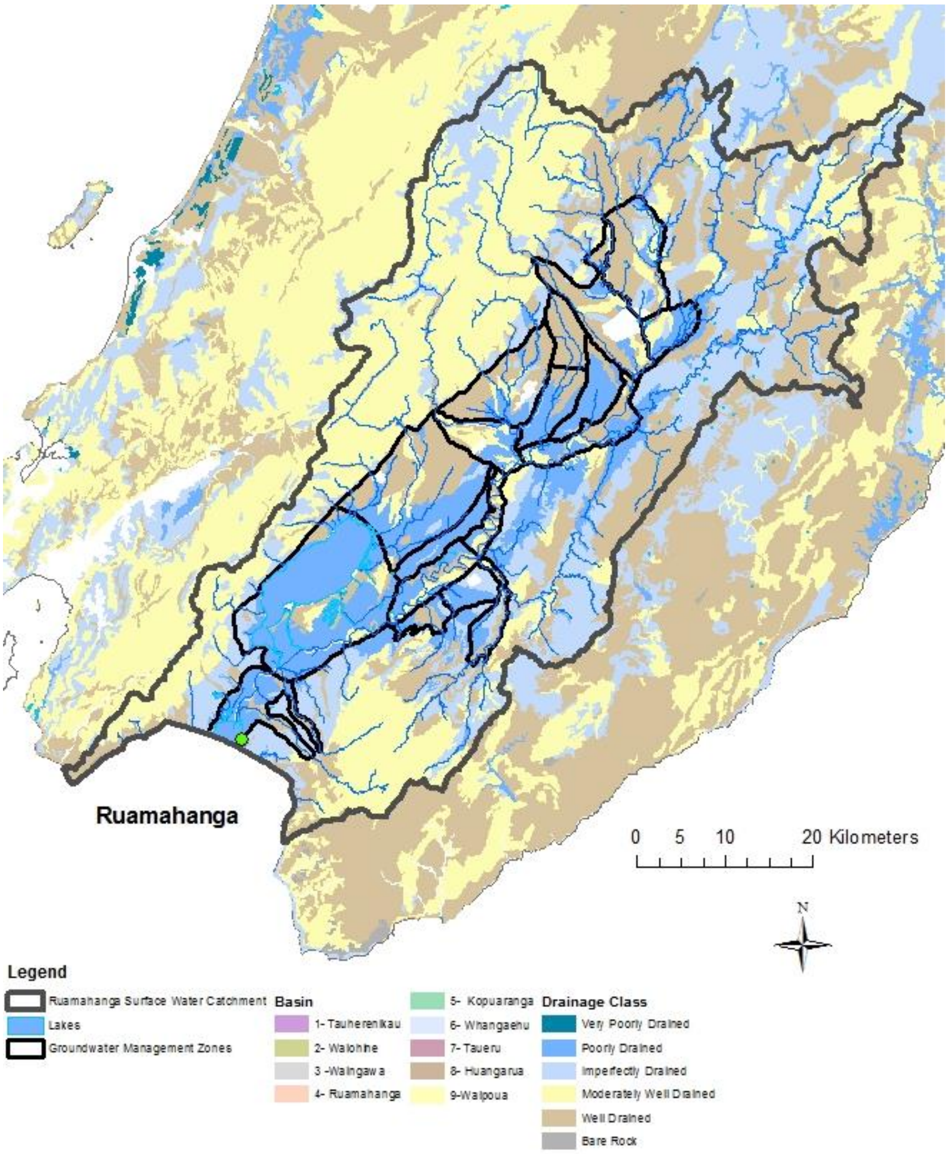

Figure 3-15: Soil drainage classification for the Ruamāhanga catchment based on the FSL soil drainage class.

Figure 3-15 presents the extent where the calibrated TopNet parameters are applied based on the regionalisation process.

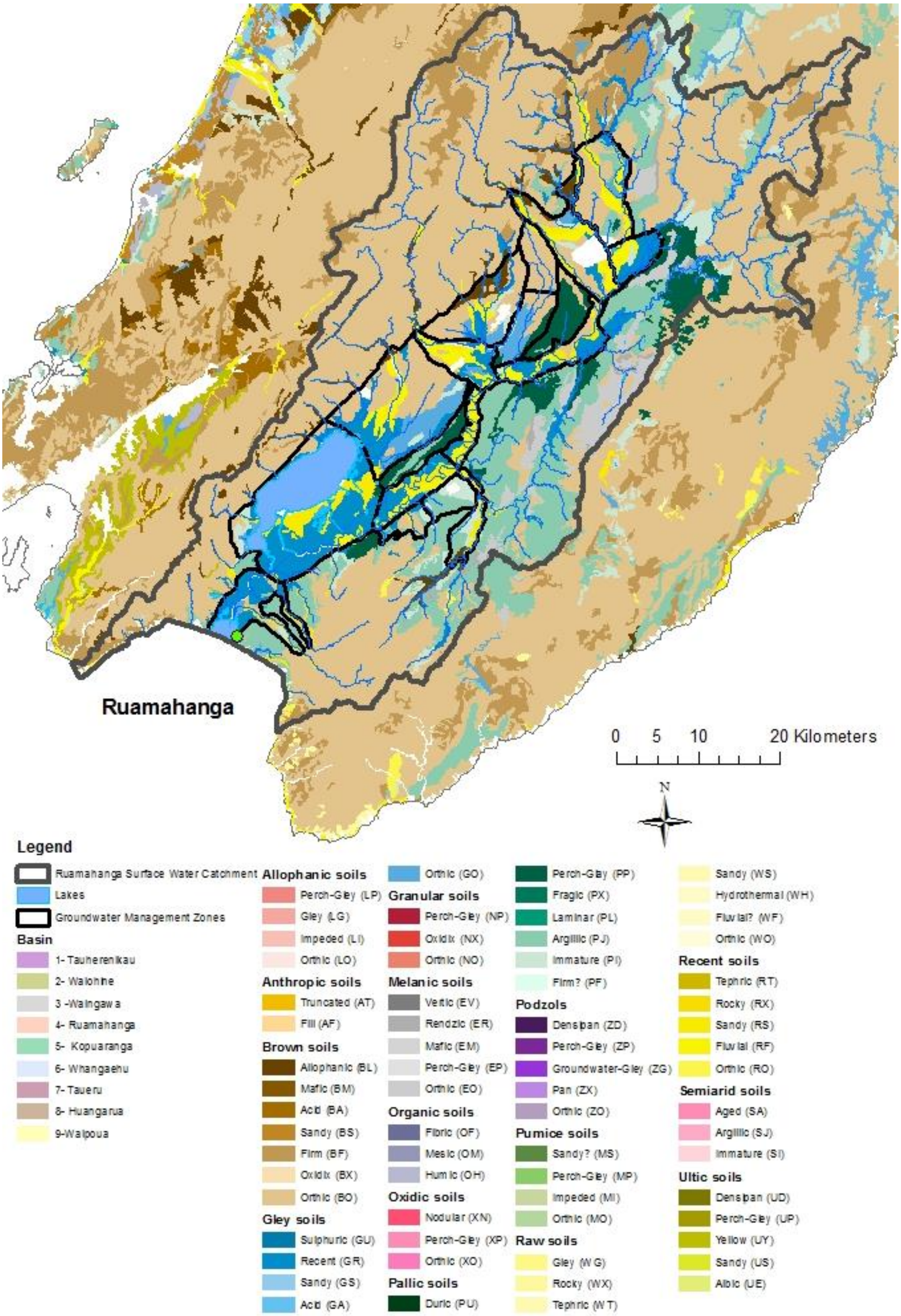
Ruamahanga
0 5 10 20 Kilometers
N
Legend
Ruamahanga Surface Water Catchment
Lakes
Groundwater Management Zones
Basin
1- Tauherenikau
2- Waiohine
3 -Waingawa
4- Ruamahanga
5- Kopuaranga
6- Whangaehu
7- Taueru
8- Huangarua
9-Waipoua
Allophanic soils
Perch-Gley (LP)
Gley (LG)
Impeded (LI)
Orthic (LO)
Anthropic soils
Truncated (AT)
Fill (AF)
Brown soils
Allophanic (BL)
Mafic (BM)
Acid (BA)
Sandy (BS)
Firm (BF)
Oxidic (BX)
Orthic (BO)
Gley soils
Sulphuric (GU)
Recent (GR)
Sandy (GS)
Acid (GA)
Orthic (GO)
Granular soils
Perch-Gley (NP)
Oxidic (NX)
Orthic (NO)
Melanic soils
Vertic (EV)
Rendzic (ER)
Mafic (EM)
Perch-Gley (EP)
Orthic (EO)
Organic soils
Fibric (OF)
Mesic (OM)
Humic (OH)
Oxidic soils
Nodular (XN)
Perch-Gley (XP)
Orthic (XO)
Pallic soils
Duric (PU)
Perch-Gley (PP)
Fragic (PX)
Laminar (PL)
Argillic (PJ)
Immature (PI)
Firm? (PF)
Podzols
Densipan (ZD)
Perch-Gley (ZP)
Groundwater-Gley (ZG)
Pan (ZX)
Orthic (ZO)
Pumice soils
Sandy? (MS)
Perch-Gley (MP)
Impeded (MI)
Orthic (MO)
Raw soils
Gley (WG)
Rocky (WX)
Tephric (WT)
Sandy (WS)
Hydrothermal (WH)
Fluvial? (WF)
Orthic (WO)
Recent soils
Tephric (RT)
Rocky (RX)
Sandy (RS)
Fluvial (RF)
Orthic (RO)
Semiarid soils
Aged (SA)
Argillic (SJ)
Immature (SI)
Ultic soils
Densipan (UD)
Perch-Gley (UP)
Yellow (UY)
Sandy (US)
Albic (UE)

Figure 3-16: Soil map for the Ruamāhanga catchment based on the FSL soil layer.

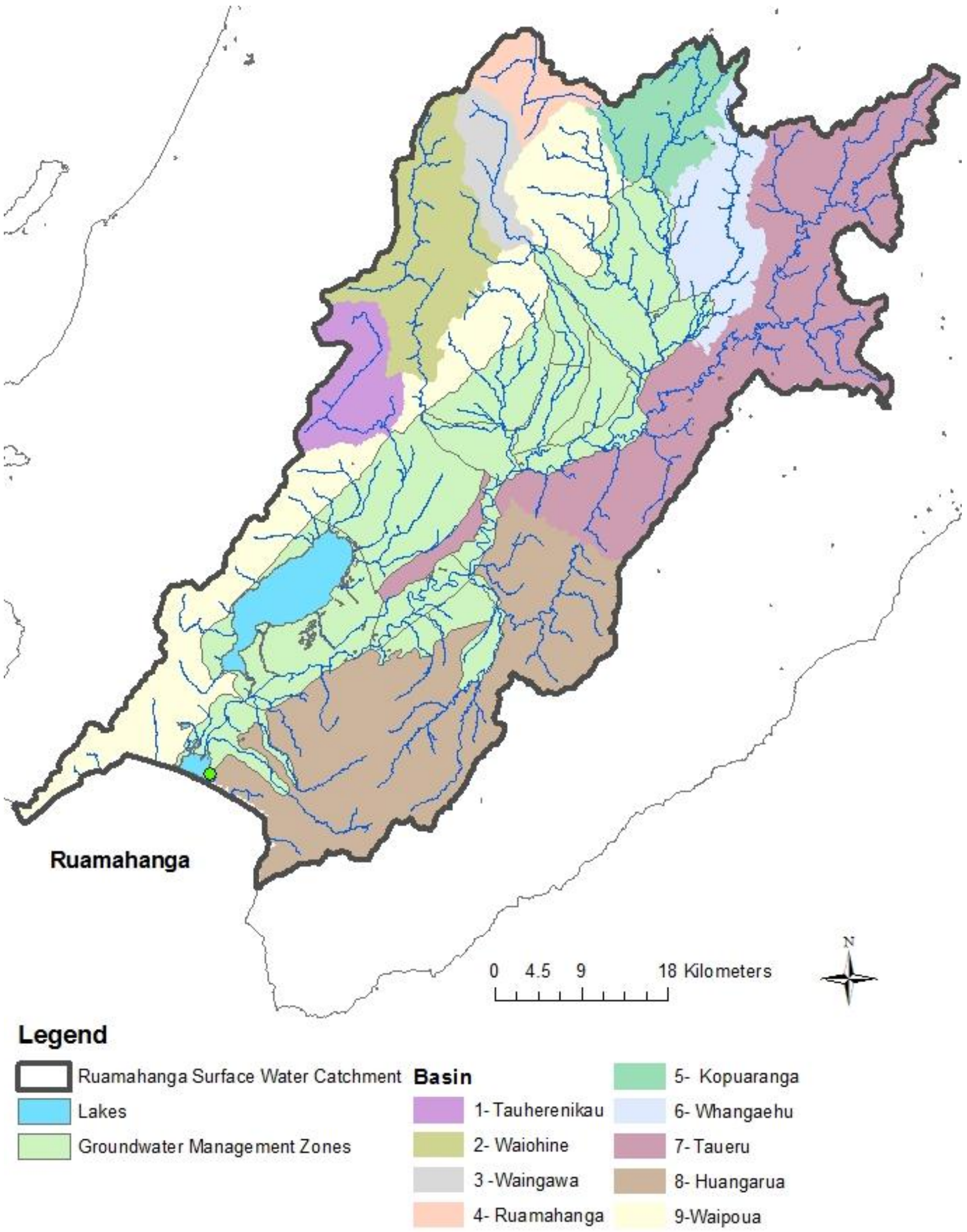

Figure 3-17: TopNet basin identifier for TopNet modelling of the Ruamāhanga Hill country catchment.

4 Model calibration

4.1 Calibration methodology

One of the main assumptions of TopNet is that the spatial distribution of the parameters is a-priori determined from catchment physiographic information from the sources described in Section 3 above (referred to as default value in Table 4-1 hereafter). The calibration process involves determination of seven parameter multipliers for each sub-catchment, whose initial values are set to a value of 1. Prior to each model calibration, sensitivity analysis was conducted by using the Morris method (Morris 1991). Then the optimization was carried out using the Shuffled Complex Evolution algorithm (SCE-A) (Duan 1992), which is widely used in hydrologic modelling. Table 4-1 presents the usual range of the parameter multipliers used during the calibration process.

Table 4-1: Range of TopNet parameter multipliers used during calibration process.

Parameter name (internal name)	Parameter description	Calibrated range
Saturated store sensitivity (topmodf)	Describes exponential decrease of soil hydraulic conductivity with depth	[0.01-2] * default
Drainable soil water (swater1)	Range between saturation and field capacity	[0.05-10] * default
Plant available soil water (swater2)	Range between field capacity and wilting point	[0.05-10] * default
Hydraulic Conductivity at saturation (hydcond0)		[0.1-10000] * default
Overland flow velocity (overvel)		[0.1-10] * default
Manning n	Characterises the roughness of each reach	[0.1-10] * default
Atmospheric lapse rate (atmlaps)	Change in temperature with elevation, used to adjust temperatures from climate data sites to basin centroid	[0.7-1.5] * default
Gauge Undercatch (gucatch)	Adjustment for non-representative precipitation	[0.5-1.5] * default

The TopNet models were calibrated on hourly river discharge records. The calibration period is chosen as 2001-2003, except for the Waipoua catchment for which the calibration period was chosen as 2007-2009 (GWRC, pers. comm.), as the available low flow data period was much shorter than other sites. The calibration period has been chosen to represent diverse water resource hydrological conditions (e.g., annual flow below and above the observed mean flow at each of the gauging station) while validation was carried out at daily time step (Ruamāhanga Whaitua Modelling project, pers. comm.) over the 2001-2012 period (except the Waipoua and Huangarua catchments). In this application the calibration parameter set mainly represented low flow periods at each gauging station, with a focus on the flows over the period November to March. The evaluation of the calibration of TopNet models was completed through a combination of performance measures on hourly streamflow and log-transformed streamflow to assess overall model performance, as well as flow duration curves (observed and predicted) to assess the accuracy of the statistical distribution of streamflow throughout the time period considered. Due to the aim of the project, the TopNet models were calibrated mainly based on log-transformed streamflow with the aim of better representing low flow conditions. In addition, further care was taken to ensure that the model parameters remained between physically reasonable limits.

For these nine catchments, as no significant consented activities are impacting observed discharge at the gauging sites, calibration was carried out over both high and low flow periods.

The accuracy of the calibration/validation process is estimated using the following hydrological criteria and statistics:

- The accuracy of the calibration process is estimated in terms of the Nash-Sutcliffe efficiency coefficient calculated on the discharge (NS) and on the logarithm of the discharge (NS Log). The NS score represents a measure of the residual variance versus the data variance. A NS score of 1 indicates that the calibration perfectly mimics the observations in time and volume. A negative NS score indicates that the average of the observation is a better predictor than the model flow. The NS score represents the ability of the model to mimic the observations during high flow periods, while the NS Log score represents the ability of the model to mimic the observations during low flow periods. Based on the objective of the model, the main objective function was chosen to be the NS Log score.
- Total water balance of the upstream catchment presented as annual average precipitation, evaporation and discharge at the gauging station over the period of simulation.
- Comparison of the daily observed and predicted flow duration curve (to identify potential mismatches in the statistical distribution of the flows) and cumulative flow (to identify potential issues related to systematic bias in the calibration process).
- Comparison of observed and predicted average monthly flows over the period of simulation (to identify potential issues on the seasonality of the water balance).
- Comparison of observed and predicted mean flow and 7-day Mean Annual Low Flow (7-day MALF) characteristics calculated over the period of simulation (to identify the ability of the model to represent low flow conditions).
- Comparison of observed and predicted flow deciles over the period of simulation (to identify potential skewness of the calibrated model towards specific flow conditions). The flow deciles presented hereafter are subject to some artificial bias towards the low flow values as missing observations were given a value of 0. The flow deciles are presented in Appendix A.
- Comparison of the monthly average flows during the potential water stress season (i.e., January to March).
- Validation of the model prediction carried out at daily time steps over the period 2001-2012, including the calibration period, (except for the Waipoua catchment for which validation was carried out over the period 2007-2012).

The calibration/validation results and associated analysis is presented hereafter for each catchment. Based on our experience with the calibration of the TopNet model, Table 4-2 presents a classification describing the goodness of fit of the NS or NSLog score.

Table 4-2: Classification of Nash-Sutcliffe score obtained using TopNet.

NS/NSLog score	Classification
<0.4	Poor
0.4< NS< 0.6	Adequate
0.6< NS< 0.8	Good
NS> 0.8	Excellent

4.2 Parameter sensitivity

The sensitivity analysis associated with the TopNet parameters is reported for each catchment hereafter.

4.2.1 Methodology

In this study, the Morris method (Morris 1991) was used to perform parameter sensitivity analysis. The Morris method is a global sensitivity analysis which studies parameter sensitivity across the entire parameter space instead of a nominal point, and it can measure both parameter sensitivity and interaction or nonlinearity between parameters. Its basic idea is that for a random variable X, the local sensitivity measure is computed based on OAT (One-At-a-Time) as follows:

$$d_i(X) = \frac{f(x_1, \cdots, x_{i-1}, x_i + \Delta, \cdots, x_n) - f(x_1, \cdots, x_{i-1}, x_i, \cdots, x_n)}{\Delta} \qquad (1)$$

Where $d_i(X)$ is the local sensitivity measure at the random point $X = (x_1, \dots, x_{i-1}, x_i, \cdots, x_n)$, and $\Delta = p/(2(p-1))$ is the predefined increment and p normally takes integer values [5, 11].

Local sensitivity measures are computed for each parameter by randomly sampling the parameter space, by which a finite distribution of the sensitivity measures is obtained. From the distribution, two statistics are used in the Morris method: i) the sample mean of absolute values of the elementary effects (μ^*) measuring the degree of parameter sensitivity; and ii) the standard deviation of elementary effects (σ) measuring the degree of nonlinearity or parameter interaction. The higher μ^* is, the more important the parameter is to the model output; and the higher σ is, the more nonlinear the parameter is to the model output or more interactions with other parameters.

The Morris method requires m*(n+1) model runs to get *m* estimates of elementary effects for each parameter, where *n* is the basic sample size (set usually to n=50). The method can obtain satisfactory sensitivity results efficiently (Yang 2011; Yang et al. 2012) and it is important to note that the outcome of the analysis depends largely on the objective function chosen.

4.2.2 Results

The sensitivity analysis was carried out for each of the nine calibrated catchments discharging to the GWZ area. Table 4-3 presents the TopNet parameters considered during the sensitivity analysis as well as their range.

Table 4-3: TopNet parameter multiplier considered as part of the sensitivity analysis.

Parameter name (internal name)	Parameter description	Minimum	Maximum
topmodf	Describes exponential decrease of soil hydraulic conductivity with depth	0.2	2
hydcon0	Hydraulic conductivity at saturation	0.01	9999
swater1	Range between saturation and field capacity	0.05	10
swater2	Range between field capacity and wilting point	0.05	10
dthetat	Soil water content	0.1	20
overvel	Overland flow velocity	0.05	10
canscap	Canopy storage	0.1	15
canenhf	Canopy evaporation enhancement factors	0.1	15
salbedo	Surface albedo	1	5
atmlaps	Change in temperature with elevation, used to adjust temperatures from climate data sites to basin centroid	0.5	1.5
gucatch	Adjustment for non-representative precipitation	-	-
r_man_n	Characterises the roughness of each reach	0.1	10

Due to the extreme sensitivity of the modelling outputs to the value of the gucatch parameter multiplier, it was decided to limit the sensitivity of this parameter to +/- 10% centred on the value of the parameter calibrated for each catchment. This sensitivity represents a reasonable estimation of the sensitivity to wind conditions (WMO 2008).

Table 4-4 presents the result of the sensitivity analysis, in terms of local sensitivity ranking, carried out for each catchment (identified by its most downstream reachID- see Table 3-2) using the NSLog as the objective function. The choice of the objective function is aligned with the aim of the TopNet model to reproduce low flow conditions.

Table 4-4: Local sensitivity ranking for each TopNet parameter. '1' indicates the most sensitive parameter.

Parameter name (internal name)	Tauherenikau 9259046	Waiohine 9257741	Waingawa 9254309	Waipoua 92553108	Ruamāhanga 9250417	Kopuaranga 9252319	Whangaehu 9252727	Taueru 9257216	Huangarua 9265072
topmodf	1	1	2	1	2	2	1	2	3
hydcon0	6	6	5	5	6	7	7	6	4
swater1	4	4	4	6	4	6	3	4	6
swater2	2	2	1	2	1	1	2	1	2
dthetat	3	3	3	3	3	3	4	3	1
overvel	8	8	10	8	8	9	9	11	11
canscap	11	12	11	10	12	11	10	10	10
canenhf	9	9	8	9	9	8	8	8	8
salbedo	7	5	7	4	7	4	5	5	5
atmlaps	10	10	12	12	11	12	12	12	12
gucatch	12	11	9	11	10	10	11	9	9
r_man_n	5	7	6	7	5	5	6	7	7

Study of the sensitivity analysis indicates that:

- Notwithstanding the extreme sensitivity of the model outputs to gucatch, in general sensitivity ranking indicates the saturated store sensitivity (topmodf) is one of the most sensitive parameters in the model. It controls the responsiveness of shallow subsurface flow, and thus has a major impact on hydrograph shape for many catchments in New Zealand.
- The second most sensitive parameters are swater2 and dthetat. Swater2 controls the hydraulically active "soil depth" in TopNet, while dthetat controls the amount of soil moisture available in each sub catchment.
- The third group of parameters is the hydraulic conductivity at saturation (hydrocon0) that controls surface water/groundwater interaction processes and swater1, which controls the amount of water available (within the water column) for the plant to access through evaporation processes.
- The least sensitive parameters are salbedo, r_man_n and overvel.

The ranking of parameter sensitivities indicates those aspects of the landscape where small changes in parameter values would result in the largest change in TopNet simulation results. There are several initiatives to collect better water-related parameters in the NZ landscape. A key one of these is S-Map being developed by Landcare Research, but as yet the coverage does not extend to the Ruamāhanga Hill Country.

The sensitivity ranking obtained in Table 4-4 is comparable to the sensitivity ranking expected for any TopNet calibration targeting low flow conditions. However, it is important to stress that any sensitivity analysis is subject to model setup (e.g., climate information input, accuracy of land cover-soil and geological information), parameter range, and the chosen objective function. As a result, in this application the sensitivity analysis outcome represents sensitivity to the objective function used to calibrate the model (i.e., NSLog).

4.3 Tauherenikau catchment

The accuracy of the streamflow model prediction is presented in Table 4-5 for the calibration phase and the validation phase. The final values of parameters are provided in Table 4-6 and expressed as a parameter multiplier of the a-priori value described in section 4.1. Table 4-7 provides the simulated water balance and a comparison of simulated precipitation and evaporation with the long-term average climatology (calculated over the period 1966-2006). Table 4-8 provides the simulated and observed mean flow and 7-day MALF, while Table 4-9 presents the observed and simulated monthly average flows over the period of simulation.

Figure 4-1 and Figure 4-2 present the simulation results at the streamflow gauging station in terms of comparison between simulated and observed hydrographs, cumulative hydrograph and flow duration curve during the calibration period (Figure 4-1) and validation period (Figure 4-2). Figure 4-3 presents the observed and simulated hourly low flows hydrograph (i.e., for discharge below mean flow) over the calibration and simulation period. Figure 4-4 presents the observed and predicted monthly average discharge at the gauging station over the validation period.

Table 4-5: Calibration- validation statistics for Tauherenikau catchment.

	Calibration (2001-2003)		Validation (2001-2012)	
Location	**NSlog**	**NS**	**NSlog**	**NS**
Tauherenikau at Gorge	0.614	0.438	0.754	0.444

Table 4-6: TopNet parameters for Tauherenikau catchment.

Parameter name (internal name)	Parameter description	Calibrated value
Saturated store sensitivity (topmodf)	Describes exponential decrease of soil hydraulic conductivity with depth	1.321 * default
Drainable soil water (swater1)	Range between saturation and field capacity	1.397 * default
Plant available soil water (swater2)	Range between field capacity and wilting point	0.051 * default
dthetat	Soil water content	2.955 * default
Hydraulic Conductivity at saturation (hydcond0)		0.114 * default
Overland flow velocity (overvel)		3.485 * default
Manning n	Characterises the roughness of each reach	0.533 * default
Atmospheric lapse rate (atmlaps)	Change in temperature with elevation, used to adjust temperatures from climate data sites to basin centroid	1.433 * default
Gauge Undercatch (gucatch)	Adjustment for non-representative precipitation	1.100 * default

Table 4-7: Simulated water balance by TopNet for Tauherenikau catchment over the period of observations and simulation (2001-2012) compared with GWRC historic observations (Gordon 2013) and the long term average climatology.

Annual Average Flux	TopNet (2001-2012) (mm/yr)	GWRC (2001-2012) (mm/yr)	GWRC (1976-2012) (mm/yr)	Long term average climatology (1966-2006) (mm/yr)
Mean annual precipitation	2850	NA	NA	3270
Mean annual evaporation	447	NA	NA	724
Mean annual runoff	2303	2332	2541	NA

Table 4-8: Simulated and Observed flow characteristics for Tauherenikau catchment over the period 2001-2012 and the historic record (Gordon 2013).

Annual Average hydrological characteristics	TopNet (2001-2012) (m3/s)	GWRC (2001-2012) (m3/s)	GWRC (1976-2012) (m3/s)
Mean Flow	8.335	8.440	9.10
7-day Mean Annual Low Flow	1.526	1.377	1.321

Table 4-9: Simulated and Observed monthly average flows for Tauherenikau catchment over the period 2001-2012 and the historic record (Gordon 2013).

Months	Observed (2001-2012) (m^3/s)	TopNet (2001-2012) (m^3/s)	Observed (1976-2012) (m^3/s)
January	4.659	4.414	5.370
February	4.923	6.351	5.141
March	5.856	5.087	5.859
April	4.520	5.128	6.636
May	6.986	7.634	9.206
June	8.976	9.520	11.630
July	11.966	11.042	13.437
August	10.399	10.251	11.703
September	8.178	7.647	10.703
October	11.148	10.764	11.833
November	6.830	6.245	8.169
December	6.809	6.366	8.345

Monthly average flows are close to the recorded seasonal flow pattern. In contrast, the representation of catchment rain vs. the Bull Mound rain gauge show a distinct bias (see Figure 3-8). In part this is because the rain gauge is at the high point of the catchment, and the model representation is over an area that has a much larger elevation range, as well as being just under 1 km^2 in area.

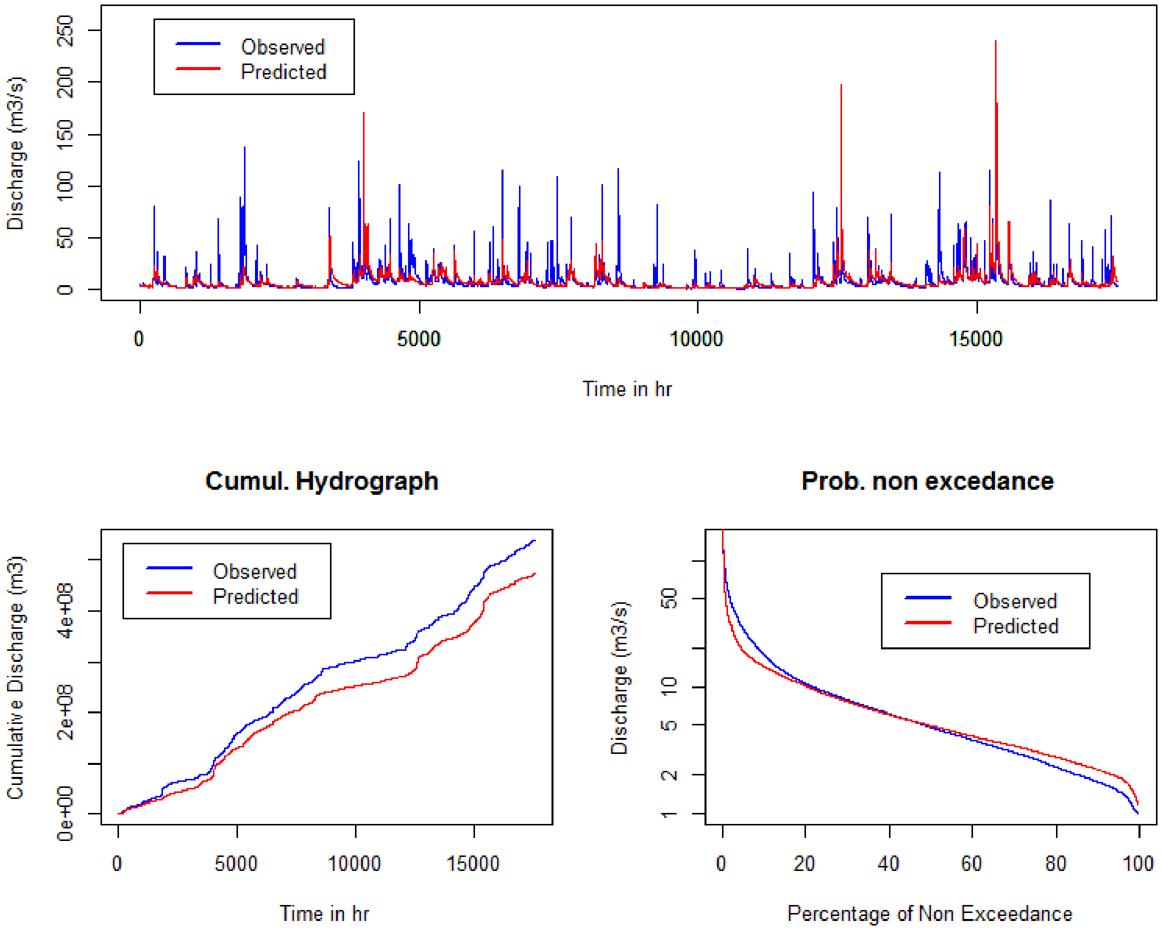

Figure 4-1: Calibrated hourly hydrograph, cumulative hydrograph and flow duration curve of Tauherenikau at Gorge over the calibration period 2001-2003.

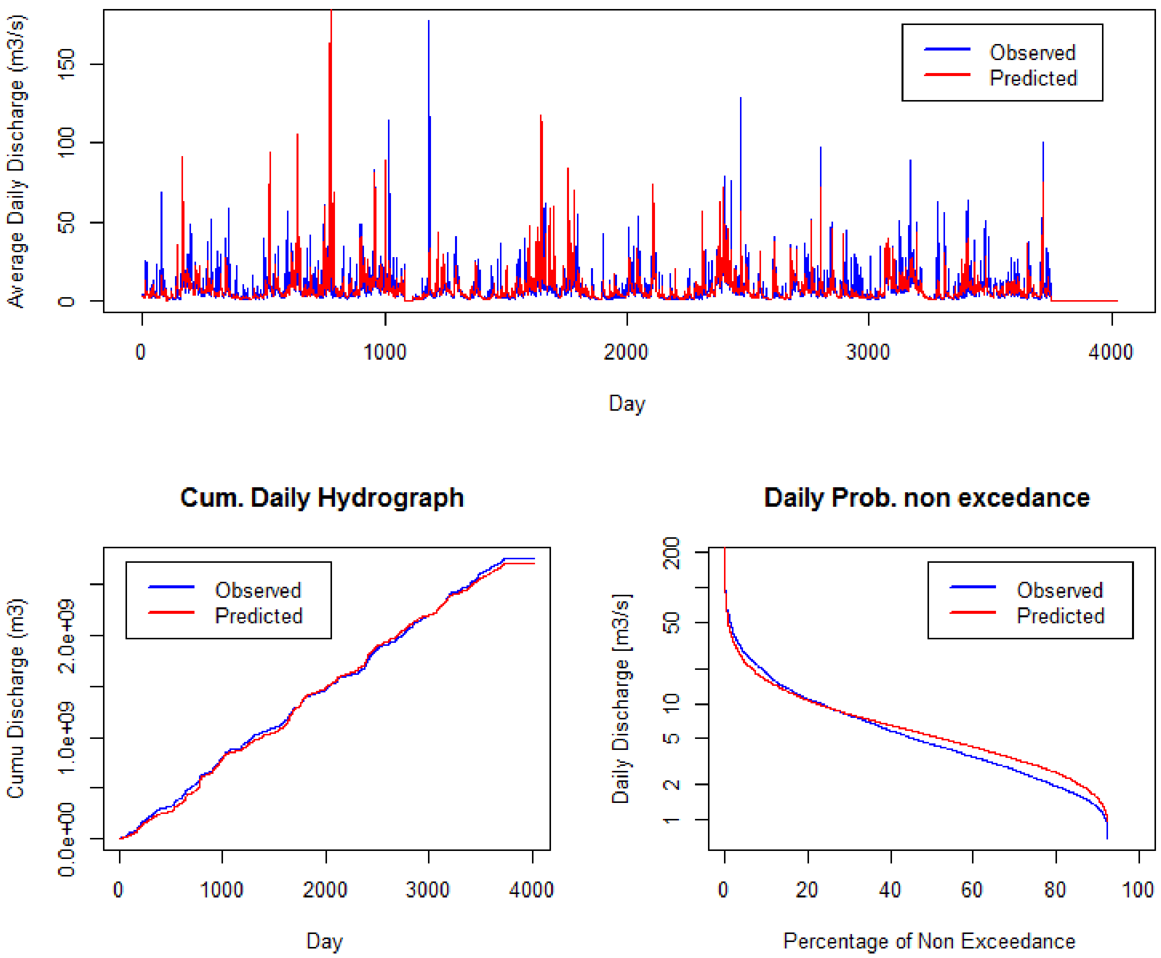

Figure 4-2: Simulated daily hydrograph, cumulative hydrograph and flow duration curve of Tauherenikau at Gorge over the validation period 2003-2012.

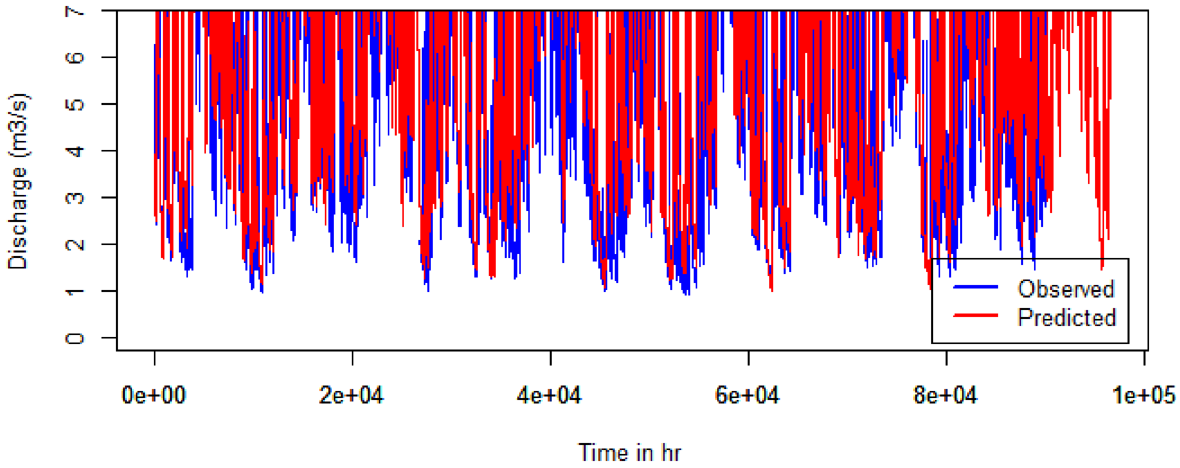

Figure 4-3: Observed and simulated hourly low flow hydrograph (i.e., flow below mean flow) for Tauherenikau at Gorge over the calibration period and validation periods.

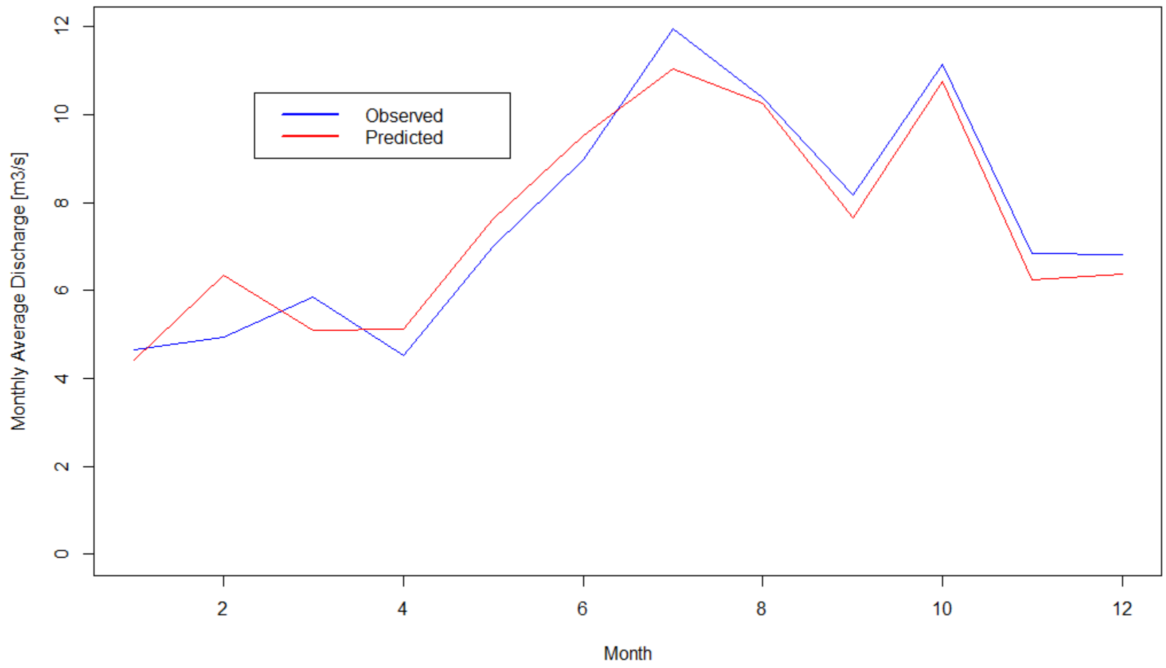

Figure 4-4: Observed and simulated monthly average flow for Tauherenikau at Gorge over the period 2001-2012.

Analysis of the simulations indicates:

- Analysis by GWRC of observed flow time series indicates that low flow and some flood peak measurements are subject to caution (Gordon 2013).
- The adequate NS score obtained during the calibration and validation period is linked to the underestimation of the peak discharges (Figure 4-1 and Figure 4-2) that is currently not well reproduced by TopNet. This underestimation of peak discharge (timing and magnitude) is thought to be associated with underestimation of daily VCSN and the lack of correct hourly precipitation information in the Tauherenikau catchment over the period simulated.
- The calibrated model is able to reasonably reproduce observed low flows (based on NSLog score) for most of time during the calibration and validation period). However hydrological conditions around February and March tend to be (on average) under and over predicted respectively (Table 4-9).
- The calibrated model is able to reproduce the hydrological behaviour (in terms of mean flow and 7-day MALF) encountered during simulation and validation periods. Hence timing and magnitude of seasonal change are correctly reproduced by the calibrated model.
- TopNet simulations underestimate long term average precipitation and evaporation (compared to the long-term climatology) over the Tauherenikau catchment. However, their difference is consistent with the mean flow observed over the period of simulation. This indicates a potential underestimation of climate conditions over the catchment.

- Low flow hydrological conditions tend to be slightly over-predicted (Figures 4.2- 4.3), especially in the flow recession component of the hydrographs (i.e., flows under 10 m3/s). This is likely to be associated with the misrepresentation of subsurface soil process, which is related to the soil and geological data used in this study.
- Analysis of the simulated annual water balance indicates that the simulated annual average evaporation is less than expected. This is thought to be linked with under representation of the mean annual precipitation for the upper catchment by the VCSN. This is confirmed by the fact that mean flow is correctly represented over the time of the model validation as well as little difference between the cumulative daily observed and simulated flows.
- Seasonal flows are correctly reproduced except for February where larger differences between observed and predicted flows are observed. This is thought to be related to TopNet not being able to reproduce a large flow event in February 2005 (at approximately 800 days in Figure 4-2).

4.4 Waiohine catchment

The accuracy of the streamflow model prediction is presented in Table 4-10 for the calibration phase and the validation phase. The final values of parameters are provided in Table 4-11. Table 4-12 provides the simulated water balance and a comparison of simulated precipitation and evaporation with the long-term average climatology (calculated over the period 1966-2006). Table 4-13 provides the simulated and observed mean flow and 7-day MALF, while Table 4-14 presents the observed and simulated monthly average flows over the period of simulation.

Figure 4-5 and Figure 4-6 present the simulation results at the streamflow gauging station in terms of comparison between simulated and observed hydrographs, cumulative hydrograph and flow duration curve during the calibration period (Figure 4-5) and validation period (Figure 4-6). Figure 4-7 presents the observed and simulated hourly low flows hydrograph (i.e., for discharge below mean flow) over the calibration and simulation period. Figure 4-8 presents the observed and predicted monthly average discharge at the gauging station over the validation period.

Table 4-10: Calibration- validation statistics for Waiohine catchment.

	Calibration (2001-2003)		Validation (2001-2012)	
Location	**NSlog**	**NS**	**NSlog**	**NS**
Waiohine at Gorge	0.554	0.372	0.784	0.501

Table 4-11: TopNet parameters for Waiohine catchment.

Parameter name (internal name)	Parameter description	Calibrated value
Saturated store sensitivity (topmodf)	Describes exponential decrease of soil hydraulic conductivity with depth	1.356 * default
Drainable soil water (swater1)	Range between saturation and field capacity	9.740 * default
Plant available soil water (swater2)	Range between field capacity and wilting point	0.050 * default
Soil water content (dthetat)		1.416 * default
Hydraulic Conductivity at saturation (hydcond0)		3640 * default
Overland flow velocity (overvel)		0.463 * default
Manning n	Characterises the roughness of each reach	0.193 * default
Atmospheric lapse rate (atmlaps)	Change in temperature with elevation, used to adjust temperatures from climate data sites to basin centroid	1.455 * default
Gauge Undercatch (gucatch)	Adjustment for non-representative precipitation	0.610 * default

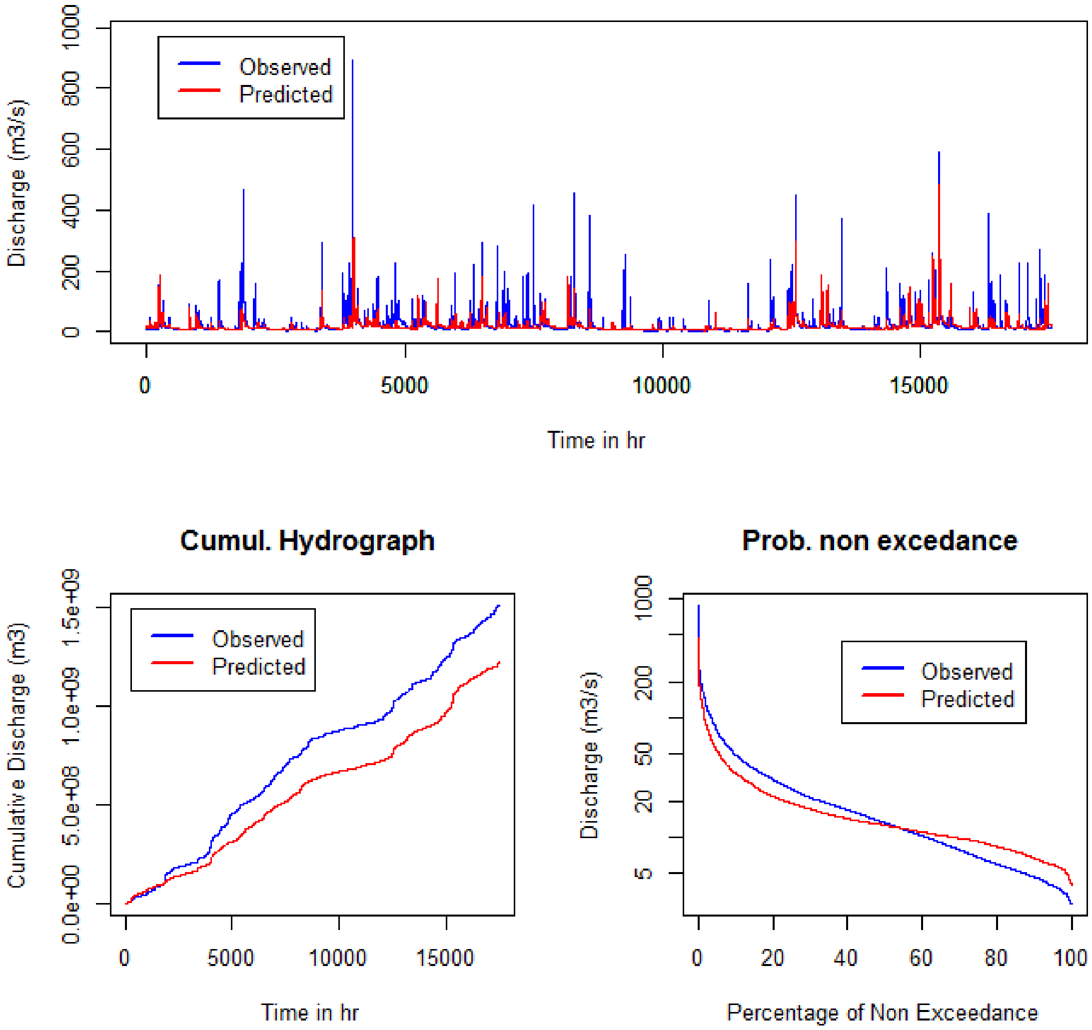

Figure 4-5: Calibrated hourly hydrograph of Waiohine at Gorge (new site) over the calibration period 2001-2003.

Table 4-12: Simulated water balance by TopNet for Waiohine catchment over the period of observations and simulation (2001-2012) compared with GWRC historic observations (Gordon 2013) and the long term average climatology.

Annual Average Flux	TopNet (2001-2012) (mm/yr)	GWRC (2001-2012) (mm/yr)	GWRC (1979-2012) (mm/yr)	Long term average climatology (1966-2006) (mm/yr)
Mean annual precipitation	3888	NA	NA	4934
Mean annual evaporation	225	NA	NA	703
Mean annual runoff	3628	4000	4099	NA

Table 4-13: Simulated and observed flow characteristics for Waiohine catchment over the period 2001-2012 and the historic record (Gordon 2013).

Annual Average hydrological characteristics	TopNet (2001-2012) (m^3/s)	GWRC (2001-2012) (m^3/s)	GWRC (1979-2012) (m^3/s)
Mean Flow	18.242	20.426	24.51
7-day Mean Annual Low Flow	6.110	3.664	3.612

Table 4-14: Simulated and observed monthly average flows for Waiohine catchment over the period 2001-2012 and the historic record (Gordon 2013)

Months	Observed (2001-2012) (m^3/s)	TopNet (2001-2012) (m^3/s)	Observed (1979-2012) (m^3/s)
January	15.494	15.913	17.084
February	16.334	16.908	17.014
March	16.311	12.134	16.768
April	12.238	11.821	18.128
May	18.742	16.299	22.873
June	23.644	19.612	27.009
July	29.390	21.701	30.643
August	25.612	23.353	28.458
September	24.071	21.432	28.064
October	30.706	28.888	33.514
November	22.108	20.257	26.710
December	21.855	21.202	26.078

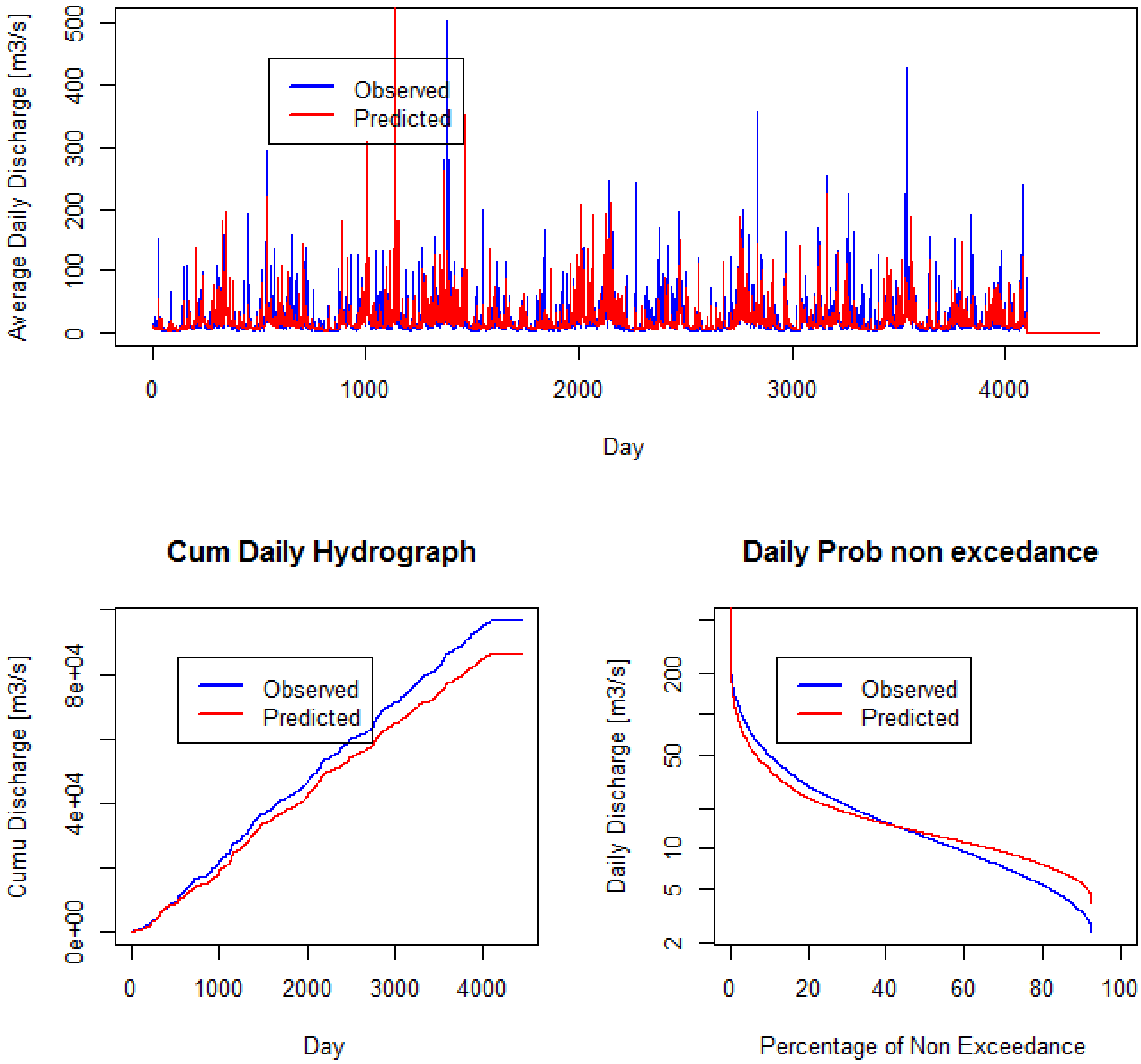

Figure 4-6: **Simulated daily hydrograph of Waiohine at Gorge (new site) over the validation period 2001-2012.**

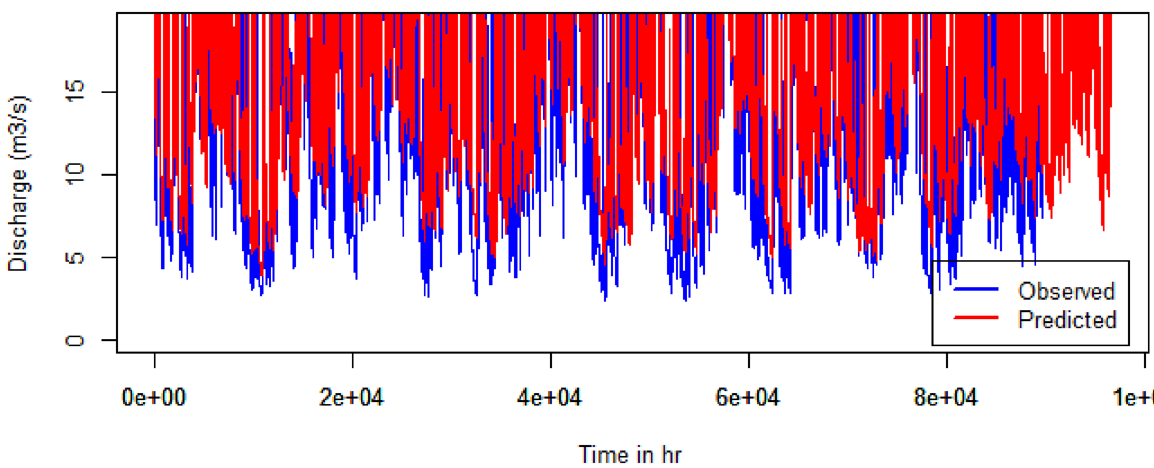

Figure 4-7: **Observed and simulated hourly low flow hydrograph (i.e., flow below mean flow) for Waiohine at Gorge (new site) over the calibration and validation periods.**

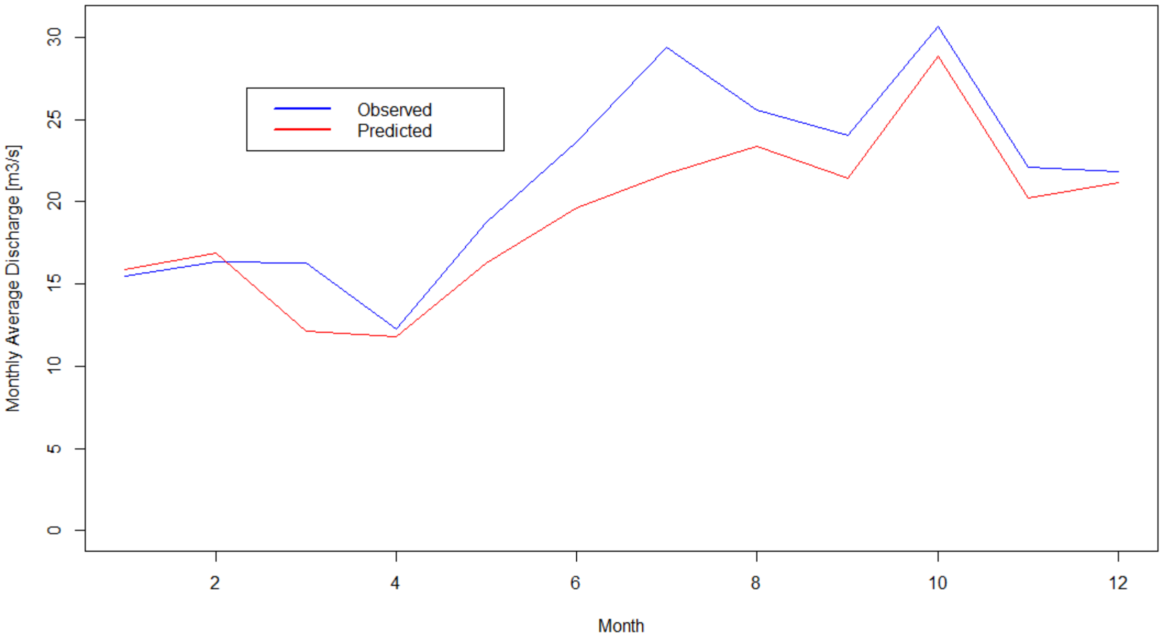

Figure 4-8: Observed and simulated monthly average flow for Waiohine at Gorge (new site) Branch over the validation period.

Analysis of the simulations indicates:

- Analysis by GWRC of observed flow time series indicates that high flow rating curves might have large uncertainties in high flow (following ratings done in October 2000), but the current rating is considered to be of excellent quality at low flow conditions.
- The poor NS score obtained during the calibration and validation period is linked to the underestimation of the winter discharges (Figure 4-8). This underestimation of winter discharge (timing and magnitude) is thought to be associated with a potential underestimation of daily VCSN in the upper Waiohine catchment during winter over the period simulated.
- The calibrated model is able to reproduce observed low flows (based on NSLog score) for most of time during the calibration and validation period. However further analysis indicates that the TopNet model is consistently overestimating observed low flows, while overestimating mid-range to high flow conditions. Further investigation in the spatial representation of the source of flow within the Waiohine catchment would provide some understanding of such behaviour.
- Annual average evaporation estimated by TopNet is lower than the expected long term average annual evaporation across the catchment. This is thought to be linked to the underestimation of the annual average precipitation over the catchment (no precipitation information available to constrain VCSN interpolation over the Waiohine catchment). This will result in an underestimation of the long term evaporation to reproduce correctly the average annual flow and the annual average catchment water balance.

- Large difference with the average annual evaporation simulated for Tauherenikau indicates potential issues with the FSL driven soil parametrisation in the catchment or issues with the spatial distribution of the precipitation over the catchment. This was not further investigated at the time of this project.
- The calibrated model is not able to reproduce accurately the hydrological behaviour (in term of mean flow and 7-day MALF) encountered during simulation and validation periods. However, timing and magnitude of seasonal change are correctly reproduced by the calibrated model. However hydrological conditions around March tend to be (in average) largely underpredicted by TopNet (Figure 4-13).
- Low flow hydrological conditions tend to be over-predicted (Figure 4-7) by around 2 m^3/s, especially in the flow recession component of the hydrographs (i.e., flows under 15 m^3/s). This is likely to be associated with the misrepresentation of subsurface soil process, which is related to the soil and geological data used in this study, or the spatial distribution of the climate variables across the Waiohine catchment.
- High flow events in the Waiohine catchment are underestimated by TopNet. This is likely to be associated with a misrepresentation of the timing of those events by the high frequency precipitation interpolation procedure across the catchment (high frequency precipitation gauge located at the outlet and the upper reaches of the catchment only- see Figure 3-3). In addition, misrepresentation of the high flow conditions within the catchment might be a by-product of the calibration strategy and process carried out within this project (focussing on the reproduction of low flow conditions for water allocation purpose).
- Seasonal flows are correctly reproduced (magnitude and timing) during the summer months. Magnitude of the winter flows are largely underpredicted and it is thought to be associated with a potential under-representation of the winter precipitation magnitude in the upper Waiohine catchment.

4.5 Waingawa catchment

The accuracy of the streamflow model prediction is presented in Table 4-15 for the calibration phase and the validation phase. The final values of parameters are provided in Table 4-16. Table 4-17 provides the simulated water balance and a comparison of simulated precipitation and evaporation with the long-term average climatology (calculated over the period 1966-2006). Table 4-18 provides the simulated and observed mean flow and 7-day MALF, while Table 4-19 presents the observed and simulated monthly average flows over the period of simulation.

Figure 4-9 and Figure 4-10 present the simulation results at the streamflow gauging station in terms of comparison between simulated and observed hydrographs, cumulative hydrograph and flow duration curve during the calibration period (Figure 4-9) and validation period (Figure 4-10). Figure 4-1111 presents the observed and simulated hourly low flows hydrograph (i.e., for discharge below mean flow) over the calibration and simulation period. Figure 4-12 presents the observed and predicted monthly average discharge at the gauging station over the validation period.

Table 4-15: Calibration- validation statistics for Waingawa catchment.

	Calibration (2001-2003)		Validation (2001-2012)	
Location	NSlog	NS	NSlog	NS
Waingawa at Upper Kaituna Branch	0.554	0.437	0.661	0.443

Table 4-16: TopNet parameters for Waingawa catchment.

Parameter name (internal name)	Parameter description	Calibrated value
Saturated store sensitivity (topmodf)	Describes exponential decrease of soil hydraulic conductivity with depth	0.586 * default
Drainable soil water (swater1)	Range between saturation and field capacity	0.289 * default
Plant available soil water (swater2)	Range between field capacity and wilting point	0.209 * default
Soil water content (dthetat)		1.543 * default
Hydraulic Conductivity at saturation (hydcond0)		5095 * default
Overland flow velocity (overvel)		9.625 * default
Manning n	Characterises the roughness of each reach	0.101 * default
Atmospheric lapse rate (atmlaps)	Change in temperature with elevation, used to adjust temperatures from climate data sites to basin centroid	1.494 * default
Gauge Undercatch (gucatch)	Adjustment for non-representative precipitation	0.669 * default

Table 4-17: Simulated water balance by TopNet for Waingawa catchment over the period of observations and simulation (2001-2012) compared with observations (Gordon 2013) and the long term average climatology.

Annual Average Flux	TopNet (2001-2012) (mm/yr)	GWRC (2001-2012) (mm/yr)	GWRC (1976-2012) (mm/yr)	Long term average climatology (1966-2006) (mm/yr)
Mean annual precipitation	3688	NA	NA	3975
Mean annual evaporation	111	NA	NA	699
Mean annual runoff	3489	3271	4224	NA

Table 4-18: Simulated and observed flow characteristics for Waingawa catchment over the period of (2001-2012 and the historic record (Gordon 2013).

Annual Average hydrological characteristics	TopNet (2001-2012) (m^3/s)	GWRC (2001-2012) (m^3/s)	GWRC (1976-2012) (m^3/s)
Mean Flow	8.470	7.930	10.24
7-day Mean Annual Low Flow	1.527	1.428	1.427

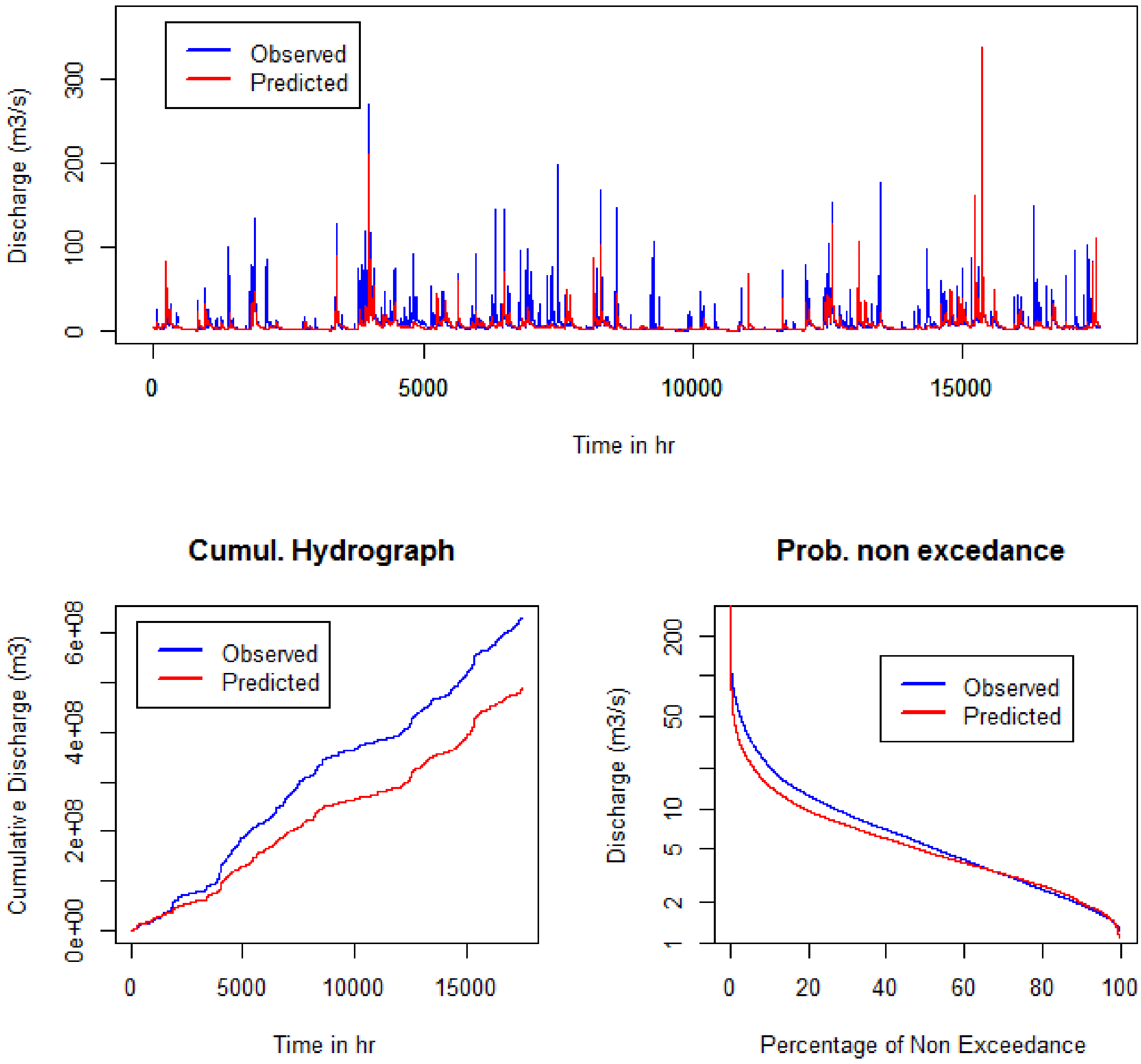

Figure 4-9: Calibrated hourly hydrograph of Waingawa at Upper Kaituna Branch over the calibration period 2001-2003.

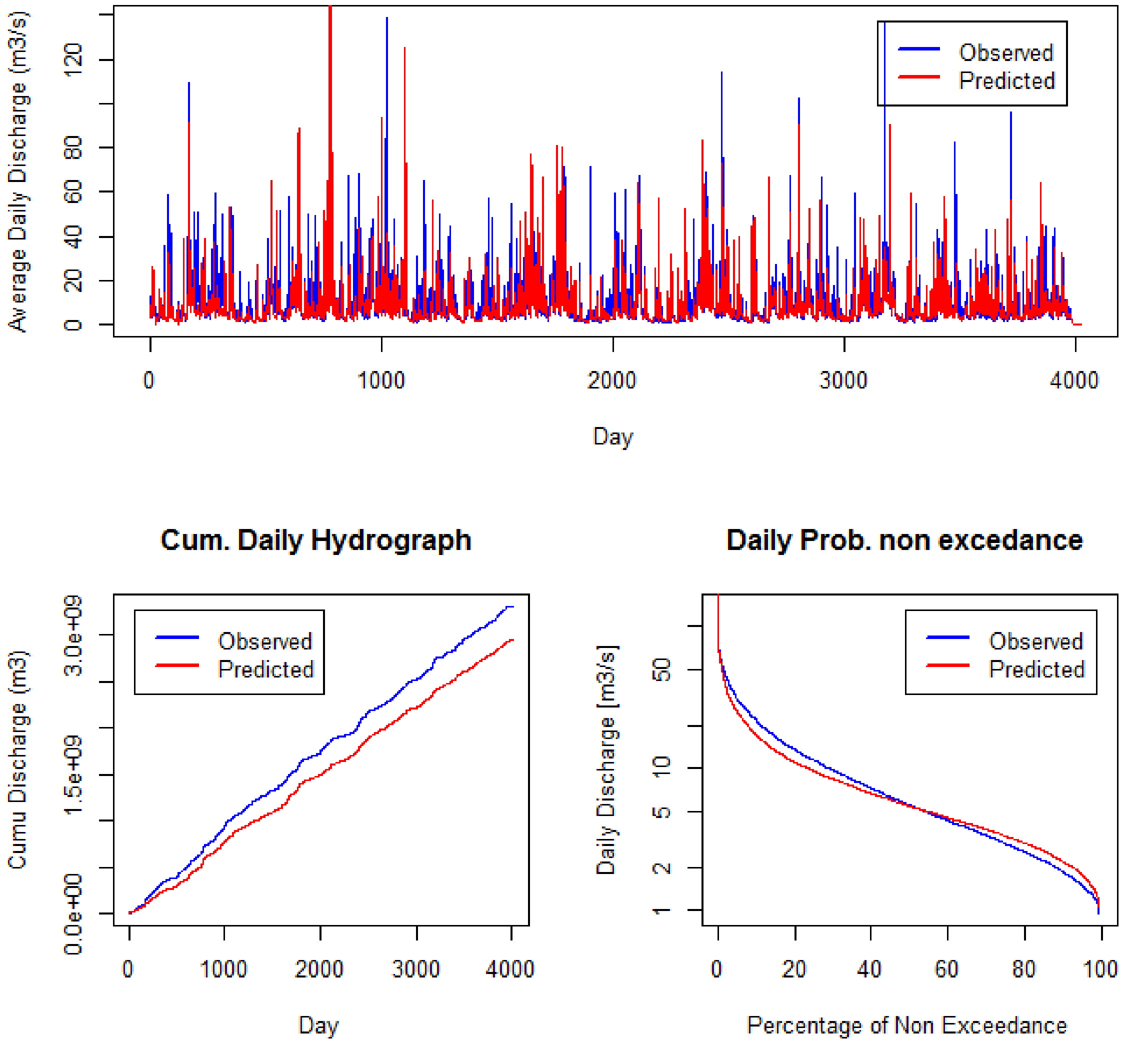

Figure 4-10: Simulated daily hydrograph of Waingawa at Upper Kaituna Branch over the validation period 2001-2012.

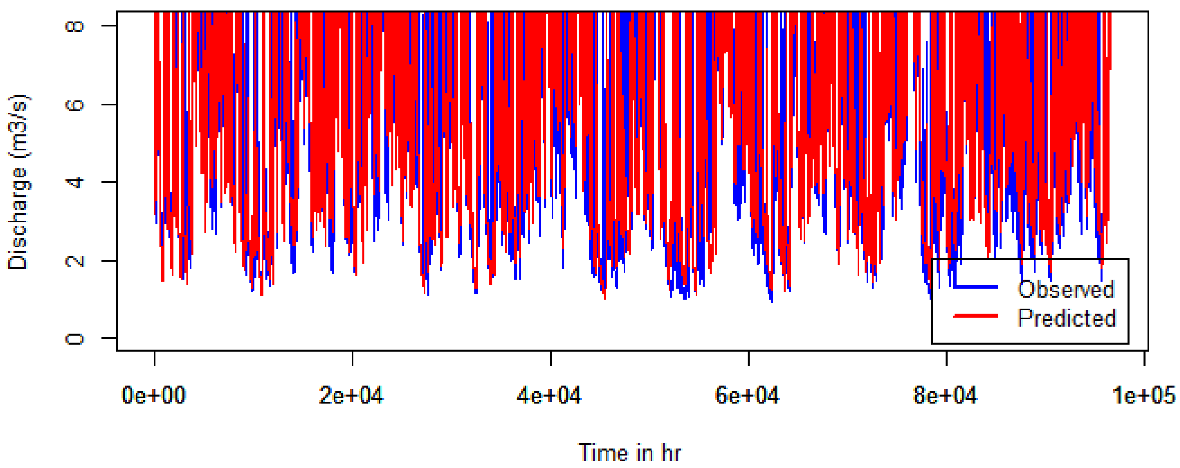

Figure 4-11: Observed and simulated hourly low flow hydrograph (i.e., flow below mean flow) for Waingawa at Upper Kaituna Branch over the calibration and validation periods.

Table 4-19: Simulated and observed monthly average flows for Waingawa catchment over the period 2001-2012 and the historic record. (Gordon 2013)

Months	Observed (2001-2012) (m^3/s)	TopNet (2001-2012) (m^3/s)	Observed (1976-2012) (m^3/s)
January	5.844	6.011	6.732
February	6.486	6.802	6.848
March	6.884	5.558	6.968
April	5.217	5.428	7.704
May	8.618	7.608	9.873
June	10.845	8.970	11.896
July	13.146	9.744	13.300
August	11.647	9.829	12.780
September	10.551	9.185	12.379
October	12.976	12.104	13.051
November	8.795	7.780	10.401
December	8.237	8.679	10.021

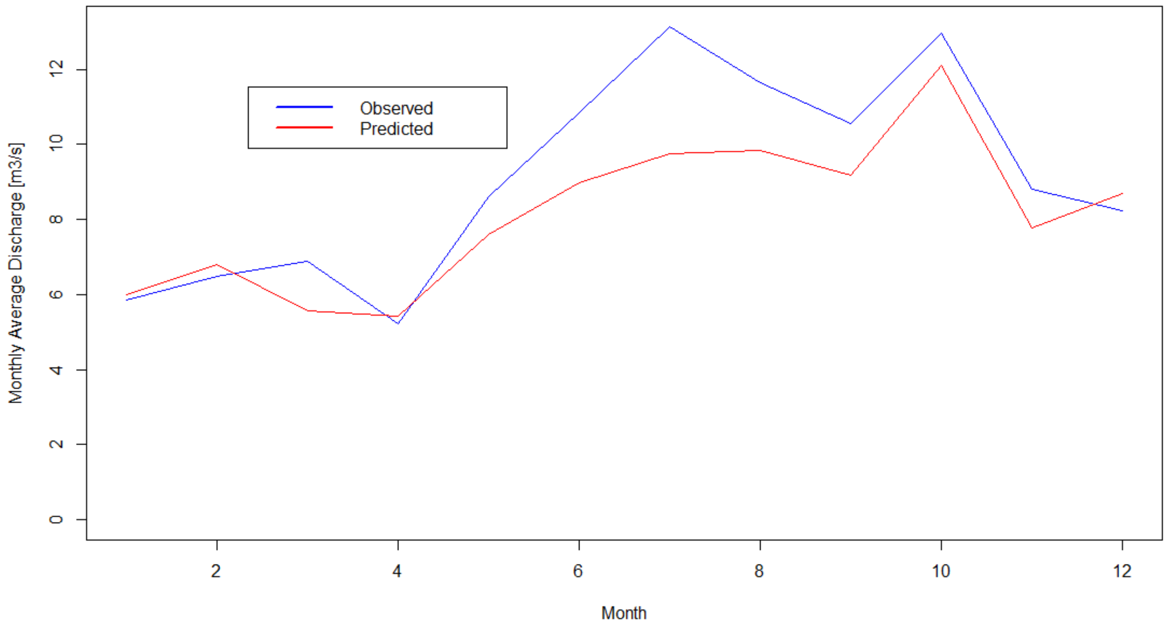

Figure 4-12: Observed and simulated monthly average flow for Waingawa at Upper Kaituna Branch over the validation period.

Analysis of the simulations indicates:

- Analysis by GWRC of observed flow time series indicates that flow rating curve is considered excellent across the range of hydrological conditions.
- The adequate NS score obtained during the calibration and validation period is linked to the underestimation of mid-range to high flow discharges across all seasons (Figure 4-9 and Figure 4-10). This can be seen on Figure 4-9 where observed discharges above 5 m^3/s are consistently underestimated. This indicates a potential underestimation of winter precipitation over the catchment as no precipitation information is available to constraint the VCSN interpolation over the catchment- see Figure 3-8. In addition, misrepresentation of the high flow conditions within the catchment might be a by-product of the calibration strategy and process carried out within this project (focussing on the reproduction of low flow conditions for water allocation purpose).
- The calibrated model is able to reasonably reproduce observed low flows (based on NSLog score) for most of time during the calibration and validation period. However further analysis indicates that the TopNet model is slightly over estimating observed low flows condition during the validation period (Figure 4-11).
- The calibrated model is able to reproduce the hydrological behaviour (mean flow and 7-day MALF) encountered during simulation and validation periods. Hence timing and magnitude of seasonal change are correctly reproduced by the calibrated model. However hydrological conditions over March are generally underestimated by TopNet.
- Annual average evaporation estimated by TopNet is lower than the expected long term average annual evaporation across the catchment. This is thought to be linked to the underestimation of the annual average precipitation (compared to the long term climatology). However, their difference is consistent with the mean flow observed over the period of simulation. This indicates a potential underestimation of climate conditions over the catchment.
- Low flow hydrological conditions tend to be slightly over-predicted (Figure 4-10 and Figure 4-11) especially in the flow recession component of the hydrographs (i.e., flows under 4 m^3/s). This could be associated with the misrepresentation of subsurface soil process, which is related to the soil and geological data used in this study.
- Seasonal flows are correctly reproduced (magnitude and timing) during the summer months. Magnitude of the winter flows are largely underpredicted and it is thought to be associated with an underrepresentation of the winter precipitation magnitude in the upper Waingawa catchment.

4.6 Waipoua catchment

The accuracy of the streamflow model prediction is presented in Table 4-20 for the calibration phase and the validation phase. The final values of parameters are provided in Table 4-21. Table 4-22 provides the simulated water balance and a comparison of simulated precipitation and evaporation with the long-term average climatology (calculated over the period 1966-2006). Table 4-23 provides the simulated and observed mean flow and 7-day MALF, while Table 4-24 presents the observed and simulated monthly average flows over the period of simulation.

Figure 4-13 and Figure 4-14 present the simulation results at the streamflow gauging station in terms of comparison between simulated and observed hydrographs, cumulative hydrograph and flow duration curve during the calibration period (Figure 4-13) and validation period (Figure 4-14). Figure 4-15 presents the observed and simulated hourly low flows hydrograph (i.e., for discharge below mean flow) over the calibration and simulation period. Figure 4-16 presents the observed and predicted monthly average discharge at the gauging station over the validation period. Note that the calibration and validation period for the Waipoua catchment was changed to 2007-2009 and 2007-2012 (respectively) due to QAQC process on the observed flow as noted at section 4.1 above (GWRC, pers. comm.).

Table 4-20: Calibration- validation statistics for Waipoua catchment.

	Calibration (2007-2009)		Validation (2007-2012)	
Location	NSlog	NS	NSlog	NS
Waipoua at Mikimiki	0.571	0.520	0.572	0.604

Table 4-21: TopNet parameters for Waipoua catchment.

Parameter name (internal name)	Parameter description	Calibrated value
Saturated store sensitivity (topmodf)	Describes exponential decrease of soil hydraulic conductivity with depth	0.351 * default
Drainable soil water (swater1)	Range between saturation and field capacity	0.158* default
Plant available soil water (swater2)	Range between field capacity and wilting point	1.035 * default
Soil water content (dthetat)		6.414 * default
Hydraulic Conductivity at saturation (hydcond0)		60.935 * default
Overland flow velocity (overvel)		8.885 *default
Manning n	Characterises the roughness of each reach	0.129 * default
Atmospheric lapse rate (atmlaps)	Change in temperature with elevation, used to adjust temperatures from climate data sites to basin centroid	1.445 * default
Gauge Undercatch (gucatch)	Adjustment for non-representative precipitation	1.358 * default

Table 4-22: Simulated water balance by TopNet for the Waipoua catchment over the period of observations and simulations (2007-2012) compared with GWRC historic observations (Gordon 2013) and the long term average climatology.

Annual Average Flux	TopNet (2007-2012) (mm/yr)	GWRC (2007-2012) (mm/yr)	Long term average climatology (1966-2006) (mm/yr)
Mean annual precipitation	2465	NA	1926
Mean annual evaporation	1105	NA	733
Mean annual runoff	1287	1414	NA

Table 4-23: Simulated flow characteristics for Waipoua catchment over the period 2007-2012 and the historic record (Gordon 2013).

Annual Average hydrological characteristics	TopNet (2007-2012) (m^3/s)	GWRC (2007-2012) (m^3/s)
Mean Flow	0.959	3.580
7-day Mean Annual Low Flow	0.199	0.375

Table 4-24: Simulated and observed monthly average flows for Waipoua catchment over the period 2007-2012. Observed monthly average flows corresponds to historic record (Gordon 2013).

Months	Observed (2007-2012) (m^3/s)	TopNet (2007-2012) (m^3/s)
January	0.735	0.496
February	0.522	0.360
March	0.829	0.645
April	0.572	0.885
May	1.227	1.666
June	1.285	1.793
July	2.240	2.021
August	1.586	1.270
September	1.924	1.154
October	1.252	0.687
November	0.475	0.263
December	0.404	0.229

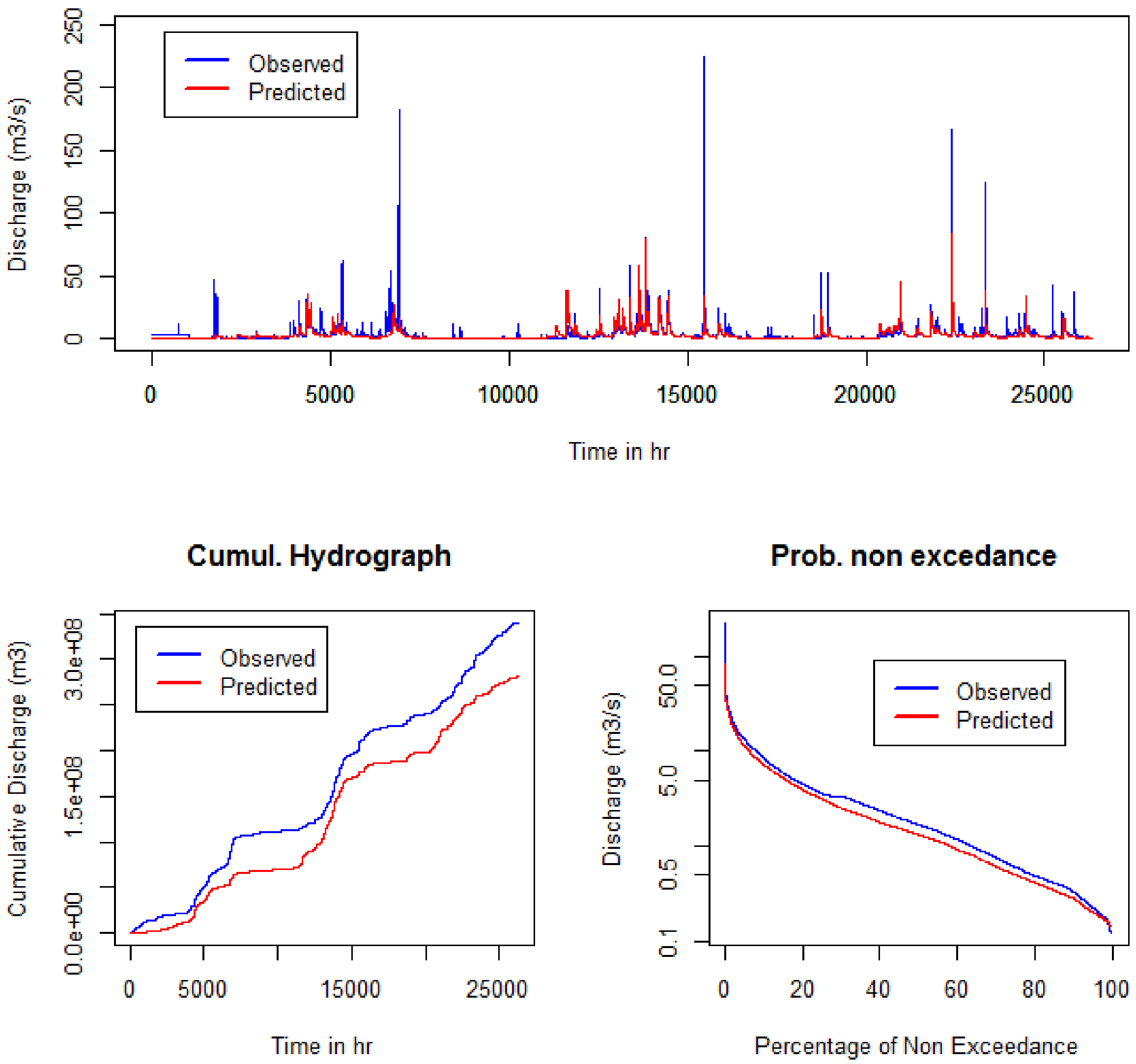

Figure 4-13: Calibrated hourly hydrograph of Waipoua at Mikimiki over the calibration period 2008-2009.

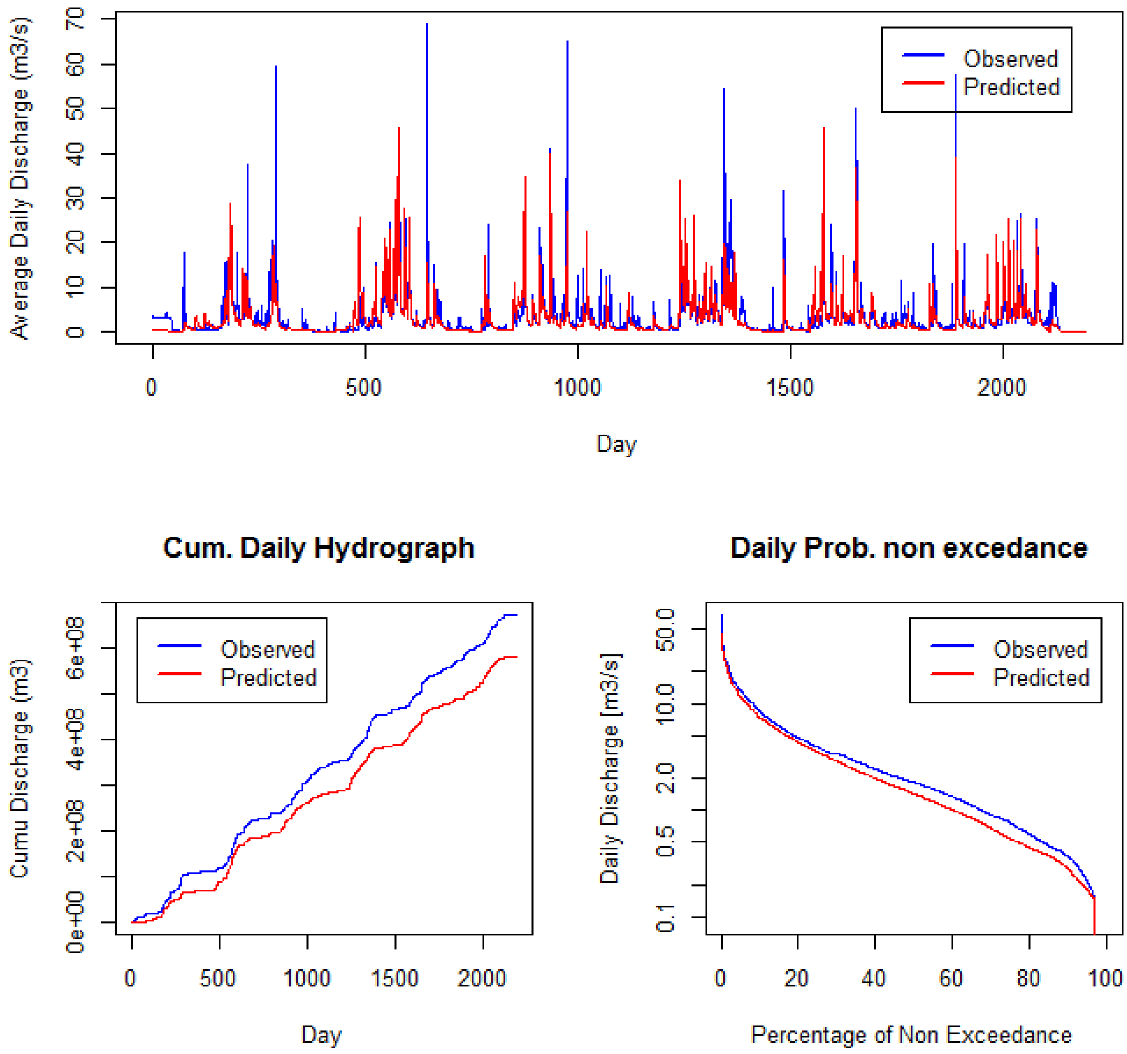

Figure 4-14: Simulated daily hydrograph of Waipoua at Mikimiki over the calibration and validation periods 2007-2012.

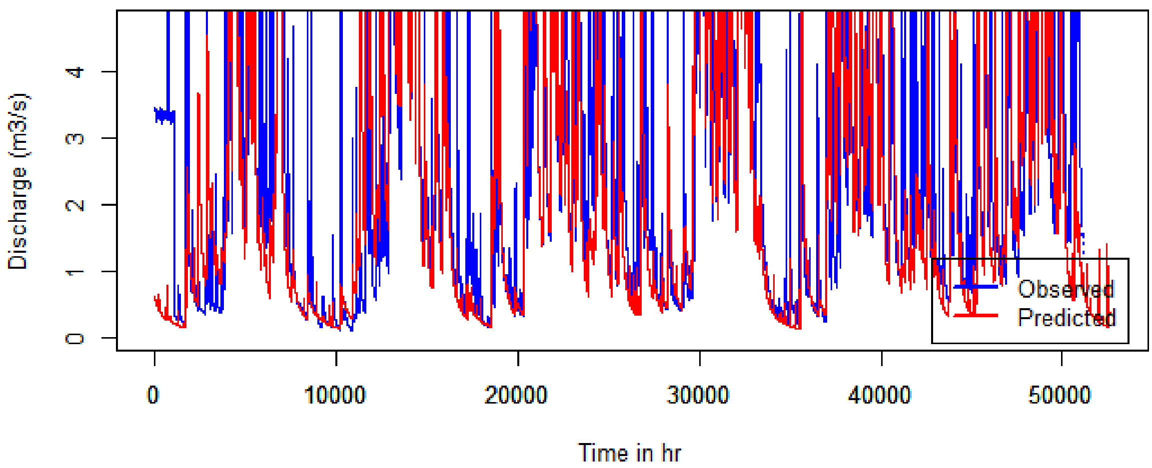

Figure 4-15: Observed and simulated hourly low flow hydrograph (i.e., flow below mean flow) for Waipoua at Mikimiki over the calibration and validation periods.

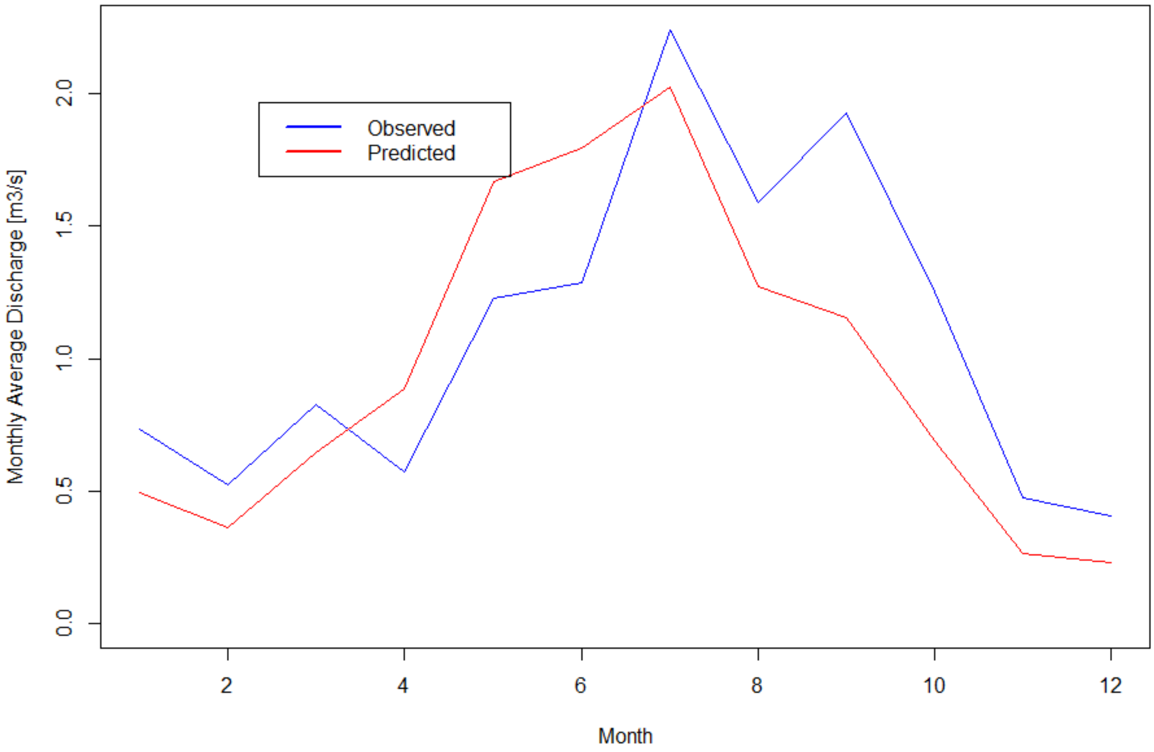

Figure 4-16: Observed and simulated monthly average flow for Waipoua at Mikimiki over the validation period (2008-2012).

Analysis of the simulations indicates:

- Analysis by GWRC of observed flow time series indicates that the streamflow station was relocated to its current location in February 2007 to record both high and low flows. However marked degradations are still occurring during high flood events. In addition low flow statistics were derived from a correlation between a modified copy of the Atiwhakatu flow recorder in association with low flow gauging at the site. As a result, all flow information prior to 2007 was discarded in the calibration/validation process.
- Analysis of the observed flow duration curve indicates a slight shift in hydrological behaviour that could characterise a potential non negligible groundwater inflow to the catchment.
- The adequate NS score obtained during the calibration and validation period is linked to the relatively large error of the estimation of the discharge during the shoulder seasons (Figure 4-16). This underestimation of shoulder season discharge (timing and magnitude) is thought to be associated with underestimation of flow within the 0.5-3 m^3/s range. Analysis of the low flow time series indicates that TopNet is not able to represent the “flashiness” of the observed flows within this flow range. This might be due to a potential misrepresentation of the timing and intensity of the sub-daily precipitation over the catchment. This could be reinforced by the calibration strategy

and process carried out within this project (focussing on the reproduction of low flow conditions for water allocation purpose).

- The calibrated model is able to reasonably reproduce observed low flows (based on NSLog score) for most of time during the calibration and validation period. One can note that from a statistical point of view that low flows are reproduced as well as high flows by TopNet, which is markedly different from the calibration results for the Tauherenikau, Waiohine and Waingawa catchments. However further analysis indicates that the TopNet model is consistently underestimating observed average low flow conditions over the period November to March (Figure 4-16). As a result, TopNet is able to represent the general state of the water resource across those months, but failed to reproduce small-quick discharge events, indicating potential issues with the sub-daily precipitation information generated as part of TopNet or misrepresentation of the soil characteristics over the catchments.
- There is a large difference between the simulated and observed hydrological behaviour (mean flow and 7-day MALF). As a result further analysis is required to better understand this difference which could be related to the conceptualisation and parametrisation of hydrological processes across this catchment.
- Annual average evaporation and precipitation estimated by TopNet are higher than the expected long term average climate statistics across the catchment. However, their relative difference is consistent with the mean flow observed over the period of simulation.

4.7 Ruamāhanga catchment

The accuracy of the streamflow model prediction is presented in Table 4-24 for the calibration phase and the validation phase. The final values of parameters are provided in Table 4-25. Table 4-26 provides the simulated water balance and a comparison of simulated precipitation and evaporation with the long-term average climatology (calculated over the period 1966-2006). Table 4-27 provides the simulated and observed mean flow and 7-day MALF, while Table 4-28 presents the observed and simulated monthly average flows over the period of simulation.

Figure 4-17 and Figure 4-18 present the simulation results at the streamflow gauging station in terms of comparison between simulated and observed hydrographs, cumulative hydrograph and flow duration curve during the calibration period (Figure 4-17) and validation period (Figure 4-18). Figure 4-19 presents the observed and simulated hourly low flows hydrograph (i.e., for discharge below mean flow) over the calibration and simulation period. Figure 4-20 presents the observed and predicted monthly average discharge at the gauging station over the validation period

Table 4-25: Calibration- validation statistics for Ruamāhanga catchment.

	Calibration (2001-2003)		Validation (2001-2012)	
Location	NSlog	NS	NSlog	NS
Ruamāhanga at Mt Bruce	0.501	0.318	0.630	0.427

Table 4-26: TopNet parameters for Ruamāhanga catchment.

Parameter name (internal name)	Parameter description	Calibrated value
Saturated store sensitivity (topmodf)	Describes exponential decrease of soil hydraulic conductivity with depth	0.986 * default
Drainable soil water (swater1)	Range between saturation and field capacity	0.267 * default
Plant available soil water (swater2)	Range between field capacity and wilting point	0.146 * default
Soil water content (dthetat)		1.488 * default
Hydraulic Conductivity at saturation (hydcond0)		1714 * default
Overland flow velocity (overvel)		8.612 * default
Manning n	Characterises the roughness of each reach	0.105 * default
Atmospheric lapse rate (atmlaps)	Change in temperature with elevation, used to adjust temperatures from climate data sites to basin centroid	1.495 * default
Gauge Undercatch (gucatch)	Adjustment for non-representative precipitation	0.732 * default

Table 4-27: Simulated water balance by TopNet for Ruamāhanga catchment over the period of observations and simulation (2001-2012) compared with GWRC historic observations (Gordon 2013) and the long term average climatology.

Annual Average Flux	TopNet (2001-2012) (mm/yr)	GWRC (2001-2012) (mm/yr)	GWRC (1975-2012) (mm/yr)	Long term average climatology (1966-2006) (mm/yr)
Mean annual precipitation	3697	NA	NA	4786
Mean annual evaporation	119	NA	NA	600
Mean annual runoff	3513	3835	4065	NA

Table 4-28: Simulated and observed flow characteristics for Ruamāhanga catchment over the period 2001-2012 and the historic record (Gordon 2013).

Annual Average hydrological characteristics	TopNet (2001-2012) (m^3/s)	GWRC (2001-2012) (m^3/s)	GWRC (1975-2015) (m^3/s)
Mean Flow	8.698	9.566	10.140
7-day Mean Annual Low Flow	0.781	1.282	1.304

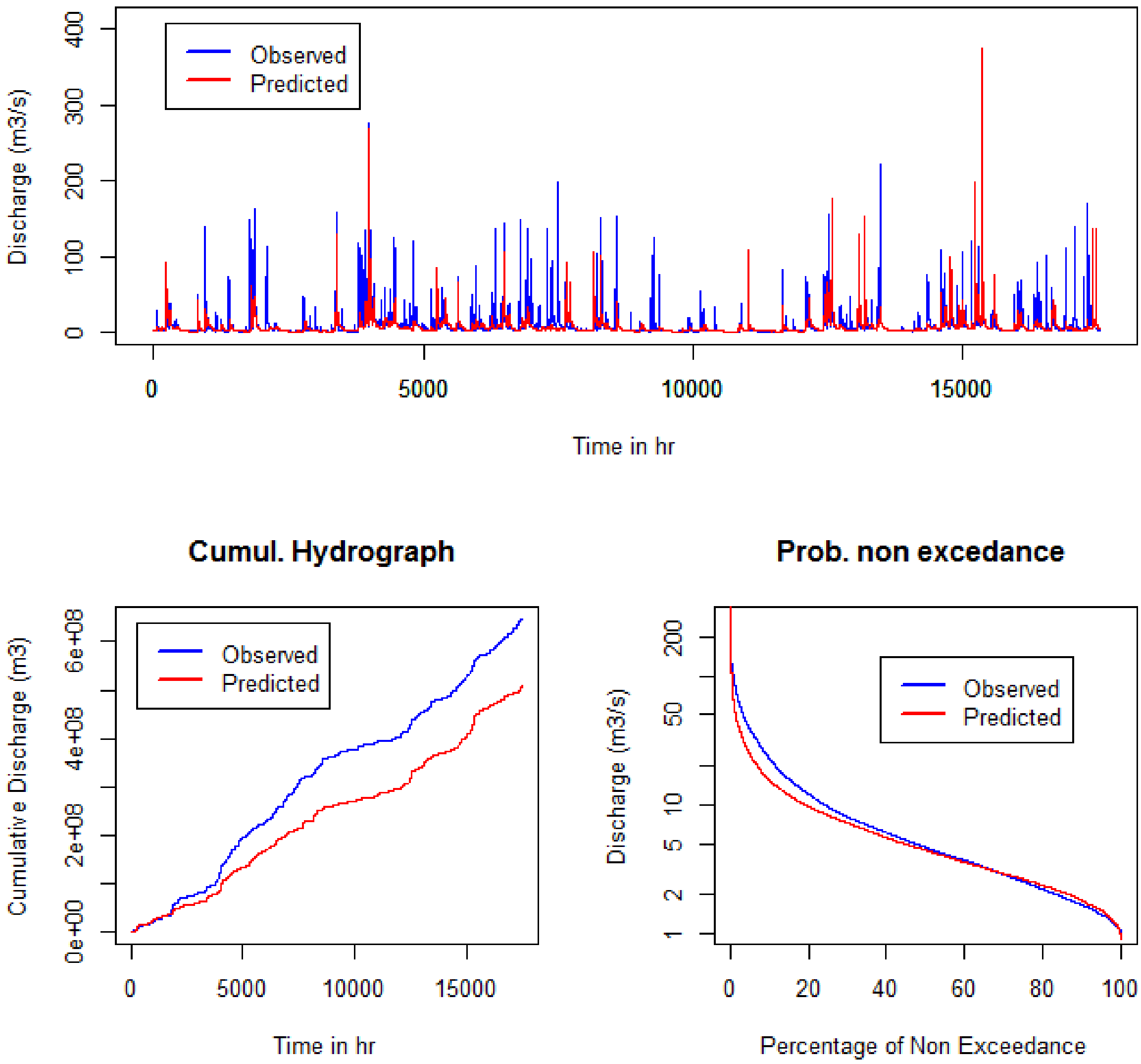

Figure 4-17: Calibrated hourly hydrograph of Ruamāhanga at Mt Bruce over the calibration period 2001-2003. Flows are plotted in log scale.

Table 4-29: Simulated and Observed monthly average flows for Ruamāhanga catchment over the period 2001-2012 and the historic record (Gordon 2013).

Months	Observed (2001-2012) (m^3/s)	TopNet (2001-2012) (m^3/s)	GWRC (1975-2012) (m^3/s)
January	6.572	6.725	7.118
February	7.325	7.653	6.820
March	6.954	5.683	7.173
April	5.394	5.618	7.442
May	8.631	7.907	9.737
June	11.507	9.542	11.814
July	13.091	10.534	12.974
August	11.878	10.342	12.435
September	11.578	9.458	12.346
October	14.044	12.421	13.140
November	9.830	7.813	10.581
December	9.936	9.391	10.185

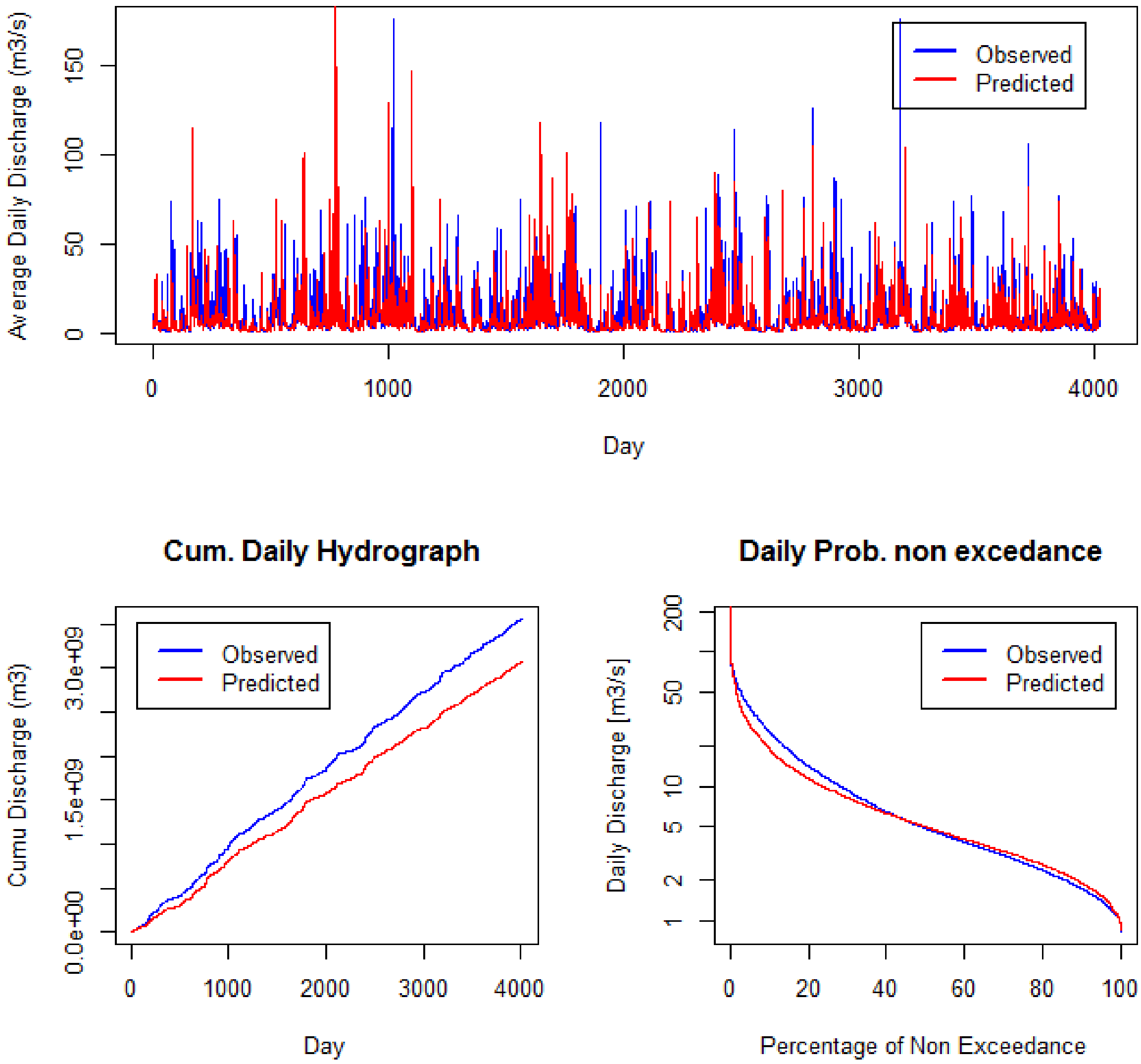

Figure 4-18: Simulated daily hydrograph of Ruamāhanga at Mt Bruce over the calibration and validation periods (2001-2012).

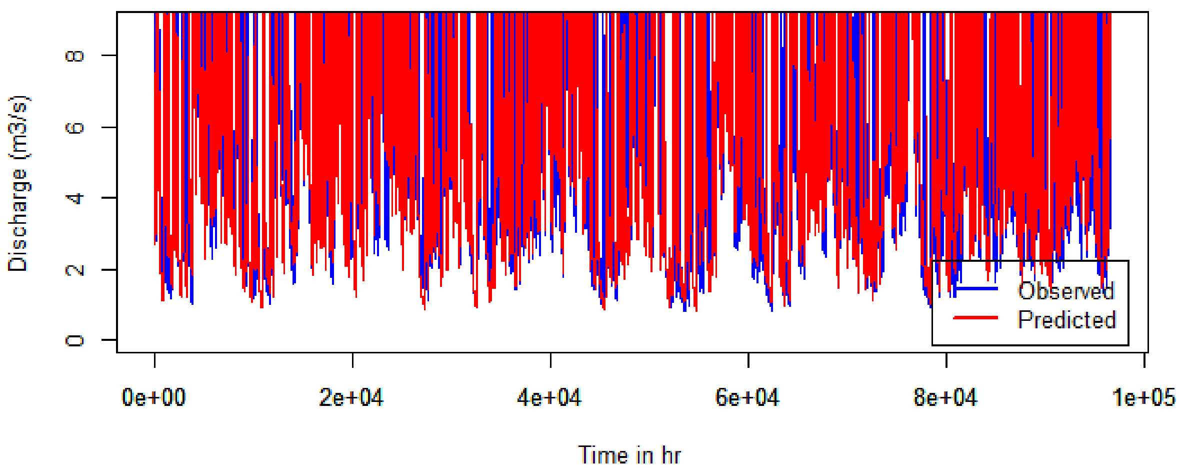

Figure 4-19: Observed and simulated hourly low flow hydrograph (i.e., flow below mean flow) for Ruamāhanga at Mt Bruce over the calibration and validation periods.

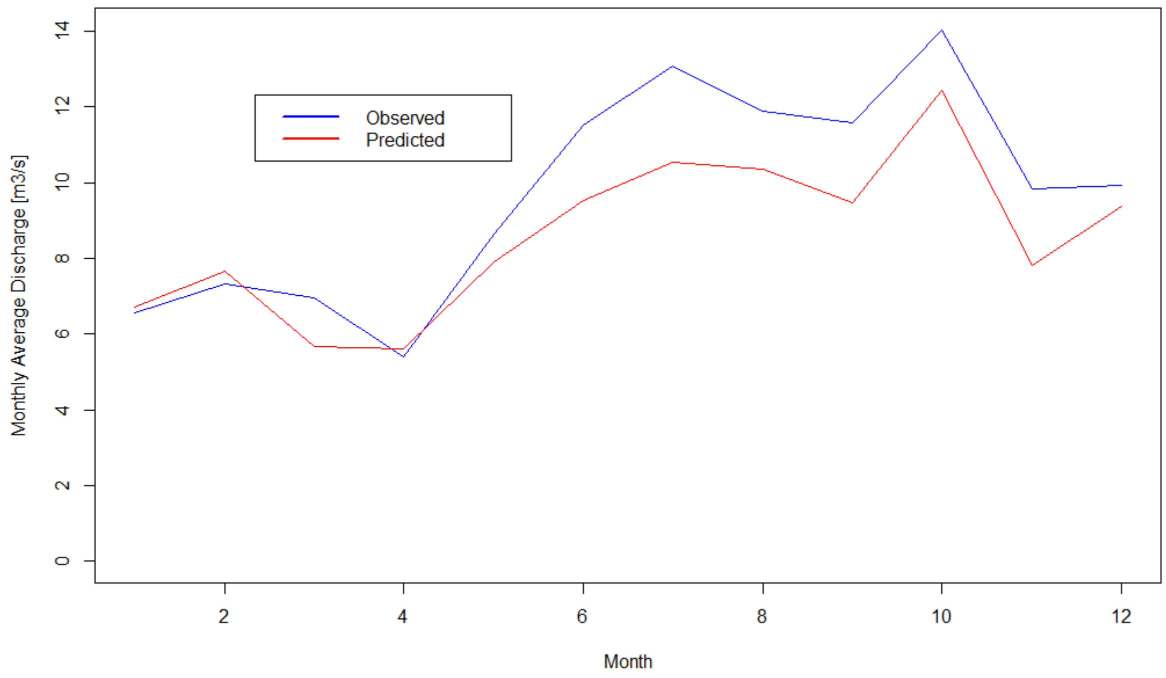

Figure 4-20: Observed and simulated monthly average flow for Ruamāhanga at Mt Bruce over the validation period.

Analysis of the simulations indicates:

- Analysis by GWRC of observed flow time series indicates that the streamflow station was relocated to its current location in February 1997. Due to the nature of the channel at the site, the control is subject to regular rating change. However, the current rating is of excellent quality across the range of hydrological conditions.
- The calibrated model correctly reproduces the hydrological behaviour encountered during simulation and validation periods.
- The poor NS score obtained during the calibration and validation period is linked to the underestimation of the mid-range to high flows conditions (i.e., flow having a probability of non-exceedance of less than 40% (Figure 4-17 and Figure 4-18)) that are currently not well reproduced by TopNet. Underprediction or misrepresentation of the timing of hourly peak discharge is thought to be associated with underestimation of daily VCSN and the lack of correct hourly precipitation information in the Ruamāhanga catchment over the period simulated. In addition, misrepresentation of the high flow conditions within the catchment might be a by-product of the calibration strategy and process carried out within this project (focussing on the reproduction of low flow conditions for water allocation purpose).
- The poor NS score is also linked to the underestimation of the winter discharges (Figure 4-20). This underestimation of winter discharge (magnitude) is thought to be associated with underestimation of daily VCSN in the Ruamāhanga Hill country catchment over the period simulated.

- Based on NSlog score, generally the calibrated model is able to correctly mimic low flow periods for most of time during the calibration and validation period. Flow recession process looks reasonable, except during March where TopNet tends to under-predict hydrological conditions over the Ruamāhanga catchment (Figure 4-28).
- The calibrated model is able to reasonably reproduce observed low flows (based on NSLog score) for most of time during the calibration and validation period.
- The calibrated model is able to reproduce the average hydrological behaviour (mean flow) encountered during simulation and validation periods. However large difference between observed and simulated 7-day MALF tends to indicate that TopNet is currently not able to reproduce the timing and extend of low flow condition over a 7-day period. This might be associated with the calibration procedure aiming to reproduce low flow conditions at hourly time step.
- Annual average evaporation estimated by TopNet is lower than the expected long term average annual evaporation across the catchment, as per the annual average precipitation. In addition the net difference between precipitation and evaporation is quite different from the net difference of the long term climate average. This would indicate some issues with the spatial disaggregation of those climate variables across the Ruamāhanga catchment.
- Seasonal flows are correctly reproduced (magnitude and timing) during the summer months. Magnitude of the winter flows are largely underpredicted and it is thought to be associated with an under-representation of the winter precipitation magnitude in the Ruamāhanga Hill country catchment.

4.8 Kopuaranga catchment

The accuracy of the streamflow model prediction is presented in Table 4-30 for the calibration phase and the validation phase. The final values of parameters are provided in Table 4-31. Table 4-32 provides the simulated water balance and a comparison of simulated precipitation and evaporation with the long-term average climatology (calculated over the period 1966-2006). Table 4-33 provides the simulated and observed mean flow and 7-day MALF, while Table 4-34 presents the observed and simulated monthly average flows over the period of simulation.

Figure 4-21 and Figure 4-22 present the simulation results at the streamflow gauging station in terms of comparison between simulated and observed hydrographs-cumulative hydrograph and flow duration curve during the calibration period (Figure 4-21) and validation period (Figure 4-22). Figure 4-23presents the observed and simulated hourly low flows hydrograph (i.e., for discharge below mean flow) over the calibration and simulation period. Figure 4-24 presents the observed and predicted monthly average discharge at the gauging station over the validation period.

Table 4-30: Calibration- validation statistics for Kopuaranga catchment.

	Calibration (2001-2003)		Validation (2001-2012)	
Location	NSlog	NS	NSlog	NS
Kopuaranga at Palmers Br	0.665	0.740	0.620	0.571

Table 4-31: TopNet parameters for Kopuaranga catchment.

Parameter name (internal name)	Parameter description	Calibrated value
Saturated store sensitivity (topmodf)	Describes exponential decrease of soil hydraulic conductivity with depth	0.451 * default
Drainable soil water (swater1)	Range between saturation and field capacity	0.051 * default
Plant available soil water (swater2)	Range between field capacity and wilting point	9.067 * default
Soil water content (dthetat)		6.624 * default
Hydraulic Conductivity at saturation (hydcond0)		8117 * default
Overland flow velocity (overvel)		2.676 * default
Manning n	Characterises the roughness of each reach	0.555 * default
Atmospheric lapse rate (atmlaps)	Change in temperature with elevation, used to adjust temperatures from climate data sites to basin centroid	0.840 * default
Gauge Undercatch (gucatch)	Adjustment for non-representative precipitation	1.071 * default

Table 4-32: Simulated water balance by TopNet for Kopuaranga catchment over the period of observations and simulation (2001-2012) compared with GWRC historic observations (Gordon 2013) and the long term average climatology.

Annual Average Flux	TopNet (2001-2012) (mm/yr)	GWRC (2001-2012) (mm/yr)	GWRC (1985-2012) (mm/yr)	Long term average climatology (1966-2006) (mm/yr)
Mean annual precipitation	1537	NA	NA	1434
Mean annual evaporation	545	NA	NA	747
Mean annual runoff	960	865	815	NA

Table 4-33: Simulated and observed flow characteristics for Kopuaranga catchment over the period 2001-2012 and the historic record (Gordon 2013).

Annual Average hydrological characteristics	TopNet (2001-2012) (m^3/s)	GWRC (2001-2012) (m^3/s)	GWRC (1985-2012) (m^3/s)
Mean Flow	2.814	2.494	2.60
7-day Mean Annual Low Flow	0.178	0.327	0.314

Table 4-34: Simulated and observed monthly average flows for Kopuaranga catchment over the period 2001-2012 and the historic record (Gordon 2013).

Months	Observed (2001-2012) (m^3/s)	TopNet (2001-2012) (m^3/s)	GWRC (1985-2015) (m^3/s)
January	1.371	1.279	0.988
February	1.543	1.866	1.631
March	1.018	1.325	1.089
April	0.959	1.744	1.411
May	2.102	3.310	2.476
June	3.977	4.936	4.022
July	4.831	6.243	5.122
August	4.465	4.719	4.302
September	3.307	2.960	3.444
October	4.238	3.810	3.776
November	1.913	1.672	2.205
December	1.494	1.670	1.391

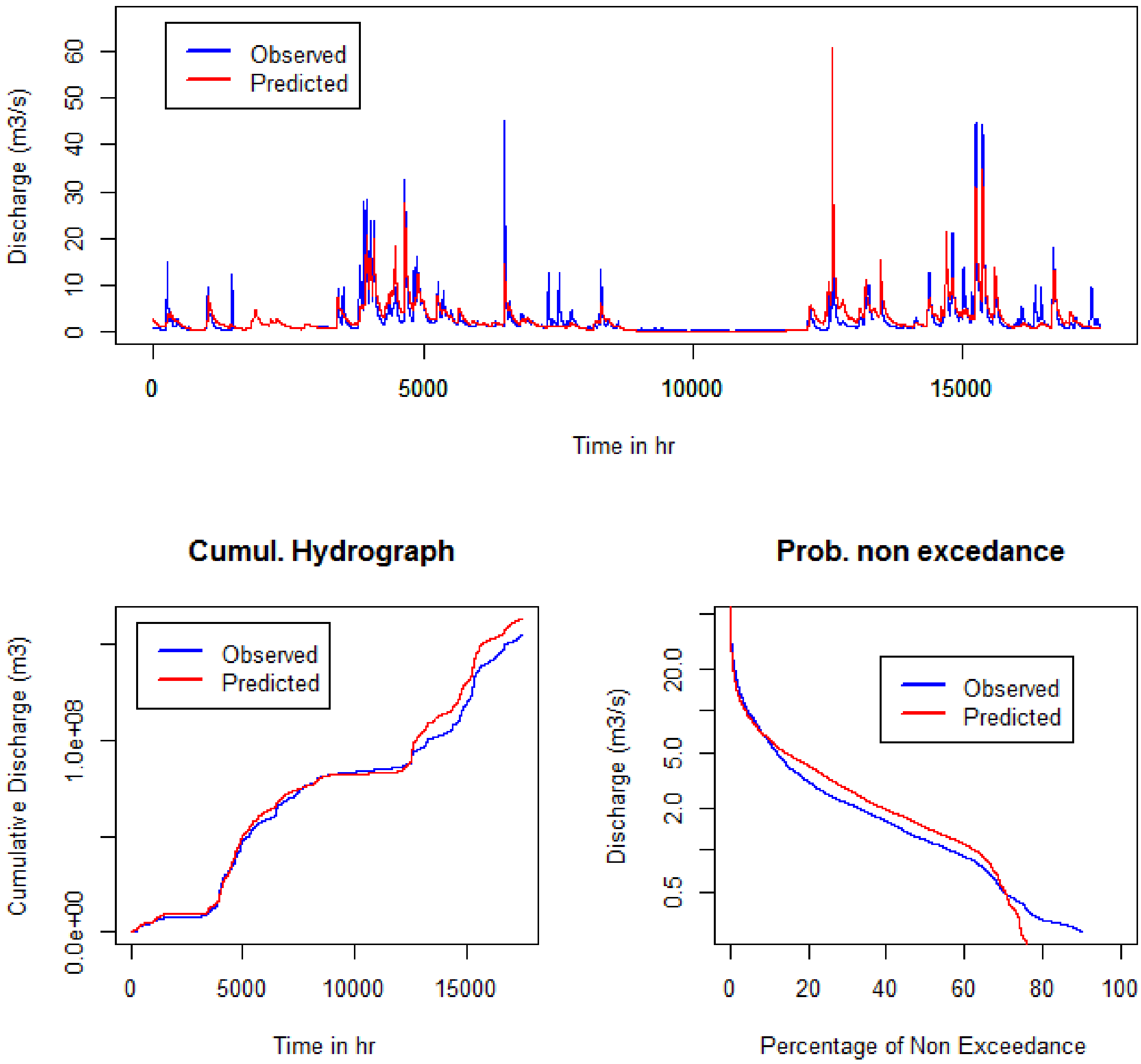

Figure 4-21: Calibrated hourly hydrograph of Kopuaranga at Palmers Bridge over the calibration period 2001-2003.

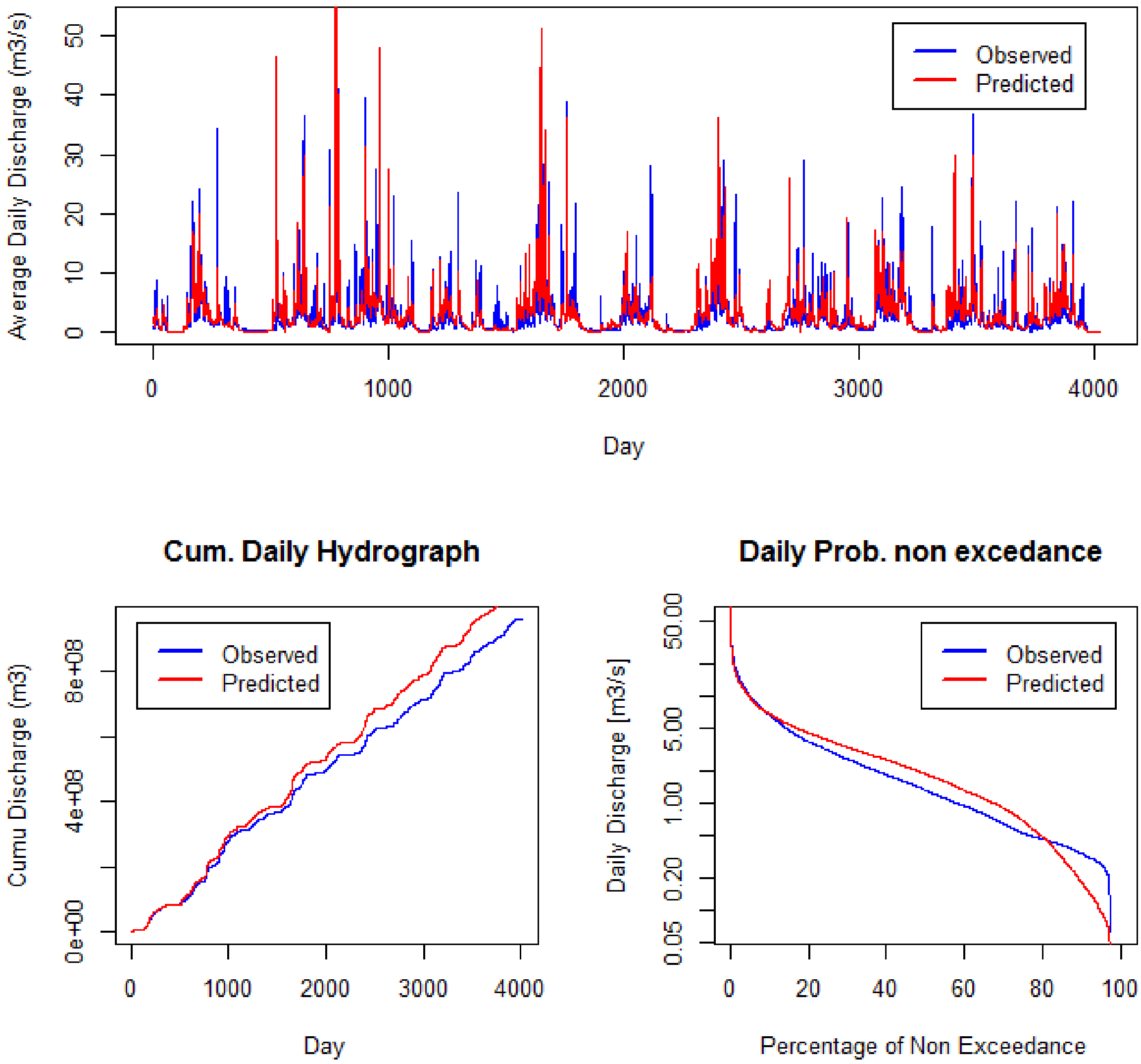

Figure 4-22: Simulated daily hydrograph of Kopuaranga at Palmers Bridge over the calibration and validation periods.

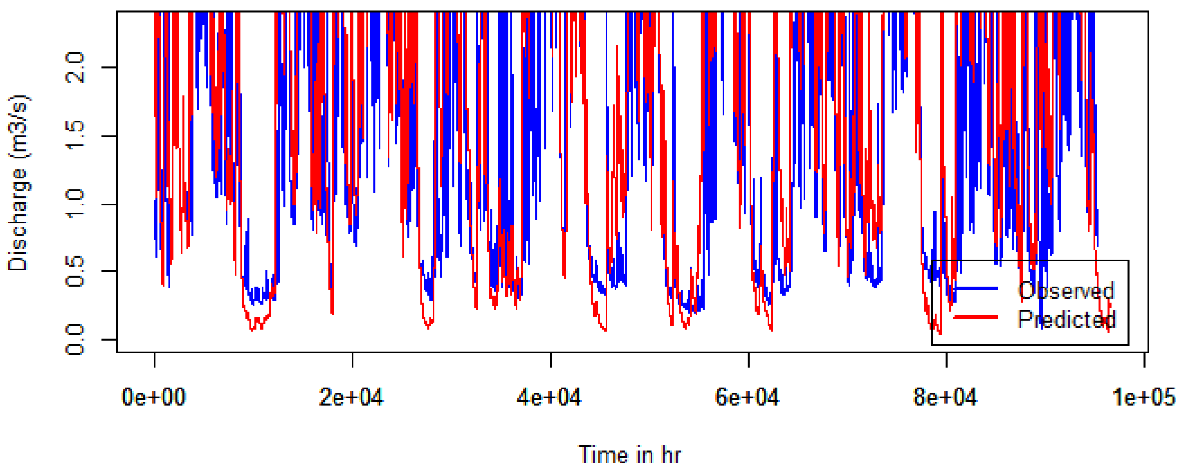

Figure 4-23: Observed and simulated hourly low flow hydrograph (i.e., flow below mean flow) for Kopuaranga at Palmers Bridge over the calibration and validation periods.

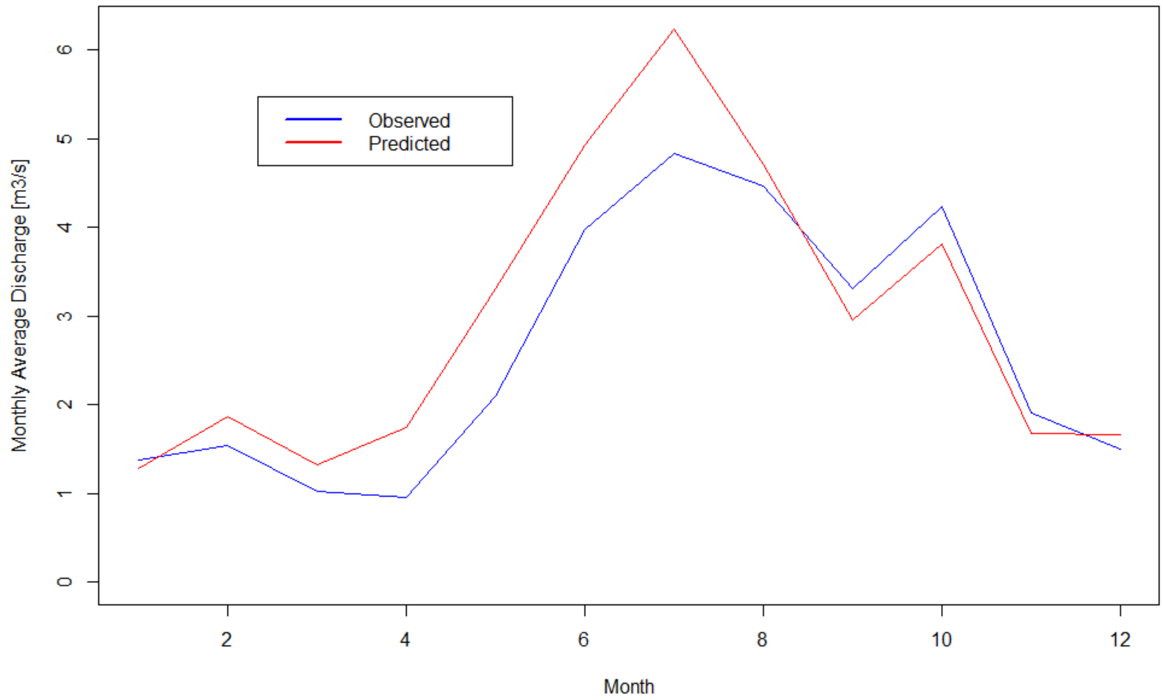

Figure 4-24: Observed and simulated monthly average flow for Kopuaranga at Palmers Bridge over the validation period.

Analysis of the simulations indicates:

- Analysis by GWRC of observed flow time series indicates that major willow clearing was carried out since 2006 to improve flood flow drainage. Rating curve for floods exceeding 4.5 m (i.e., 47 m^3/s) is likely to be unreliable as the river overflows its banks. In addition the mid to high stage rating curve seems to have changed over the period 2006-2010, and changes have been applied to the rating curve post September 2010. This is likely to affect the reliability of the observations pre 2006 and explain the departure between simulated and observed cumulative hydrograph (Figure 4-22).

- Further analysis indicated that spring flows enter the river upstream of the gauging station affecting low flow measurements. This is confirmed by the observed FDC analysis (Figure 4-21) that exhibits a sustained low flow discharge.

- The good NS and NSLog scores during the calibration period indicate that the hydrological model is correctly mimicking the catchment hydrological behaviour across flood and recession characteristics. However, the flood characteristics tend to be reduced during the validation period. This is thought to be linked with overprediction of the discharge in the mid to high range (Figure 4-22). This could be a by-product of the calibration strategy that aimed to reproduce low and mid-range flows.

- The good NS score is also linked to the correct representation of winter discharges (Figure 4-22) in term of precipitation intensity and timing. This is thought to be due to the high density of precipitation gauges used to derive the VCSN surrounding the catchment. This result in average simulated precipitation and evaporation similar to the long-term climate average.

- Based on NSlog score, generally the calibrated model is able to correctly mimic low flow periods for most of time during the calibration and validation period.
- The calibrated model is able to reproduce the average hydrological behaviour (mean flow) but not the low flow behaviour (7-day MALF) encountered during simulation and validation periods. This is thought to be caused by the impact of the spring on the discharge recorded at the gauging station.
- Timing of the seasonal flows is correctly reproduced across calibration and validation periods.

4.9 Whangaehu catchment

The accuracy of the streamflow model prediction is presented in Table 4-35 for the calibration phase and the validation phase. The final values of parameters are provided in Table 4-36. Table 4-37 provides the simulated water balance and a comparison of simulated precipitation and evaporation with the long-term average climatology (calculated over the period 1966-2006). Table 4-38 provides the simulated and observed mean flow and 7-day MALF, while Table 4-39 presents the observed and simulated monthly average flows over the period of simulation.

Figure 4-25 and Figure 4-26 present the simulation results at the streamflow gauging station in terms of comparison between simulated and observed hydrographs-cumulative hydrograph and flow duration curve during the calibration period (Figure 4-25) and validation period (Figure 4-26). Figure 4-27 presents the observed and simulated hourly low flows hydrograph (i.e., for discharge below mean flow) over the calibration and simulation period. Figure 4-28 presents the observed and predicted monthly average discharge at the gauging station over the validation period.

Table 4-35: Calibration- validation statistics for Whangaehu catchment.

	Calibration (2001-2003)		Validation (2004-2012)	
Location	**NSlog**	**NS**	**NSlog**	**NS**
Whangaehu at Waihi	0.726	0.678	0.722	0.755

Table 4-36: TopNet parameters for Whangaehu catchment.

Parameter name (internal name)	Parameter description	Calibrated value
Saturated store sensitivity (topmodf)	Describes exponential decrease of soil hydraulic conductivity with depth	0.319 * default
Drainable soil water (swater1)	Range between saturation and field capacity	0.063 * default
Plant available soil water (swater2)	Range between field capacity and wilting point	1.376 * default
Hydraulic Conductivity at saturation (hydcond0)		7520 * default
Overland flow velocity (overvel)		8.485 * default
Manning n	Characterises the roughness of each reach	0.156 * default
Atmospheric lapse rate (atmlaps)	Change in temperature with elevation, used to adjust temperatures from climate data sites to basin centroid	0.574
Gauge Undercatch (gucatch)	Adjustment for non-representative precipitation	0.907 * default

Table 4-37: Simulated water balance by TopNet for Whangaehu catchment over the period of observations and simulation (2003-2012) compared with GWRC historic observations (Gordon 2013) and the long term average climatology.

Annual Average Flux	TopNet (2001-2012) (mm/yr)	GWRC (2001-2012) (mm/yr)	GWRC (2008-2016) (mm/yr	Long term average climatology (1966-2006) (mm/yr)
Mean annual precipitation	1044	NA	NA	1257
Mean annual evaporation	543	NA	NA	741
Mean annual runoff	471	509	451	NA

Table 4-38: Simulated and observed flow characteristics for Whangaehu catchment over the period 2001-2012 and the historic record (Gordon 2013).

Annual Average hydrological characteristics	TopNet (2001-2012) (m^3/s)	GWRC (2001-2012) (m^3/s)	GWRC (2008-2016) (m^3/s)
Mean Annual Flow	0.571	0.594	0.526
7-day Mean Annual Low Flow	0.023	0.028	0.024

Table 4-39: Simulated and observed monthly average flows for Whangaehu catchment over the period 2001-2012 and the historic record (Gordon 2013).

Months	Observed (2001-2012) (m^3/s)	TopNet (2001-2012) (m^3/s)	GWRC (2008-2016) (m^3/s)
January	0.258	0.182	0.559
February	0.354	0.343	0.193
March	0.207	0.195	0.470
April	0.147	0.257	0.217
May	0.360	0.630	0.414
June	0.945	1.096	1.021
July	1.468	1.478	1.699
August	1.146	0.974	1.072
September	0.726	0.474	0.896
October	0.820	0.468	0.694
November	0.216	0.175	0.203
December	0.217	0.142	0.109

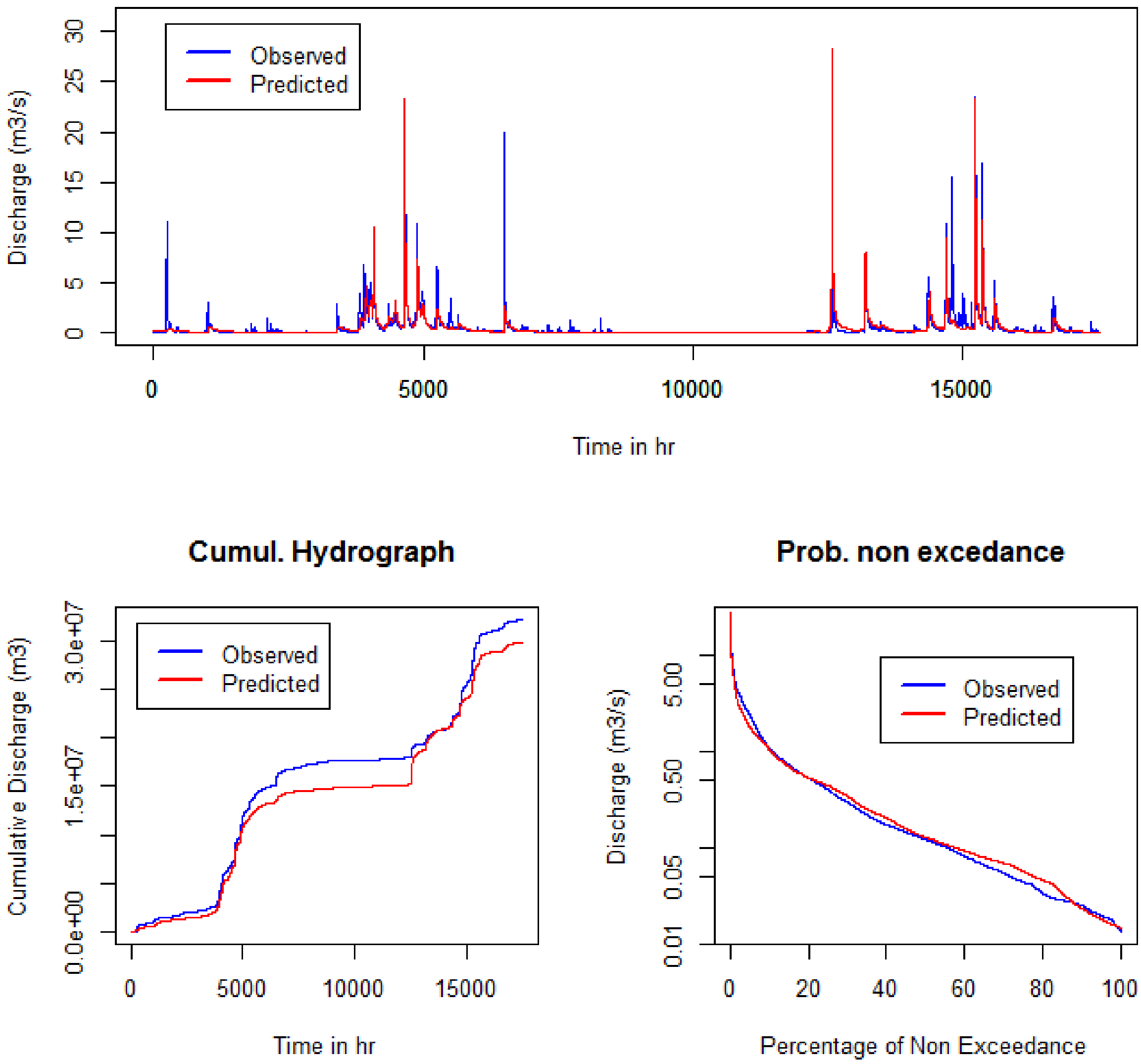

Figure 4-25: Calibrated hourly hydrograph of Whangaehu at Waihi over the calibration period 2001-2003. Flows are plotted in log scale.

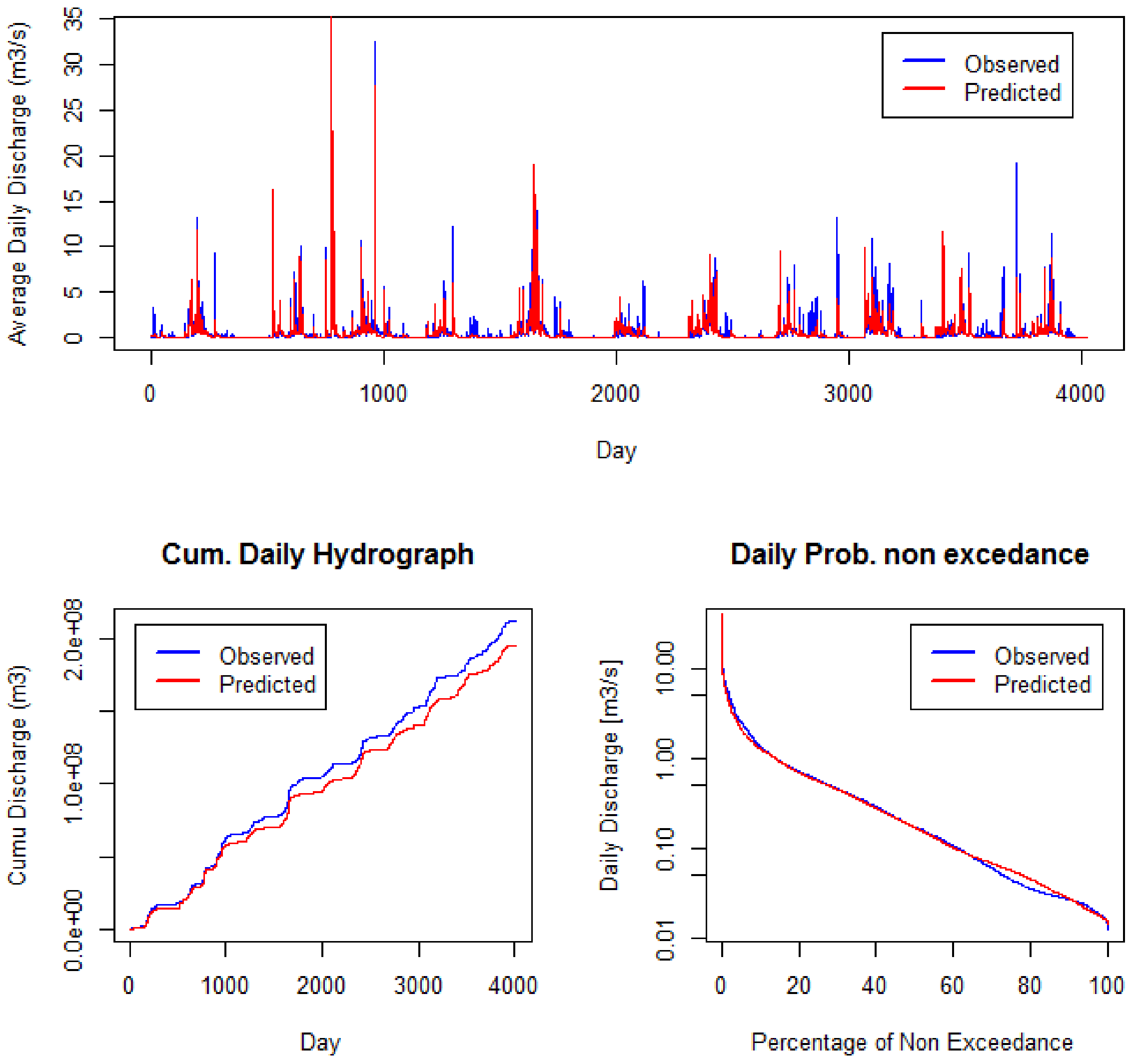

Figure 4-26: Simulated daily hydrograph of Whangaehu at Waihi over the calibration and validation periods.

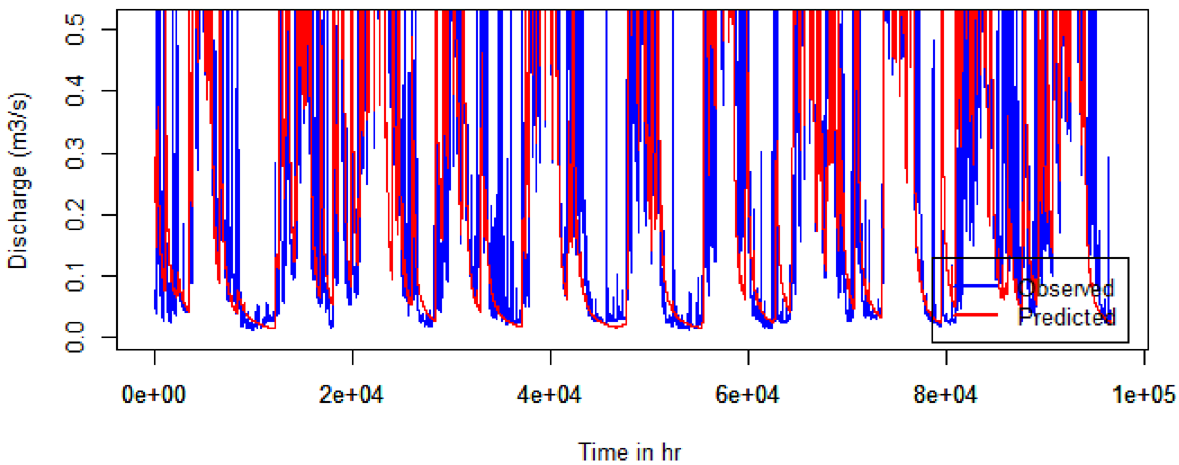

Figure 4-27: Observed and simulated hourly low flow hydrograph (ie flow below mean flow) for Whangaehu at Waihi over the calibration period and validation periods.

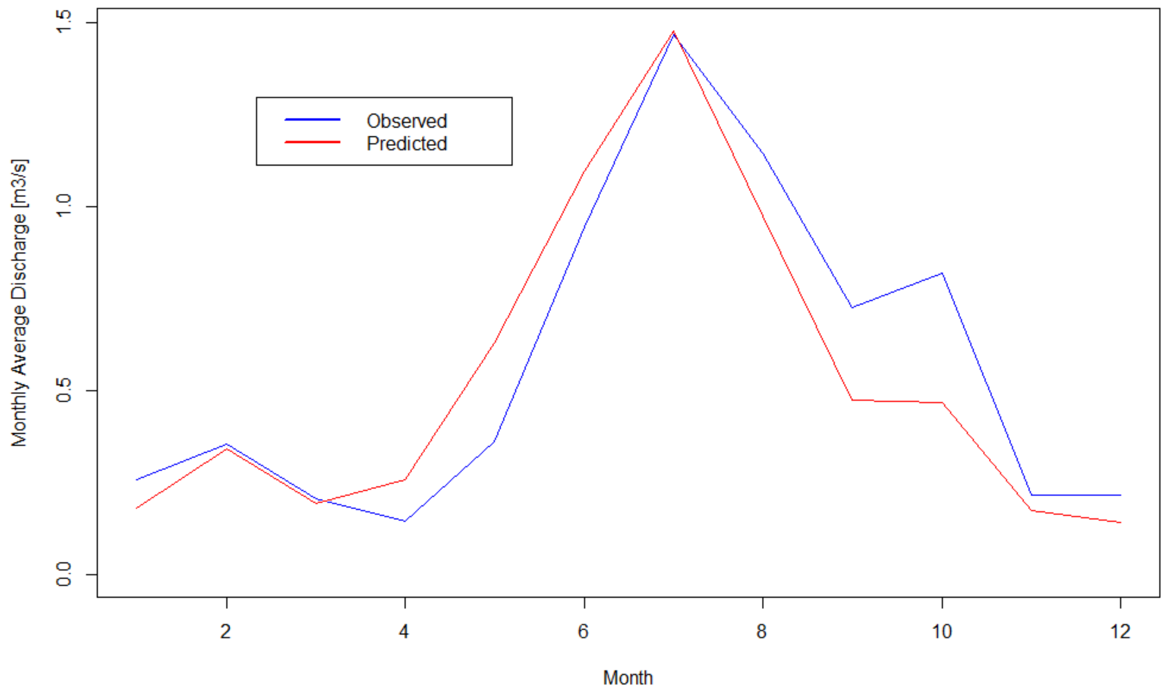

Figure 4-28: Observed and simulated monthly average flow for Whangaehu at Waihi over the validation period.

Analysis of the simulations indicates:

- The calibrated model correctly reproduces the hydrological behaviour encountered during simulation and validation periods.
- Good NS scores have been achieved for both calibration and validation period. However, there are some mismatch of flow peaks. Under- or over-prediction of hourly peak discharges is thought to be associated with spatial variability of the precipitation within the VCSN grid (inherent to the spatial resolution of the input data).
- Based on NSlog score, generally the calibrated model is able to correctly mimic low flow period for most of time during the calibration and validation period.
- Flow duration curves in Figure 4-24 and Figure 4-25 show simulation matches observation in both low and high frequencies.
- The calibrated model is able to reasonably reproduce observed low flows (based on NSLog score) for most of time during the calibration and validation period. However further analysis indicates that the TopNet model is consistently underestimating observed low flows during the period October-December.
- The calibrated model is able to reproduce the hydrological behaviour (mean flow and 7-day MALF) encountered during simulation and validation periods. Hence timing and magnitude of seasonal change are correctly reproduced by the calibrated model.

- Annual average evaporation estimated by TopNet is lower than the expected long term average annual evaporation across the catchment. However the net difference with the annual average precipitation is similar to the net difference estimated using the long term average climate. As a result, water balance in the Whangaehu catchment is expected to be correctly reproduced.

  Seasonal flows are correctly reproduced (magnitude and timing) throughout the year.

4.10 Taueru catchment

The accuracy of the streamflow model prediction is presented in Table 4-40 for the calibration phase and the validation phase. The final values of parameters are provided in Table 4-41. Table 4-42 provides the simulated water balance and a comparison of simulated precipitation and evaporation with the long-term average climatology (calculated over the period 1966-2006). Table 4-43 provides the simulated and observed mean flow and 7-day MALF, while Table 4-44 presents the observed and simulated monthly average flows over the period of simulation.

Figure 4-29 and Figure 4-30 present the simulation results at the streamflow gauging station in terms of comparison between simulated and observed hydrographs-cumulative hydrograph and flow duration curve during the calibration period (Figure 4-29) and validation period (Figure 4-30). Figure 4-31 presents the observed and simulated hourly low flows hydrograph (i.e., for discharge below mean flow) over the calibration and simulation period. Figure 4-32 presents the observed and predicted monthly average discharge at the gauging station over the validation period

Table 4-40: Calibration- validation statistics for Taueru catchment.

	Calibration (2001-2003)		Validation (2001-2012)	
Location	NSlog	NS	NSlog	NS
Taueru at Te Weraiti	0.815	0.645	0.738	0.711

Table 4-41: TopNet parameters for Taueru catchment.

Parameter name (internal name)	Parameter description	Calibrated value
Saturated store sensitivity (topmodf)	Describes exponential decrease of soil hydraulic conductivity with depth	1.065* default
Drainable soil water (swater1)	Range between saturation and field capacity	4.886 * default
Plant available soil water (swater2)	Range between field capacity and wilting point	0.057 * default
Hydraulic Conductivity at saturation (hydcond0)		152*default
Overland flow velocity (overvel)		6.244*default
Manning n	Characterises the roughness of each reach	2.306 *default
Atmospheric lapse rate (atmlaps)	Change in temperature with elevation, used to adjust temperatures from climate data sites to basin centroid	0.767 * default
Gauge Undercatch (gucatch)	Adjustment for non-representative precipitation	1.043 * default

Table 4-42: Simulated water balance by TopNet for Taueru catchment over the period of observations and simulation (2001-2012) compared with GWRC historic observations and the long term average climatology.

Annual Average Flux	TopNet (2001-2012) (mm/yr)	GWRC (2004-2012) (mm/yr)	GWRC (1970-2012) (mm/yr)	Long term average climatology (1966-2006) (mm/yr)
Mean annual precipitation	1121	NA	NA	1120
Mean annual evaporation	417	NA	Na	720
Mean annual runoff	665	465	485	NA

Table 4-43: Simulated and observed flow characteristics for Taueru catchment over the period 2001-2012 and the historic record .

Annual Average hydrological characteristics	TopNet (2001-2012) (m^3/s)	GWRC (2001-2012) (m^3/s)	GWRC (1970-2012) (m^3/s)
Mean Flow	7.011	5.978	6.022
7-day Mean Annual Low Flow	0.843	0.128	0.433

Table 4-44: Simulated and observed monthly average flows for Taueru catchment over the period 2001-2012 and the historic record.

Months	Observed (2001-2012) (m^3/s)	TopNet (2001-2012 (m^3/s)	Observed (1970-2012) (m^3/s)
January	4.765	4.181	2.604
February	4.967	4.622	3.672
March	3.476	3.960	3.302
April	3.793	4.832	1.951
May	6.434	8.137	4.299
June	10.640	11.295	8.630
July	19.965	18.541	20.174
August	15.130	12.210	12.897
September	9.728	6.451	4.613
October	10.399	6.809	4.862
November	5.078	3.623	1.029
December	4.950	3.867	0.742

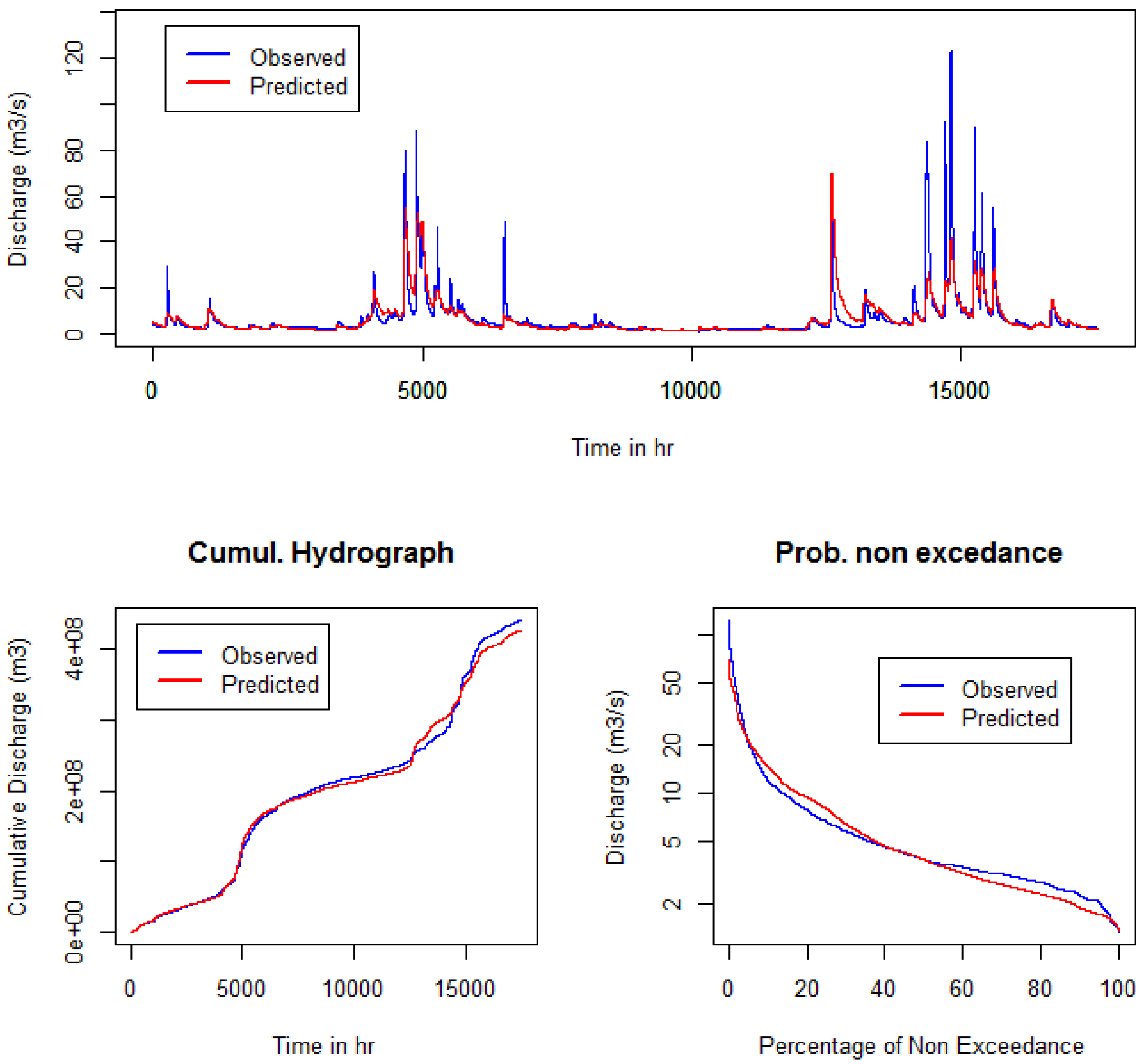

Figure 4-29: Calibrated hourly hydrograph of Taueru at Te Weraiti over the calibration period 2001-2003.

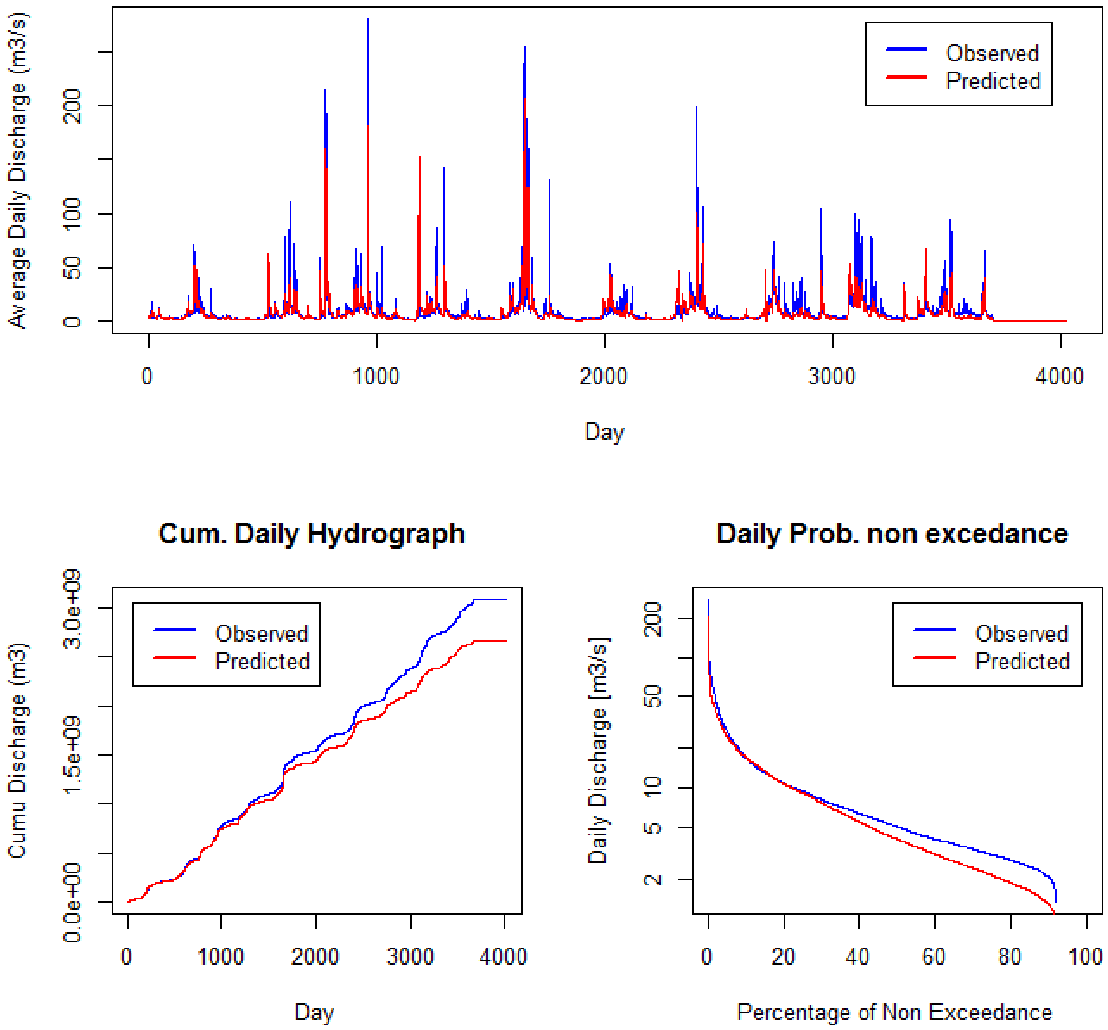

Figure 4-30: Simulated daily hydrograph of Taueru at Te Weraiti over the calibration and validation periods.

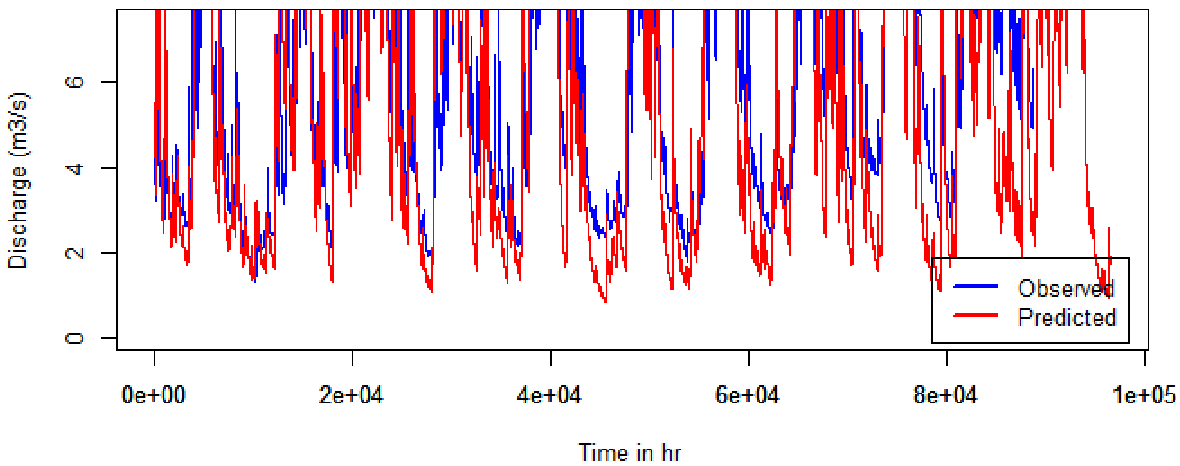

Figure 4-31: Observed and simulated hourly low flow hydrograph (i.e., flow below mean flow) for Taueru at Te Weraiti over the calibration and validation periods.

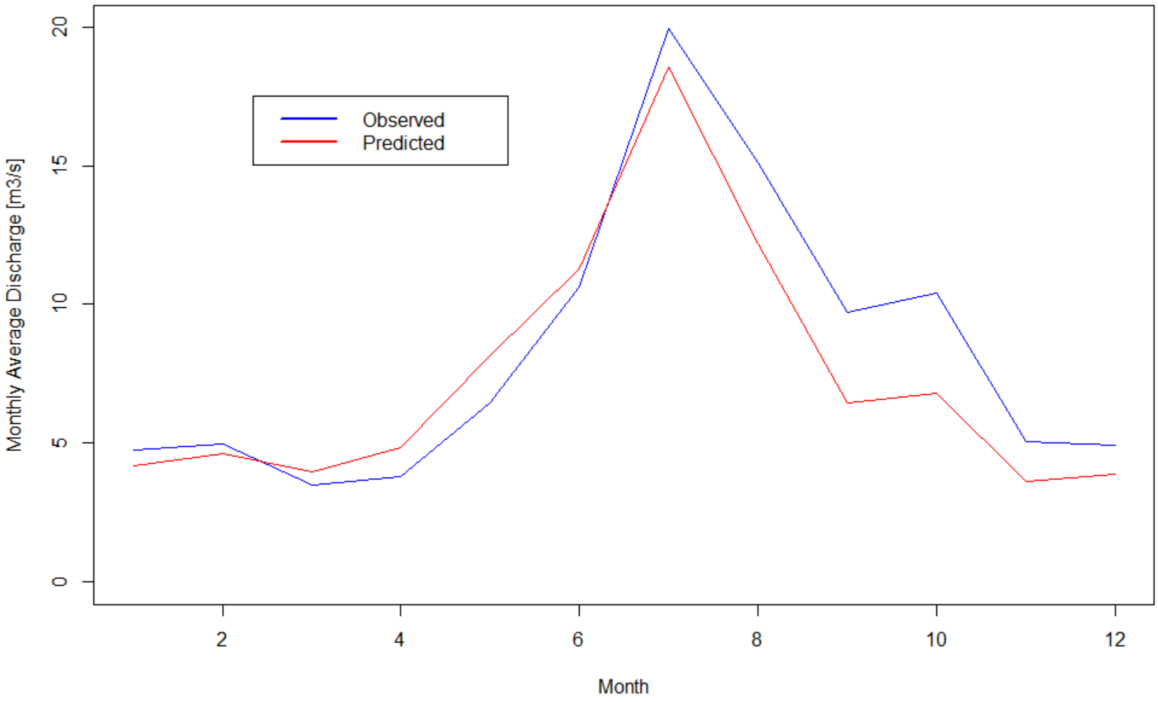

Figure 4-32: Observed and simulated monthly average flow for Taueru at Te Weraiti over the validation period.

Analysis of the simulations indicates:

- Analysis of the flow record by GWRC indicates that this site is run predominantly as a high flow/flood warning site. However it has been fully rated for high and low flows in the past, most notably between 1979 and 1985. The low flow record for the rest of the site history should be treated with caution. Anecdotal evidence indicates that flows at Te Weraiti get lower than the rated record indicates (GWRC, pers. comm.).
- The calibrated model correctly reproduces the hydrological behaviour encountered during simulation and validation periods, except during the low flow periods where TopNet consistently underestimate discharge (compared to observations)
- High NS and NSlog indicate a generally satisfactory match between simulated and observed flow data in both calibration and validation period (Figure 4-29 and Figure 4-30), except some low flow periods.
- The calibrated model is able to reasonably reproduce observed low flows (based on NSLog score) for most of time during the calibration and validation period. However further analysis indicates that the TopNet model is consistently underestimating observed low flow (Figure 4-31 and Figure 4-32). This is thought to be due to the potential issue of flow rating at low flow for this river.
- The calibrated model is not able to reproduce the hydrological behaviour (mean flow and 7-day MALF) encountered during simulation and validation periods. This is thought to be due to potential error in the observed low flow, impacting the estimation of those statistics.

- Annual average evaporation estimated by TopNet is lower than the expected long term average annual evaporation across the catchment, while modelled precipitation is similar than the long term average. Further investigation is needed once low flow rating issue are solved.
- Seasonal flows are correctly reproduced (magnitude and timing) during the summer months. Magnitude of the flows are largely underpredicted over the period September to December.

4.11 Huangarua catchment

The accuracy of the streamflow model prediction is presented in Table 4-45 for the calibration phase and the validation phase. The final values of parameters are provided in Table 4-46. Table 4-47 provides the simulated water balance and a comparison of simulated precipitation and evaporation with the long-term average climatology (calculated over the period 1966-2006). Table 4-48 provides the simulated and observed mean flow and 7-day MALF, while Table 4-49 presents the observed and simulated monthly average flows over the period of simulation. Note that due to rating issues post 2005, the validation period for this catchment was set between 2001 and 2004.

Figure 4-33 and Figure 4-34 present the simulation results at the streamflow gauging station in terms of comparison between simulated and observed hydrographs-cumulative hydrograph and flow duration curve during the calibration period (Figure 4-33) and validation period (Figure 4-34). Figure 4-35 presents the observed and simulated hourly low flows hydrograph (i.e., for discharge below mean flow) over the calibration and simulation period. Figure 4-36 presents the observed and predicted monthly average discharge at the gauging station over the validation period.

Table 4-45: Calibration- validation statistics for Huangarua catchment.

	Calibration (2001-2003)		Validation (2001-2012)	
Location	**NSlog**	**NS**	**NSlog**	**NS**
Huangarua at Hautotara Branch	0.798	0.814	0.657	0.837

Table 4-46: TopNet parameters for Huangarua catchment.

Parameter name (internal name)	Parameter description	Calibrated value
Saturated store sensitivity (topmodf)	Describes exponential decrease of soil hydraulic conductivity with depth	0.581 * default
Drainable soil water (swater1)	Range between saturation and field capacity	0.074 * default
Plant available soil water (swater2)	Range between field capacity and wilting point	0.477 * default
Hydraulic Conductivity at saturation (hydcond0)		1572 * default
Overland flow velocity (overvel)		1.743 * default
Manning n	Characterises the roughness of each reach	0.136 * default
Atmospheric lapse rate (atmlaps)	Change in temperature with elevation, used to adjust temperatures from climate data sites to basin centroid	0.587 * default
Gauge Undercatch (gucatch)	Adjustment for non-representative precipitation	0.700 * default

Table 4-47: Simulated water balance by TopNet for Huangarua catchment over the period of observations and simulation (2001-2012) compared with GWRC historic observations and the long term average climatology.

Annual Average Flux	TopNet (2001-2004) (mm/yr)	GWRC (2001-2004) (mm/yr)	Long term average climatology (1966-2006) (mm/yr)
Mean annual precipitation	1736	NA	1536
Mean annual evaporation	552	Na	750
Mean annual runoff	1132	1368	NA

Table 4-48: Simulated and observed flow characteristics for Huangarua catchment over the period of observations and simulation (2001-2012) and the historic record.

Annual Average hydrological characteristics	TopNet (2001-2004) (m^3/s)	GWRC (2001-2004) (m^3/s)
Mean Flow	3.726	5.244
7-day Mean Annual Low Flow	0.271	2.779

Table 4-49: Simulated and observed monthly average flows for Huangarua catchment over the period 2001-2004.

Months	Observed (2001-2004 (m^3/s)	TopNet (2001-2004) (m^3/s)
January	0.774	0.867
February	1.846	1.299
March	1.039	1.572
April	0.974	1.043
May	1.190	1.686
June	2.485	2.651
July	4.785	4.342
August	3.460	2.948
September	1.779	1.399
October	2.106	2.253
November	0.751	0.903
December	1.345	1.596

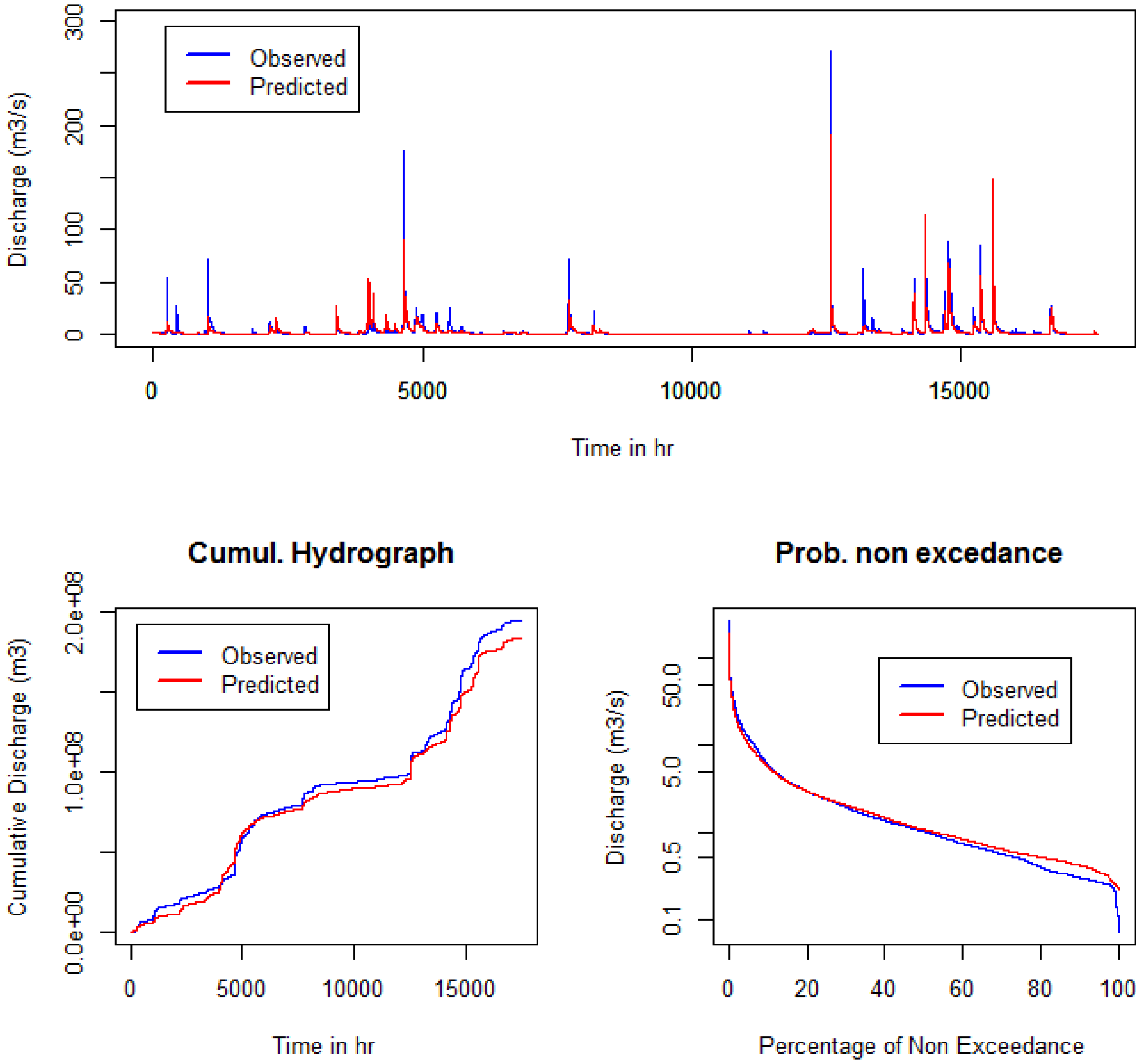

Figure 4-33: Calibrated hourly hydrograph of Huangarua at Hautotara Branch over the calibration period 2001-2003.

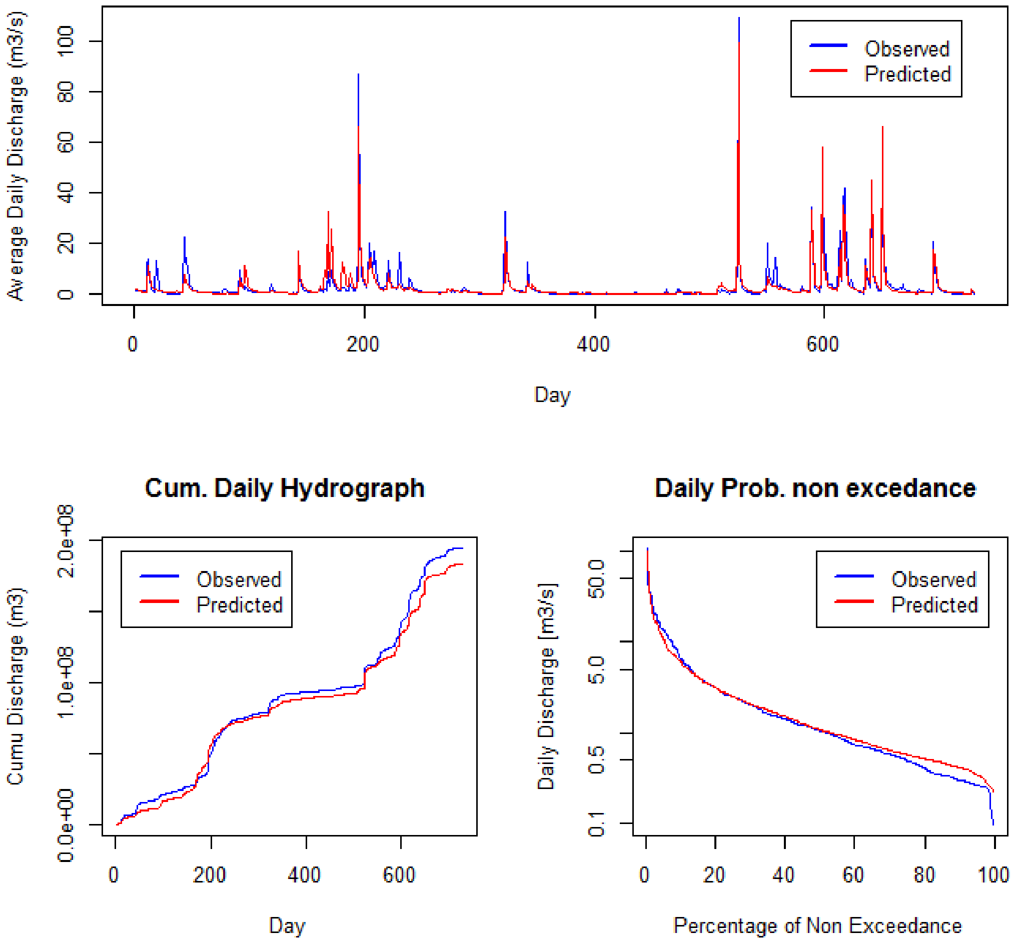

Figure 4-34: Simulated daily hydrograph of Huangarua at Hautotara Branch over the calibration and validation period 2001-2004.

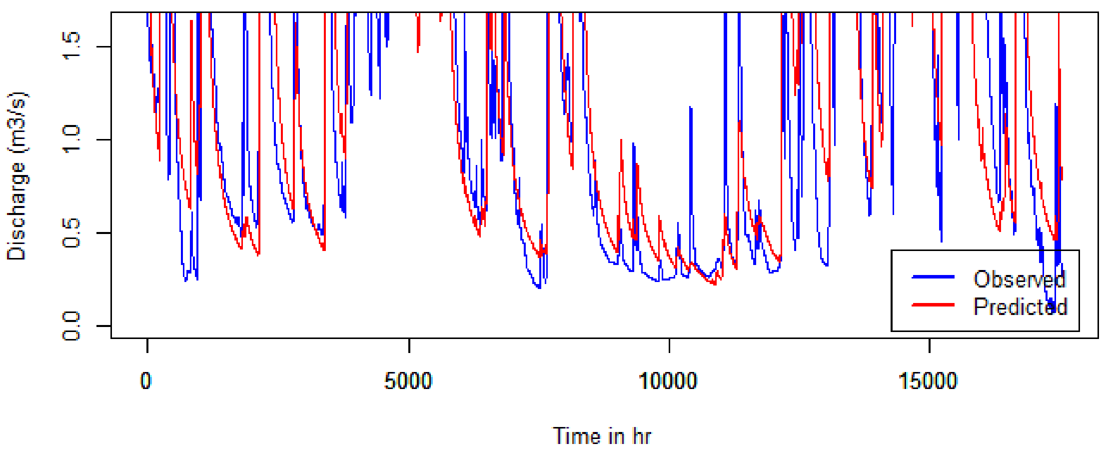

Figure 4-35: Observed and simulated hourly low flow hydrograph (i.e., flow below mean flow) for Huangarua at Hautotara Branch over the calibration and validation periods.

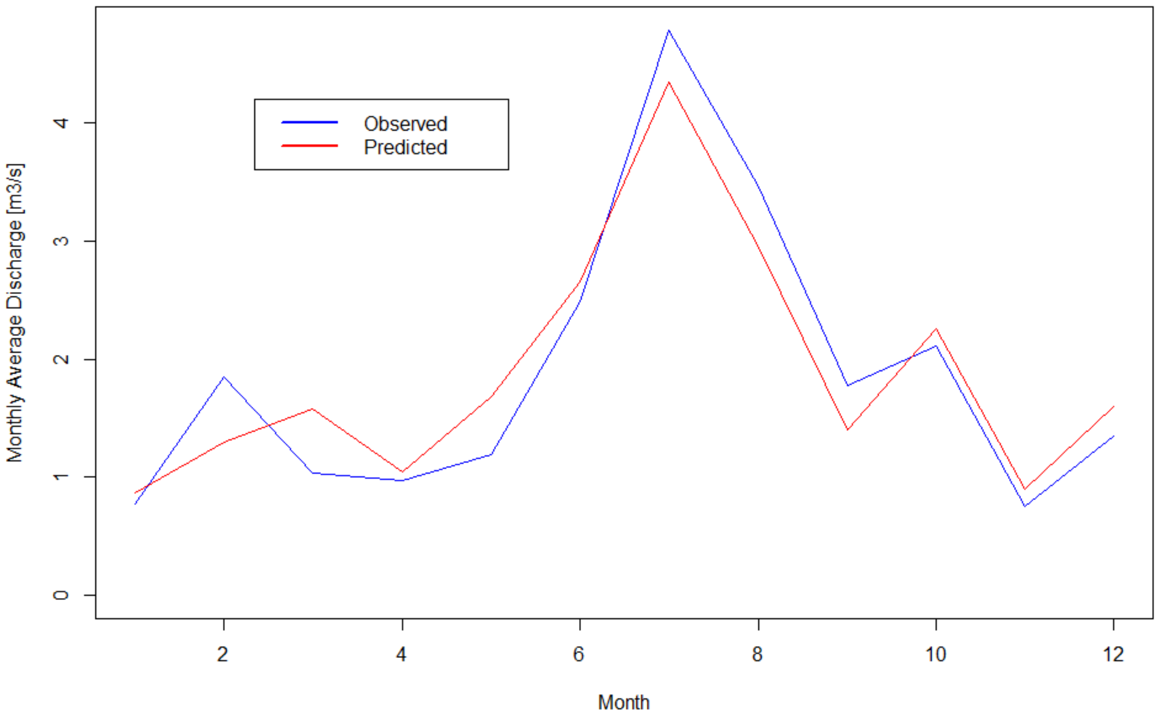

Figure 4-36: Observed and simulated monthly average flow for Huangarua at Hautotara Branch over the calibration and validation periods.

Analysis of the simulations indicates:

- Analysis by GWRC of observed flow time series indicates rating at low flow is reliable only for years 2000 to 2004.
- The calibrated model correctly reproduces the hydrological behaviour encountered during simulation and validation periods as shown by NS and NSLog values.
- High NS and NSLog values indicate a generally satisfactory match between simulated and observed flow data in both calibration and validation period (Figure 4-33 and Figure 4-34).
- Figure 4-33 and Figure 4-34 show simulation matches observed flow frequency quite well in the calibration and validation periods.
- Over the period of simulation, the calibrated model is able to reproduce the hydrological behaviour (mean flow and 7-day MALF) encountered during simulation and validation periods. Hence timing and magnitude of seasonal change are correctly reproduced by the calibrated model.
- Seasonal flows are correctly reproduced (magnitude and timing) during the summer season, however large errors are persistent for the February and March discharges.

5 Uncertainty analysis

Due to “curse of dimensionality” (e.g., number of parameters and rivers) in distributed hydrological modelling, sophisticated uncertainty analysis techniques like Bayesian inference (Yang et al. 2007) are not applicable to our study. Instead, we applied **Generalized likelihood uncertainty estimation (**GLUE) (Beven and Binley 1992), which is widely used in hydrologic modelling. The GLUE approach we applied here includes two steps: step 1 is to obtain the behavioural datasets and step 2 is to obtain the behavioural simulations.

In Step 1, GLUE was applied to these nine sub-catchments individually:

- First, the Nash Sutcliffe coefficient between simulated and observed flows in log scale (NSLog) was defined as the likelihood measure;
- Then 6000 parameter sets were randomly sampled within parameter ranges, and accordingly 6000 model simulations were obtained by running the TopNet with these 6000 model simulations;
- 200 parameter sets, which led to the first 200 highest NSLog flow simulations, were taken as behavioural parameter sets;

In Step 2, each time, we sampled one parameter set without replacement from 200 behavioural parameter sets in each of these nine sub-catchments and then regionalized into the entire Ruamāhanga catchment as a global parameter set (we used “global” to distinguish those used in the sub-catchment) and one “global” parameter set includes nine parameter sets with each from these nine sub-catchments). We repeated this process 200 times and we got 200 “global” parameter sets. Running TopNet model in Ruamāhanga with these 200 “global” parameters, one can get 200 simulations across the entire Ruamāhanga catchment, which was used to derive uncertainties in the simulated flow.

In this report, the uncertainty in simulated flow is represented by quantiles of simulated flow frequency in the flow duration curve. Table 5-1 to Table 5-9 below are results for each catchment in the Ruamāhanga Hill country catchment. In each of those tables, the frequency represents the probability of non exceedance of a flow threshold at a specific location, while the quantile provides the value of the distribution of this flow threshold within the 200 realisations. As an example, Table 5-1 indicates that the discharge in the Tauherenikau catchment is distributed around the 10% probability of non exceedance range within a distribution between 27.931m^3/s and 38.626m^3/s and a median flow of 31.608m^3/s.

As shown in these tables (Table 5-1 to Table 5-9), there are some general characteristics in the uncertainty of simulated flow frequency:

- For each catchment, uncertainties (measured as differences between quantiles) are large in the low frequency (high flow), and small in the high frequency (low flow).
- Uncertainties in catchments with large mean average flow (or large catchment size) are larger than those with small mean average flow (or small catchment size).
- Uncertainty due to the vegetation characteristics is relatively small. This indicates that large change of land use is necessary to generate large change of hydrological responses that outweigh model errors.

Table 5-1: Quantiles of simulated flow frequencies in Tauherenikau catchment. Flows in cumecs.

	Quantile				
Frequency	**5%**	**25%**	**50%**	**75%**	**95%**
5%	39.601	43.230	46.719	51.579	58.758
10%	27.931	29.793	31.608	34.567	38.626
20%	18.157	18.972	19.696	21.161	22.548
30%	13.082	13.968	14.537	15.205	16.224
40%	9.978	10.848	11.415	11.959	12.712
50%	7.866	8.629	9.185	9.663	10.140
60%	6.144	6.988	7.483	7.895	8.341
70%	4.816	5.560	5.983	6.408	6.797
80%	3.638	4.326	4.696	5.012	5.388
90%	2.546	3.109	3.406	3.683	4.009
95%	1.996	2.464	2.711	2.963	3.223

Table 5-2: Quantiles of simulated flow frequencies in Waiohine catchment. Flows in cumecs.

	Quantile				
Frequency	**5%**	**25%**	**50%**	**75%**	**95%**
5%	58.823	67.936	73.510	82.415	92.236
10%	41.881	46.446	50.045	54.507	60.432
20%	28.092	30.743	32.527	34.490	37.641
30%	21.125	23.258	24.469	25.947	28.016
40%	16.520	18.518	19.511	20.645	22.436
50%	13.344	14.941	15.988	17.055	18.545
60%	10.866	12.131	13.162	14.131	15.486
70%	8.720	9.837	10.726	11.611	12.803
80%	6.783	7.759	8.540	9.361	10.333
90%	4.878	5.692	6.316	7.034	7.877
95%	3.805	4.617	5.066	5.693	6.478

Table 5-3: Quantiles of simulated flow frequencies in Waingawa catchment. Flows in cumecs.

	Quantile				
Frequency	**5%**	**25%**	**50%**	**75%**	**95%**
5%	15.347	17.010	18.237	19.793	22.406
10%	11.826	12.839	13.453	14.232	15.803
20%	8.864	9.345	9.689	10.092	10.879
30%	7.026	7.424	7.716	8.112	8.649
40%	5.824	6.092	6.410	6.769	7.319
50%	4.757	5.077	5.396	5.765	6.278
60%	3.912	4.239	4.546	4.902	5.422
70%	3.156	3.476	3.818	4.159	4.663
80%	2.516	2.812	3.131	3.443	3.947
90%	1.835	2.131	2.400	2.687	3.138
95%	1.477	1.733	1.981	2.248	2.634

Table 5-4: Quantiles of simulated flow frequencies in Waipoua catchment. Flows in cumecs.

	Quantile				
Frequency	**5%**	**25%**	**50%**	**75%**	**95%**
5%	10.647	12.686	14.272	15.950	18.504
10%	7.675	8.741	9.401	10.273	11.439
20%	4.975	5.541	5.886	6.319	6.804
30%	3.557	3.949	4.197	4.532	4.953
40%	2.578	2.926	3.157	3.413	3.747
50%	1.870	2.200	2.395	2.571	2.903
60%	1.316	1.567	1.726	1.864	2.154
70%	0.855	1.058	1.188	1.307	1.541
80%	0.505	0.645	0.748	0.852	1.046
90%	0.250	0.335	0.422	0.519	0.661
95%	0.136	0.200	0.265	0.349	0.491

Table 5-5: Quantiles of simulated flow frequencies in Ruamāhanga catchment. Flows in cumecs.

	Quantile				
Frequency	**5%**	**25%**	**50%**	**75%**	**95%**
5%	17.305	18.877	20.578	22.627	24.666
10%	12.611	13.744	14.591	15.861	17.206
20%	8.805	9.491	10.080	10.454	11.272
30%	6.843	7.334	7.761	8.067	8.642
40%	5.473	5.954	6.288	6.588	7.120
50%	4.455	4.896	5.202	5.477	5.965
60%	3.616	4.070	4.316	4.578	5.050
70%	2.931	3.305	3.540	3.805	4.210
80%	2.288	2.630	2.866	3.108	3.459
90%	1.672	1.951	2.176	2.391	2.688
95%	1.344	1.568	1.793	1.973	2.243

Table 5-6: Quantiles of simulated flow frequencies in Kopuaranga catchment. Flows in cumecs.

	Quantile				
Frequency	**5%**	**25%**	**50%**	**75%**	**95%**
5%	8.014	9.653	10.997	12.365	14.415
10%	6.186	6.985	7.647	8.250	9.340
20%	4.254	4.643	4.956	5.266	5.738
30%	3.096	3.406	3.652	3.877	4.160
40%	2.303	2.603	2.786	2.979	3.154
50%	1.690	1.937	2.134	2.284	2.421
60%	1.191	1.359	1.537	1.676	1.815
70%	0.810	0.931	1.092	1.214	1.350
80%	0.544	0.633	0.749	0.847	0.974
90%	0.296	0.381	0.450	0.550	0.670
95%	0.170	0.252	0.322	0.405	0.507

Table 5-7: Quantiles of simulated flow frequencies in Whangaehu catchment. Flows in cumecs.

	Quantile				
Frequency	**5%**	**25%**	**50%**	**75%**	**95%**
5%	1.350	1.935	2.303	2.648	3.215
10%	1.047	1.351	1.521	1.682	1.907
20%	0.709	0.815	0.907	1.004	1.104
30%	0.461	0.548	0.615	0.682	0.752
40%	0.302	0.361	0.418	0.465	0.521
50%	0.174	0.228	0.271	0.304	0.353
60%	0.094	0.132	0.163	0.190	0.231
70%	0.052	0.074	0.101	0.122	0.152
80%	0.029	0.045	0.061	0.082	0.108
90%	0.017	0.026	0.036	0.052	0.074
95%	0.012	0.018	0.026	0.039	0.056

Table 5-8: Quantiles of simulated flow frequencies in Taueru catchment. Flows in cumecs.

	Quantile				
Frequency	**5%**	**25%**	**50%**	**75%**	**95%**
5%	21.413	23.348	25.411	28.468	31.663
10%	16.067	17.422	18.538	19.779	21.032
20%	11.053	11.954	12.589	13.166	14.147
30%	8.330	9.121	9.587	10.051	10.741
40%	6.378	7.057	7.443	7.829	8.293
50%	4.769	5.382	5.827	6.132	6.432
60%	3.536	4.022	4.433	4.700	5.012
70%	2.691	3.082	3.435	3.720	4.040
80%	1.980	2.262	2.552	2.847	3.151
90%	1.390	1.568	1.784	2.011	2.345
95%	1.097	1.267	1.427	1.625	1.960

Table 5-9: Quantiles of simulated flow frequencies in Huangarua catchment. Flows in cumecs.

	Quantile				
Frequency	5%	25%	50%	75%	95%
5%	6.307	7.462	9.114	11.696	14.129
10%	4.549	5.172	5.983	7.247	8.569
20%	2.940	3.316	3.707	4.230	4.809
30%	2.108	2.403	2.635	2.885	3.239
40%	1.622	1.799	1.969	2.121	2.366
50%	1.208	1.368	1.488	1.616	1.789
60%	0.863	1.009	1.136	1.244	1.407
70%	0.582	0.740	0.855	0.978	1.108
80%	0.384	0.517	0.624	0.733	0.844
90%	0.239	0.341	0.430	0.516	0.606
95%	0.163	0.249	0.316	0.405	0.479

In general through these tables, relative spread of uncertainty is greatest at low flows (high frequency), less at high flows (low frequency) and lowest around the mean flow (exceeded 30-40% of the time).

6 Model limitations

All models are only as good as the inputs and the assumptions made in the model construction. The above model simulations are subject to TopNet assumptions and limitations in the validity/uncertainties associated with climate inputs. These model limitations include:

1) Climate data uncertainties (precipitation, and temperature). Uncertainties in the input climate data (in terms of quantity and timing) will propagate to the hydrological model during calibration and validation processes.

   The VCSN climate information is a daily interpolation of available observed climate data on each day using an ANU spline interpolation (Tait et al. 2006) based on information available in NIWA's Climate database. As a result larger uncertainties exist in the dataset where large areas affected by orographic effects are covered without observations located across mountains. Figures 6-1 and Figure 6-2 present two types of information. Firstly, they present the location of the network of precipitation (Figure 6-1) and temperature gauges (Figure 6-2) used in the derivation of the VCSN dataset for precipitation and temperature. Secondly, Figure 6-1 and Figure 6-2 represent a measure of the number of days a specific station is used to derive the VCSN dataset over the period 1972-2012, hence its impact on the derivation of the VCSN. Furthermore, the temporal desegregation is based on the location of nearest high frequency (hourly) precipitation station.

   The model calibration process compensates for precipitation shortcomings to some degree, by adjusting the balance between precipitation and evapotranspiration, to achieve a better result for flow. This partially explains the reasonable flow simulation of the Tauherenikau (see Table 4-9), despite the differences in precipitation (see Figure 3-8 (top)). Other reasons for this difference are discussed in section 4.3.

   A version of the VCSN including all GWRC precipitation gauge was developed at a finer spatial resolution (i.e., 500m grid) by NIWA in an independent contract. However, this coverage was not used at the time of this project to limit error propagation within the model due to different spatial resolution for the climate information.

2) Current understanding of soil, geological information and landuse information. In the upper catchment landuse information is expected to be captured by LCDB version 3. Any errors in the land use will impact the model performance through errors in the hydrological flux estimation and misrepresentation of evaporation processes. Soil and geological information is provided through the use of the Fundamental Soil Layer (FSL) that is currently updated through the development of the QMAP product (GNS) and S-Maps (Landcare). Any misrepresentation of either geological or soil classification will impact surface water/groundwater interaction and evaporation processes and streamflow discharge.

3) Catchment information

   Water construction (dams), water takes and spring locations are important water features to complete an accurate water balance model. For example, in the Kopuaranga catchment, the gauging flows are constant at the low flow condition. Following review by GWRC hydrologists, this behaviour is thought to indicate the location of a spring impacting streamflow record at the gauge.

Flow data were used to calibrate and validate model parameters. Problems in the QA-QC processing of flow observations will be carried into the modelling and influence model parameters calibration and validation.

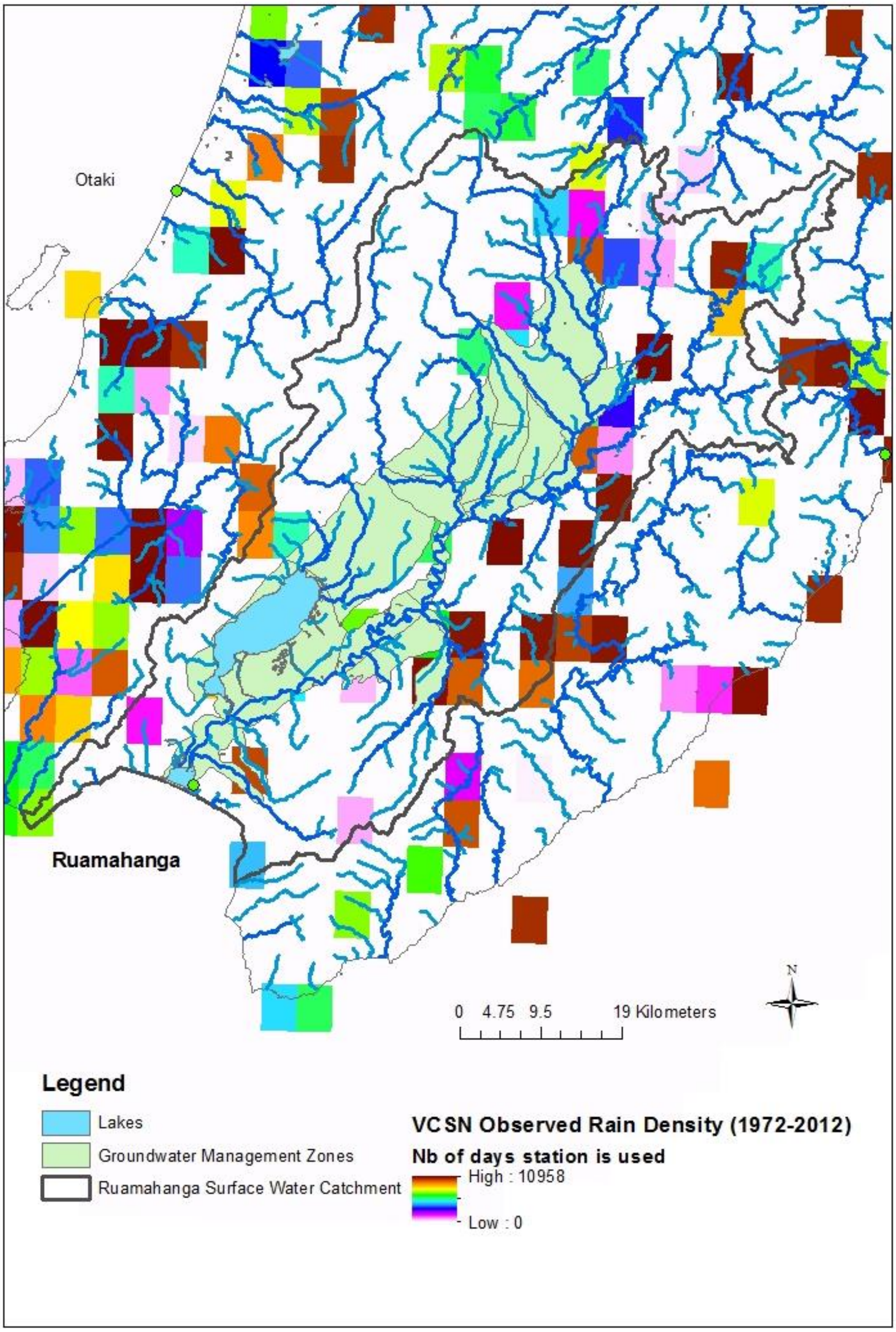

Figure 6-1: Location of the observed precipitation gauge used to derive the daily VCSN precipitation gridded information. The colour scheme represents the number of days (over a 40 year period) a particular station is used.

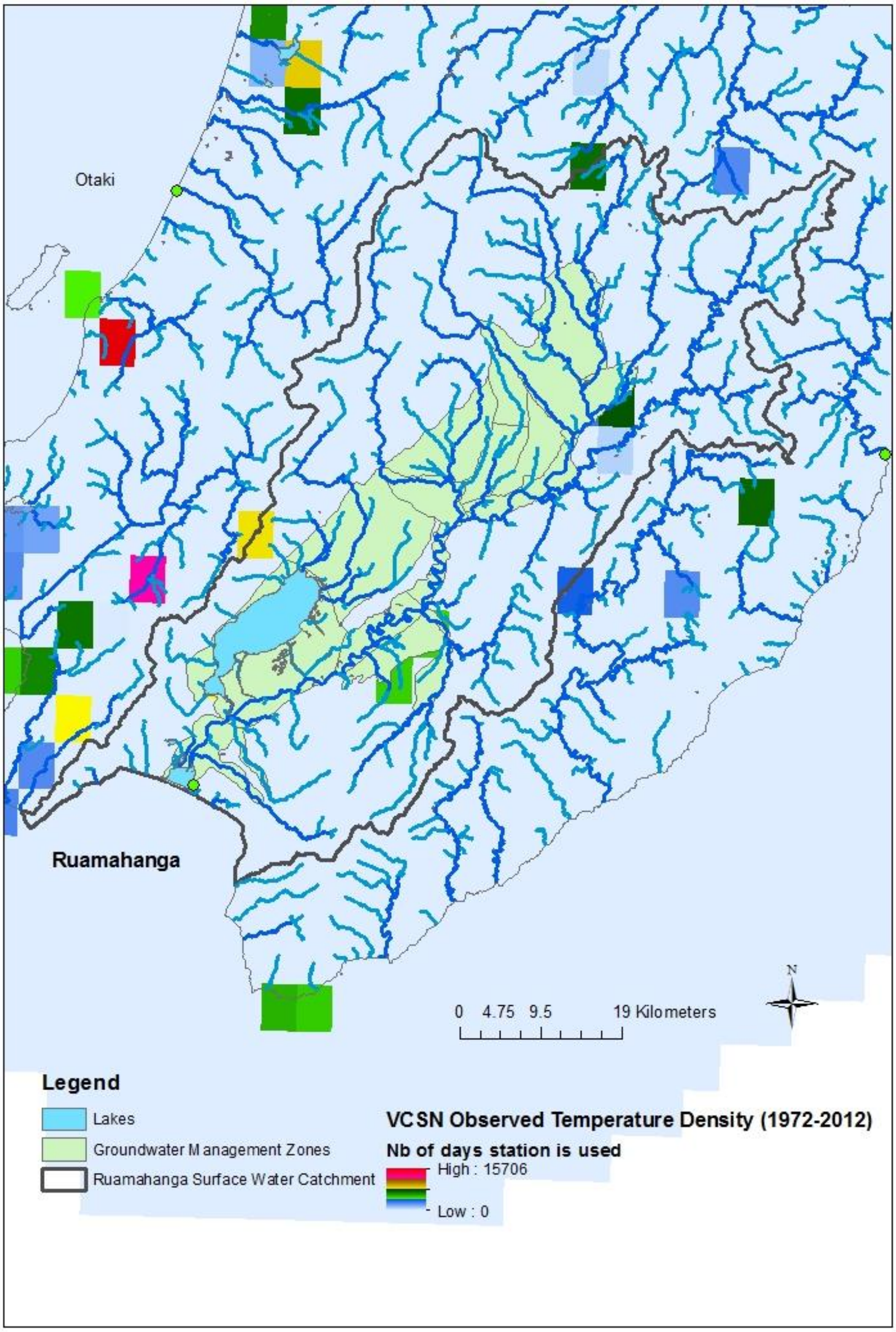

Figure 6-2: Location of the observed temperature gauge used to derive the daily VCSN precipitation gridded information. The colour scheme represents the number of days (over a 40 year period) a particular station is used.

7 Summary

A calibrated TopNet model was constructed to provide hydrological inputs to the Ruamāhanga Groundwater Management Zone (as an upper boundary condition to a MODFLOW model). Because the overall objective at the time of model building was to do with water allocation, the TopNet hydrological model was calibrated with an emphasis on low flow conditions across the Ruamāhanga catchment.

Based on the availability of flow records in the Ruamāhanga Hill country catchments, the Ruamāhanga Hill country TopNet model was subdivided into nine surface water models. The nine hydrological models were calibrated at the most downstream continuous monitoring streamflow station in each of the surface water catchments discharging to the Groundwater Management Zone. Discharges in these nine Ruamāhanga Hill country catchments are minimally impacted by water allocation activities and are thus considered to be representative of "natural conditions".

Each model used inputs based on a combination of Virtual Climate Network rainfall stations and existing sub-daily precipitation information located within each surface water catchment. Spatial information representing soil and land cover conditions was based on soil information from the Fundamental Soil Layer (FSL) and the land cover database version 3 (LCDB v3).

For consistency with the groundwater model developed as part of the Whaitua Modelling Project, the TopNet model was to simulate inputs to the groundwater model over the period 2000-2012. As a result, a common calibration period for each catchment was chosen to be 2001-2003 (representing a range of hydrological conditions), with a validation period 2001-2012. Model accuracy was represented across a range of hydrological criteria:

- Statistical measure of the goodness of fit for calibration and validation period using Nash Sutcliffe concept for the time series of flow and the log transform of the flow. This was used as the main statistical criteria as part of the calibration process.
- Post processed hydrological statistics such as mean flow and 7-day Mean Annual Low Flow (7-day MALF).
- Analysis of time series of discharge, cumulative discharge and frequency distribution of the discharge time series.
- Analysis of monthly average discharge.

In addition, a sensitivity and uncertainty analysis was carried out as part of this project for each of the models developed.

Sensitivity and uncertainty analysis indicates that:

- The most sensitive parameters of TopNet across the nine catchments are: precipitation, soil characterisation and depth of hydraulically active soil.
- Uncertainties are larger as catchment size increase.
- Uncertainties due to land cover are of second order compared to uncertainties associated with soil characterisation. This result confirms the result of the sensitivity analysis.

- Uncertainties are usually larger at high flows than low flows

Limitations associated with the model developments carried out as part of the project are:

- Uncertainties/bias in precipitation information and interpolation driving the hydrological model. The hydrological model was calibrated in order to correct the scale of the precipitation intensity, not the spatial distribution.
- Uncertainties/bias in all other related climate information used by the hydrological model (mainly temperature).
- Uncertainties in FSL driven soil characterisation in the Ruamāhanga Hill country catchment. This is potentially a large source of uncertainty considering that the most sensitive parameter is soil related.

Analysis of the calibration carried out at each catchment indicates:

- Spatial clustering of the performance of the model was observed between catchments on the West of the GWZ (i.e., Tauherenikau, Waiohine, Waingawa, Waipoua and Ruamāhanga) and East of the GWZ (Kopuaranga, Whangaehu, Taueru and Huangarua). Simulations for catchments located east of the GWZ tend to be better across the entire flow range, than catchments located on the west of the GWZ. This is thought to be associated with the variable accuracy of the climate information used to drive the hydrological model.
- Most of the calibrated models can represent average low flow conditions at monthly time scale for most of the months during the validation period. Improvement in model performance is likely to require additional model objective functions (e.g., number of consecutive days during a year/month below a flow threshold)
- Most of the calibrated models are not able to reproduced average flow conditions (especially on the west of the GWZ) due to potential underestimation of the winter gridded precipitation (used as part of this project) as well as the fact that the calibration process was deliberately focussed on low flows.
- Some of the models developed (i.e., Waingawa, Waiohine, Tauherenikau) require further development to better reproduce low flow conditions as required for the CHES Ruamāhanga tool (yet to be built).
- Some of the models developed (i.e., Taueru, Huangarua past 2006) could be further developed and improved once change are implemented in flow rating curves (to improve reliability of predictions).
- Two of the models (i.e., Kopuaranga, Waipoua) will need to consider/conceptualise substantial groundwater input as part of further development and improvement.

Overall, the TopNet model output for these nine catchments provides a suitable basis for water allocation simulations and surface water inputs to the Ruamāhanga GWZ. In order to provide some guidance of the suitability for use, we have used expert opinion to summarise the modelling results as follows.

Table 7-1: Expert assessment of Ruamāhanga Hill Country model performance.

	Model performance across hydrological regime		
Catchment	High Flows[1]	Mid Flows[2]	Low Flows[3]
Tauherenikau	Adequate	Adequate	Good
Waiohine	Adequate	Adequate	Good
Waingawa	Adequate	Adequate	Good
Waipoua	Adequate	Poor	Adequate
Ruamahanga	Good	Adequate	Adequate
Kopuaranga	Good	Poor	Good
Whangaehu	Good	Poor	Good
Taueru	Good	Poor	Excellent
Huangarua	Excellent	Poor	Good

1 Classification established for high flows on NS score as follows: Poor: NS<0.4- Adequate: 0.4<NS<0.6 – Good :0.6<NS<0.8 - Excellent NS>0.8

2 Classification established for Mid flows on annual average bias: Poor: Bias> 20%- Adequate : 10%<Bias<20% – Good :5%< Bia s<10% - Excellent: Bias <5%

3 Classification established for low flow on NsLog score: NSLog <0.4- Adequate : 0.4< NSLog <0.6 – Good :0.6< NSLog <0.8 - Excellent NSLog >0.8

Potential TopNet developments would allow:

- Improvement in hydrological processes conceptualisation to be implemented for the Kopuaranga and Waipoua catchments.
- Validation of the current model flow predictions with spot gauging information. This should provide some assurance to GWRC about the validity of model projection within and across a calibrated catchment.
- Use of spot gauging discharge measurement in uncalibrated catchments where hydrological parameters were regionalised. This step would provide GWRC with an estimation of total model uncertainties in unmonitored catchments.
- Improvement of the spatial resolution of the climate input driving the hydrological model will result in model output improvement, as it will reduce the tendency of the calibration process to produce calibration errors at high flow.
- Review of the digital river network in the upper catchment and implications for catchment scale hydrological model conceptualisation.

- Review of the current soil parametrisation available through FSL over the Ruamāhanga Hill country catchment and comparison with S-Map derived soil parametrisation (e.g., rooting depth, plant available water, macroporosity at 60 and 90 cm, soil distribution).

8 Glossary of abbreviations and terms

CHES	Cumulative Hydrological Effect Simulator Tool developed by NIWA
FDC	Flow Duration Curve
FSL	Fundamental Soil Layer, containing soil related information in New Zealand developed by Landcare Research
GWRC	Greate Wellington Regional Council
GWZ	Ruamāhanga Groundwater Management Zone
GLUE	Generalized likelihood uncertainty estimation. Industry standard to calculate and estimate uncertainty analysis in hydrology
LCDB	Land Cover Data Base
NS	Nash Sutcliffe coefficient representing a statistical measurement of the goodness of fit of a calibration of validation process
NSLog	Nash Sutcliffe coefficient calculated on the Log transformed of a variable representing a statistical measurement of the goodness of fit of a calibration of validation process
7-day MALF	Average of the lowest 7-day moving mean flow in each year of record
QMap	Hydrogeological layers for New Zealand maintained and developed by GNS Science
Strahler order	A numbering system that indicates size or relative significance of streams. Order 1 is a headwater stream with no tributaries, order 2 is downstream of where two order 1 streams meet, and so on. The highest order on the REC digital network is order 8
S-Maps	Updated version of the FSL produced by Landcare Research
VCSN	Virtual Station Climate Network- gridded network of 5km*5km over which climate information is provided routinely at daily time step since 1972

9 References

Bandaragoda, C., Tarboton, D.G., Woods R.A. (2004) Application of TOPNET in the distributed model intercomparison project. *J. Hydrol*., 298:178–201.

Beven, K. J., Lamb, R., Quinn, P., Romanowicz, R., and Freer, J. (1995) TOPMODEL, in: Computer Models of Catchment Hydrology, edited by: Singh, V. P., *Water Resour. Publ*., Highlands Ranch, Colorado, 627–668, 1995.

Beven, K.J., Binley, A.M., (1992) The future of distributed models: model calibration and uncertainty prediction, *Hydrol. Processes*, 6, p.279–298.

Clark, M.P., Rupp, D. E., Woods, R.A., Zheng, X., Ibbitt, R.P., Slater, A.G., Schmidt, J., and Uddstrom, M. J. (2008) Hydrological data assimilation with the ensemble Kalman filter: Use of streamflow observations to update states in a distributed hydrological model, *Adv. Water Resour*., 31, 1309– 1324, doi:10.1016/j.advwatres.2008.06.005.

Duan, Q., Sorooshian, S., Gupta V. (1992) Effective and efficient global optimization for conceptual rainfall-runoff models, *Water Resour. Res*., 28(4), 1015–1031, doi:10.1029/91WR02985.

Gordon, M., (2013). Hydrological statistics for surface water monitoring sites in the Wellington region. GWRC report.

Goring D.G., (1994). Kinematic shocks and monoclinal waves in the Waimakariri, a steep, braided, gravel-bed river, Proceedings of the International Symposium on Waves: Physical and Numerical Modelling, University of British Columbia, Vancouver, Canada, 21–24 August, 1994, pp. 336–345.

Ibbitt, R.P., Woods, R. (2002) Towards rainfall-runoff models that do not need calibration to flow data, in: *Friend 2002 – Regional Hydrology: Bridging the Gap Between Research and Practice*, edited by: van Lanen, H.A.J., Demuth, S., IAHS Publ., 274, 189–196.

McMillan, H., Freer, J., Pappenberger, F., Krueger, T., Clark, M. (2010) Impacts of uncertain river flow data on rainfall-runoff model calibration and discharge predictions. *Hydrol. Processes 24(10):* DOI: 10.1002/hyp.7587: 1270-1284.

McMillan, H.K., Hreinsson, E.O., Clark, M.P., Singh, S.K., Zammit, C., Uddstrom, M.J. (2013) Operational hydrological data assimilation with the recursive ensemble Kalman Filter. *Hydrol. Earth Syst. Sci.*, 17, 21-38.

Morris, M.D. (1991). Factorial sampling plans for preliminary computational experiments. *Technometrics*, 33(2), pp.161-174.

Newsome, P.F.J., Wilde, R.H., Willoughby, E.J. (2012) *Land Resource Information System Spatial Data Layers*, Technical Report, Palmerston North, Landcare Research NZ Ltd., New Zealand, 2000, Updated in 2012.

NIWA, (2012). River Environmental classification version 2.0 (https://www.niwa.co.nz/freshwater-and-estuaries/management-tools/river-environment-classification-0)

Snelder, T.H., Biggs, B.J.F. (2002) Multiscale River Environment Classification for water resources management, *J. Am. Water Resour. Assoc*., 38, 1225–1239, doi:10.1111/j.1752-1688.2002.tb04344.x.

Tait, A., Henderson, R., Turner, R., Zheng, X. (2006) Thin plate smoothing spline interpolation of daily rainfall for New Zealand using a climatological rainfall surface, *Int. J. Climatol*., 26, 2097–2115, doi:10.1002/joc.1350.

Wilson A.D., Giltrap D.J. (1982) Prediction and mapping of soil water retention properties. New Zealand Soil Bureau District Office Report WN7. 15p.

WMO (2008). Guide to hydrological practices. WMO report no 168 volume 1Hydrology-From measurement to hydrological information

Yang, J., Reichert, P., Abbaspour, K.C., Yang, H. (2007) Hydrological modelling of the Chaohe basin in China: Statistical formulation and Bayesian inference. *Journal of Hydrology* Volume 340, Issues 3–4, 15 July 2007, Pages 167–182.

Yang, J. (2011) Convergence and uncertainty analyses in Monte-Carlo based sensitivity analysis. *Environmental Modelling & Software,* 26, 444-457.

Yang, J., Liu, Y., Yang, W., Chen, Y. (2012) Multi-objective sensitivity analysis of a fully distributed hydrologic model WetSpa. *Water resources management*, 26(1), 109-128.

Appendix A Observed and simulated flow deciles

Statistics were calculated when observed discharge was present. If discharge information was missing, both observed and simulated flows were set to 0. As a result 0 value discharge threshold for any decile does not reflect the potential ephemeral character of the stream.

Table A-1: Tauherenikau catchment (2001-2012).

	Hourly		Daily		Monthly	
Decile	Observed (m3/s)	Predicted (m3/s)	Observed (m3/s)	Predicted (m3/s)	Observed (m3/s)	Predicted (m3/s)
0	0.000	0.000	0.000	0.000	0.000	0.000
10	1.151	1.465	1.171	1.482	1.858	2.119
20	1.813	2.451	1.864	2.464	3.499	3.408
30	2.436	3.191	2.546	3.252	4.059	4.445
40	3.192	4.068	3.386	4.135	5.291	5.060
50	4.128	5.041	4.376	5.126	6.970	6.349
60	5.312	6.279	5.710	6.413	8.414	7.819
70	7.076	7.854	7.708	8.026	10.046	9.015
80	9.991	10.386	10.784	10.472	12.095	11.136
90	16.863	15.477	18.106	15.582	14.857	15.224
100	388.977	819.930	176.889	344.127	24.987	38.980

Table A-2: Waiohine catchment (2001-2012).

	Hourly		Daily		Monthly	
Decile	Observed (m3/s)	Predicted (m3/s)	Observed (m3/s)	Predicted (m3/s)	Observed (m3/s)	Predicted (m3/s)
0	0.000	0.000	0.000	0.000	0.000	0.000
10	3.322	5.434	3.379	5.495	6.526	6.971
20	5.196	7.468	5.350	7.628	10.866	10.143
30	6.920	9.259	7.306	9.512	13.654	12.120
40	9.053	10.881	9.505	11.139	16.868	14.857
50	11.341	12.653	12.136	12.964	19.933	18.013
60	14.402	14.656	15.643	15.355	22.933	20.013
70	18.879	17.501	20.884	18.487	27.433	23.775
80	26.103	22.319	29.489	23.939	30.769	26.534
90	45.630	36.744	49.679	39.274	39.351	36.769
100	1259.275	945.040	504.573	689.989	79.491	89.177

Table A-3: Waingawa catchment (2001-2012).

	Hourly		Daily		Monthly	
Decile	Observed (m3/s)	Predicted (m3/s)	Observed (m3/s)	Predicted (m3/s)	Observed (m3/s)	Predicted (m3/s)
0	0.000	0.000	0.000	0.000	0.000	0.000
10	1.685	2.027	1.736	2.036	3.113	3.640
20	2.341	2.778	2.435	2.826	4.877	4.814
30	3.030	3.492	3.208	3.553	5.650	5.776
40	3.816	4.241	4.078	4.334	7.141	6.419
50	4.800	5.138	5.266	5.246	8.621	7.721
60	6.239	6.270	6.932	6.495	9.749	8.736
70	8.309	7.888	9.439	8.266	11.335	10.033
80	11.918	10.500	13.202	10.850	13.400	11.103
90	20.433	16.230	21.623	17.031	16.165	14.337
100	384.184	602.239	138.884	267.833	33.332	34.885

Table A-4: Waipoua catchment (2007-2012).

	Hourly		Daily		Monthly	
Decile	Observed (m3/s)	Predicted (m3/s)	Observed (m3/s)	Predicted (m3/s)	Observed (m3/s)	Predicted (m3/s)
0	0.000	0.000	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.000	0.000	0.000
20	0.000	0.000	0.000	0.000	0.000	0.000
30	0.000	0.000	0.000	0.000	0.000	0.000
40	0.000	0.000	0.000	0.000	0.000	0.000
50	0.000	0.000	0.000	0.000	0.000	0.000
60	0.000	0.000	0.000	0.000	0.000	0.000
70	0.374	0.245	0.378	0.249	0.690	0.371
80	1.397	1.063	1.427	1.057	2.607	1.513
90	3.121	2.976	3.295	3.051	4.096	4.102
100	232.268	121.903	64.890	45.749	13.556	9.224

Table A-5: Ruamāhanga catchment (2001-2012).

	Hourly		Daily		Monthly	
Decile	Observed (m3/s)	Predicted (m3/s)	Observed (m3/s)	Predicted (m3/s)	Observed (m3/s)	Predicted (m3/s)
0	0.807	0.838	0.830	0.870	2.108	1.823
10	1.632	1.842	1.670	1.862	3.712	3.636
20	2.193	2.496	2.300	2.545	5.026	4.986
30	2.782	3.150	2.973	3.221	6.082	6.139
40	3.452	3.852	3.723	3.965	7.293	6.912
50	4.287	4.742	4.733	4.885	9.025	8.035
60	5.470	5.938	6.252	6.214	10.221	8.989
70	7.468	7.687	8.961	8.145	12.375	10.378
80	11.309	10.628	13.783	11.391	13.961	11.213
90	22.391	17.480	25.061	19.449	16.588	14.852
100	415.000	721.388	175.646	291.054	34.158	37.650

Table A-6: Kopuaranga catchment (2001-2012).

	Hourly		Daily		Monthly	
Decile	Observed (m3/s)	Predicted (m3/s)	Observed (m3/s)	Predicted (m3/s)	Observed (m3/s)	Predicted (m3/s)
0	0.000	0.000	0.000	0.000	0.000	0.000
10	0.314	0.164	0.316	0.167	0.401	0.286
20	0.436	0.458	0.439	0.460	0.621	0.705
30	0.590	0.843	0.596	0.855	0.970	1.200
40	0.870	1.259	0.885	1.263	1.601	1.768
50	1.207	1.809	1.235	1.819	2.330	2.274
60	1.712	2.455	1.751	2.499	2.695	3.235
70	2.376	3.246	2.459	3.272	3.344	3.893
80	3.507	4.449	3.637	4.464	3.993	4.677
90	6.290	6.714	6.497	6.802	5.489	6.479
100	59.779	287.571	52.809	138.863	11.679	15.040

Table A-7: Whangaehu catchment (2001-2012).

	Hourly		Daily		Monthly	
Decile	Observed (m3/s)	Predicted (m3/s)	Observed (m3/s)	Predicted (m3/s)	Observed (m3/s)	Predicted (m3/s)
0	0.000	0.000	0.012	0.015	0.017	0.017
10	0.025	0.024	0.025	0.024	0.032	0.028
20	0.033	0.040	0.033	0.040	0.060	0.046
30	0.052	0.063	0.054	0.063	0.124	0.090
40	0.094	0.096	0.098	0.096	0.190	0.152
50	0.155	0.163	0.163	0.165	0.345	0.237
60	0.251	0.262	0.267	0.265	0.483	0.457
70	0.411	0.428	0.429	0.434	0.700	0.676
80	0.653	0.667	0.689	0.679	1.012	0.996
90	1.211	1.219	1.330	1.251	1.592	1.384
100	62.029	109.863	33.862	41.200	3.345	3.423

Table A-8: Taueru catchment (2001-2012).

	Hourly		Daily		Monthly	
Decile	Observed (m3/s)	Predicted (m3/s)	Observed (m3/s)	Predicted (m3/s)	Observed (m3/s)	Predicted (m3/s)
0	0.000	0.000	0.000	0.000	0.000	0.000
10	1.477	1.176	1.481	1.188	1.675	1.425
20	2.640	1.805	2.638	1.806	2.879	2.087
30	3.235	2.363	3.246	2.378	3.595	2.691
40	3.912	3.040	3.921	3.048	4.780	3.871
50	4.772	4.035	4.776	4.052	5.627	4.951
60	6.033	5.452	6.080	5.480	7.351	6.500
70	7.672	7.482	7.766	7.489	9.782	9.153
80	10.349	10.476	10.444	10.478	13.244	12.701
90	16.326	16.729	16.428	16.693	19.555	16.112
100	464.161	250.410	280.099	206.594	55.513	55.551

Table A-9: Huangarua catchment (2001-2004).

	Hourly		Daily		Monthly	
Decile	Observed (m3/s)	Predicted (m3/s)	Observed (m3/s)	Predicted (m3/s)	Observed (m3/s)	Predicted (m3/s)
0	0.000	0.000	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.000	0.000	0.000
20	0.000	0.000	0.000	0.000	0.000	0.000
30	0.000	0.000	0.000	0.000	0.000	0.000
40	0.000	0.000	0.000	0.000	0.000	0.000
50	0.000	0.000	0.000	0.000	0.000	0.000
60	0.201	0.280	0.211	0.291	0.387	0.430
70	0.549	0.764	0.568	0.782	1.554	1.903
80	1.245	1.669	1.286	1.701	3.103	2.873
90	3.235	3.621	3.303	3.801	6.332	6.040
100	499.663	431.643	274.293	214.951	22.574	23.928