Surface hydrology in the Upper Ruamahanga watershed

Prepared for Greater Wellington Regional Council

April 2016

Draft report for restricted release to greater Wellington Regional Council

6 May 2016 4.05 p.m.

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NIWA CLIENT REPORT No: CC
Report date: February 2016
NIWA Project: WRC15505

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Quality Assurance Statement		
	Draft report reviewed by:	Roddy Henderson
	Formatting checked by:	
	Draft report approved for release by:	

6 May 2016 4.05 p.m.

Contents

Tables

Figures

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 Ruamahanga watershed (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 GNS Science. There are a total of 297 inflow streams whose location is presented in Figure 1-2.

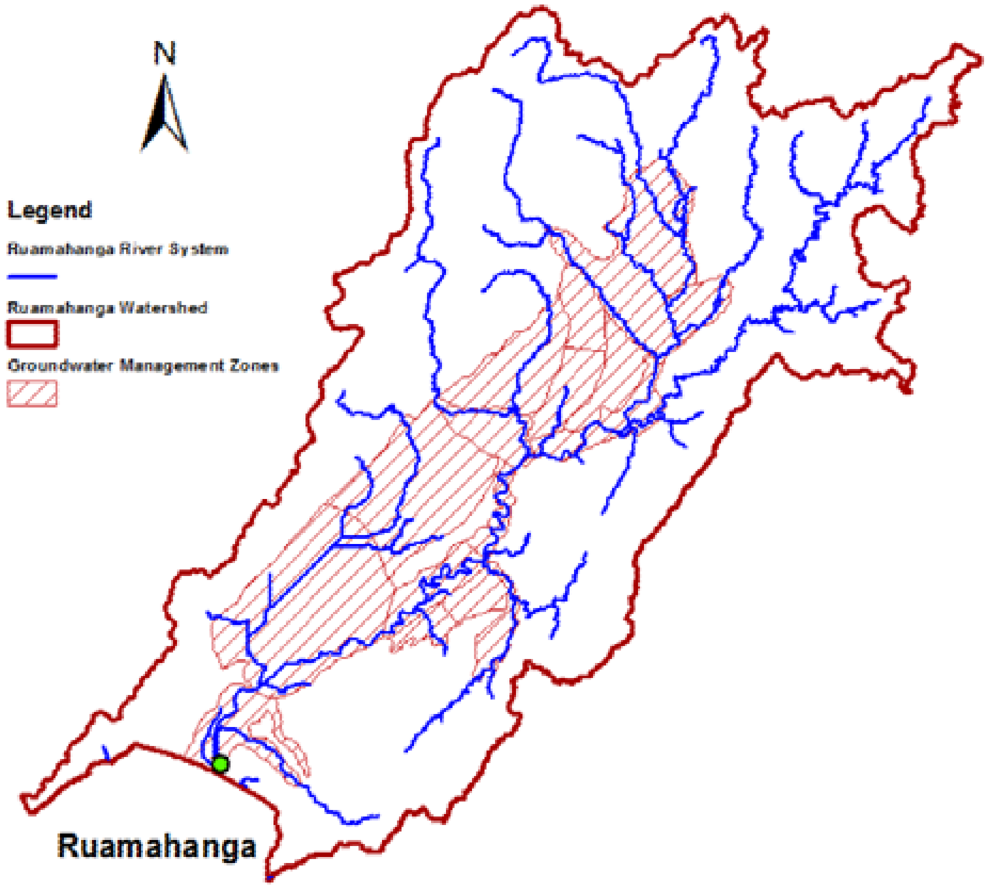


Figure 1-1: Location of GWZ in the Ruamahanga watershed. The main river system in the Ruamahanga (blue lines) is represented by the Strahler order 4 river network.

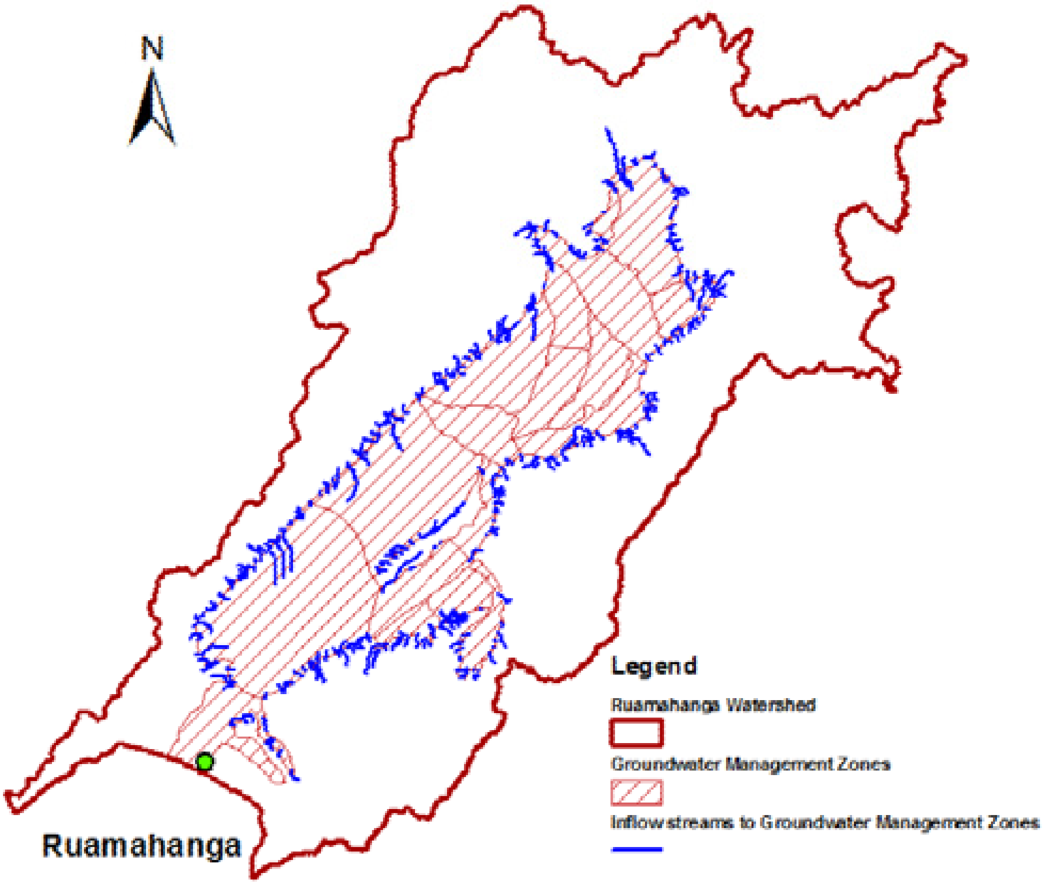


Figure 1-2: **Locations of inflow streams to GWZ. Inflow streams (blue lines) are depicted at Strahler order 1 river network.**

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 watersheds 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., 30m digital elevation model), physical (Land Cover Database version 3, Land Resource Inventory, Newsome et al. 2000) 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)

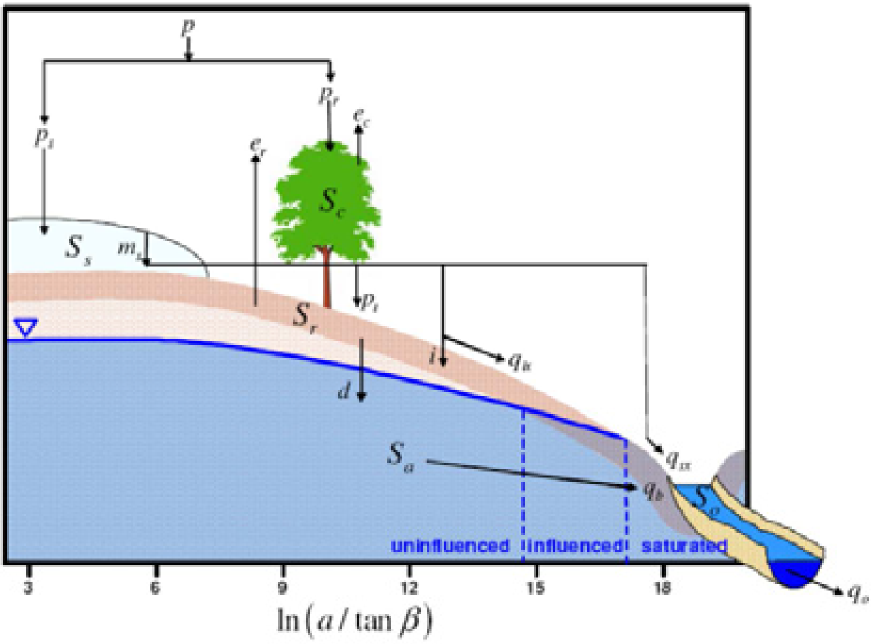


Figure 2-1: **TopNet model structure within each sub-basin, showing modelled water fluxes and storages.**

3 Model design

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

3.1 Physiographic characteristics

The study area is the surface water catchments discharging to the Ruamahanga GWZ, as illustrated in Figure 3-1, while Figure 3-2 presents land use information. Land use in Upper Ruamahanga (i.e., outside of the GWZ zone) is predominantly pastoral (see Figure 3-2).

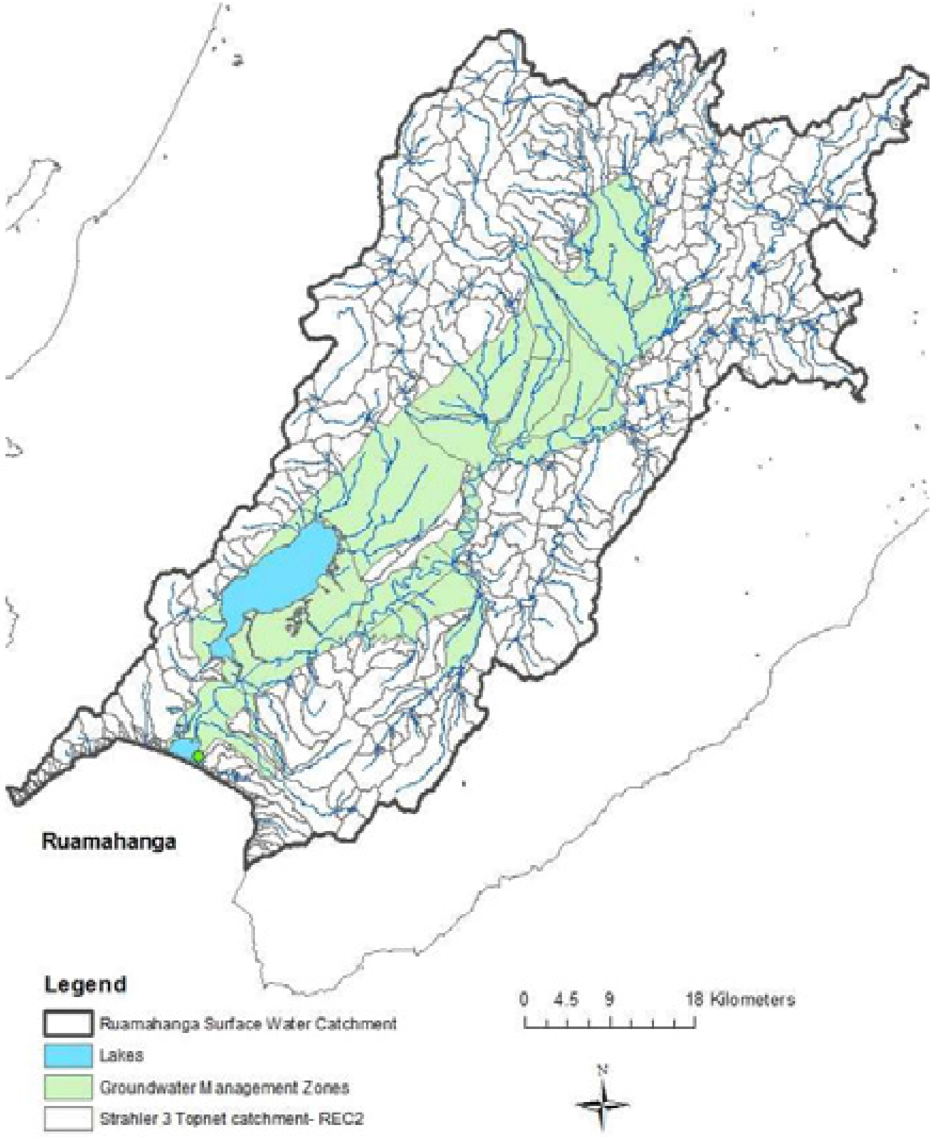


Figure 3-1: Ruamahanga surface water catchment (blue lines represent Strahler 3 streams from the REC coverage).

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-watershed using national soil information (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 Ruamahanga watershed; the differences between the GWRC land use layer and the LCDB3 in the upper parts of the watershed are considered negligible with respect to the likely impact on TopNet model outputs.

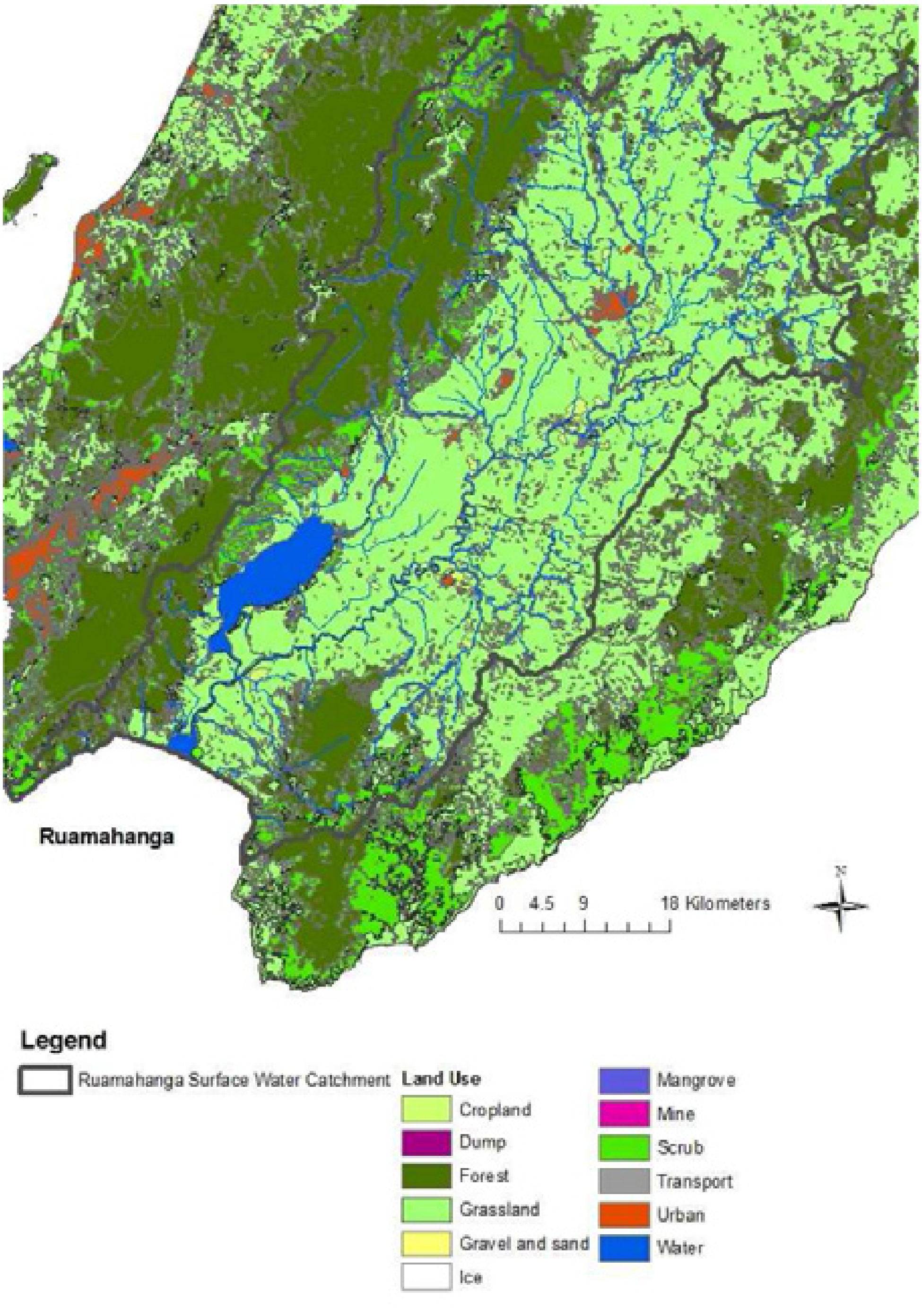


Figure 3-2: Land Use.

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

As the Upper Ruamahanga surface water catchment is outside of the area covered by the recent SMaps soil classification, soil definition in the Upper Ruamahanga catchment were derived from the current FSL layer.

3.2 Climate

11 climate stations are located within the boundaries of the Upper Ruamahanga surface water catchment (Figure 3-3). Table 3-1 provides a summary of the information available for those stations

Table 3-1: Climate station location in the Upper Ruamahanga watersheds.

Name	Tideda ID	Watershed	Elevation (masl)	Period of record
Tauherenikau at Bull Mound	59310	Tauherenikau	949	1976-present
Waiohine at Gorge	1503191	Waiohine	141	
Waiohine at Carkeek	58411	Waiohine	1013	1974-present
Waingawa at Kaituna	58582	Waingawa	243	1994-present
Waipoua at Mikimiki	58506	Waipoua	321	1979-1997
Ruamahanga at Bannister Basin	57511	Ruamahanga	932	1974-present
Ruamahanga at Mt Bruce	57514	Ruamahanga	341	1984-2000
Ruamahanga River at Mt Bruce river site	57559	Ruamahanga	299	1984-2000
Whangaehu at Tiki Tapu	57710	Whangaehu	192	1993-1997
Taueru at Castlehill	57958	Taueru	261	1993-present
Taueru at Te Weraiti	59795	Taueru	77	1997-present

An additional source of climate information n, 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 station, present in the Ruamahanga catchment, are included in the VCSN "dataset".

Figure 3-4 and Figure 3-5 present the annual average precipitation and evaporation, as estimated by NIWA. Figure 3-6 presents the median monthly catchment average precipitation and temperature simulated by TopNet for the Ruamahanga River catchment (reach ID: 09267243), while Figure 3-7 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 Duration Curve (IDC).

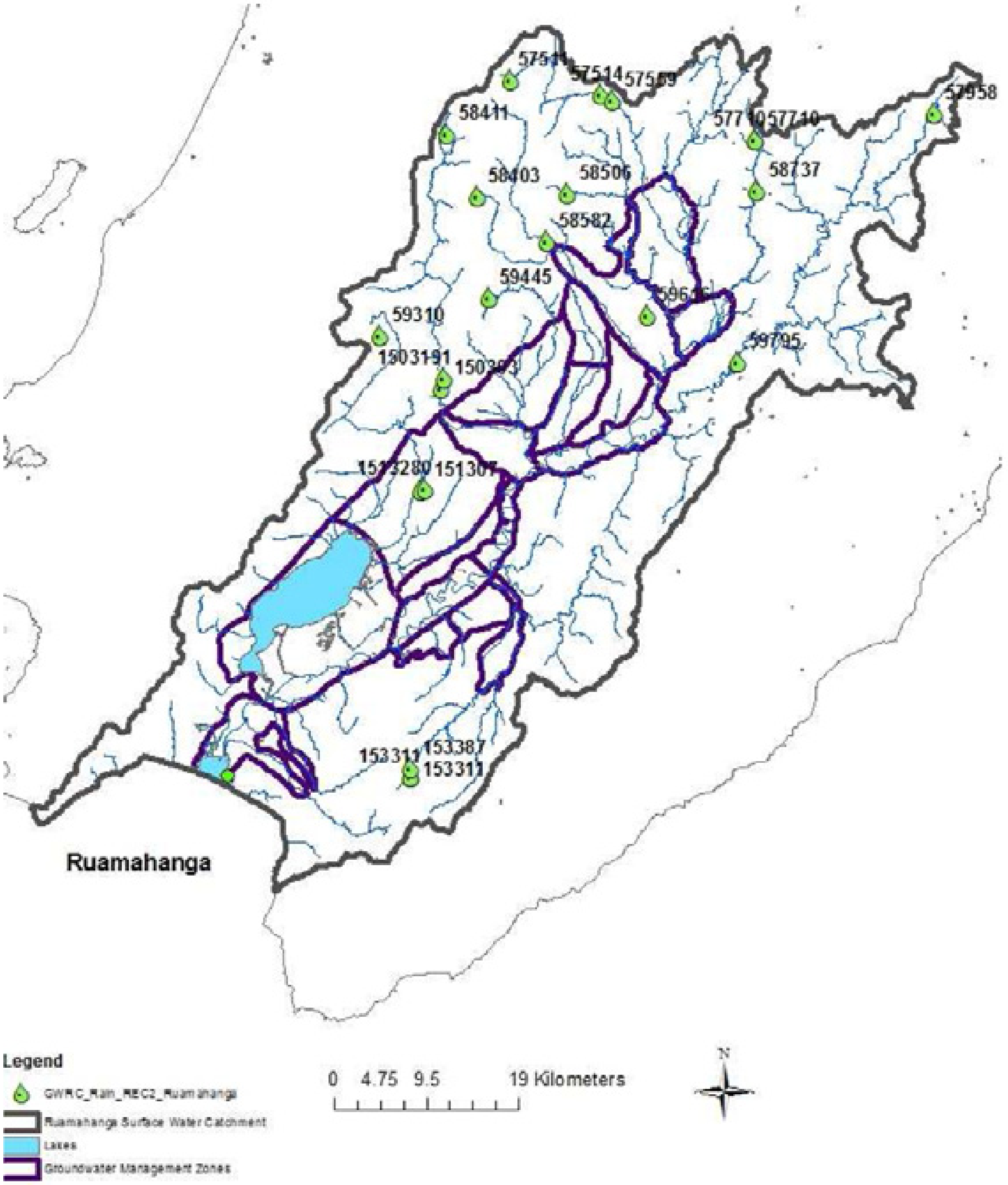


Figure 3-3: Location of the GWRC high frequency intensity in each sub-watersheds and associated precipitation station sites (represented by their Tideda ID) in the Ruamahanga watershed.

The climate in the focus area is characterised by:

- Annual average rainfall around 6000 mm/year along the Tararua Range, decreasing to 760 mm/year along the Ruamahanga River, increasing to 1200 mm/year over the eastern boundary.

- Annual evaporation around 600 mm/year along the Tararua Range, increasing to 700 mm/year along the Ruamahanga River and up to the eastern boundary.
- For the Ruamahanga surface water catchment relatively low monthly accumulated rainfall during the summer months (40 mm/month in February) and larger monthly accumulated rainfall during winter (up to 100 mm/month in June).
- Monthly mean temperature ranges between 8.9 deg C in winter to 18.6 deg C in summer across the Ruamahanga surface water catchment
- Appendix A (not yet provided) presents the comparison of observed and simulated precipitation at the location of the GWRC precipitation gauges. Comparison with GWRC precipitation measurements, that are not included in the climate database (CliDB) used by NIWA to generate the VCSN, indicates that the seasonality of the precipitation is represented by the VCSN (Figure 3-7). However VCSN driven precipitation is usually lower than observed precipitation, due to the fact that existing VCSN observation points are not able to correctly reproduce the orographic effects on the precipitation in the Tararua and Rimutaka Ranges.

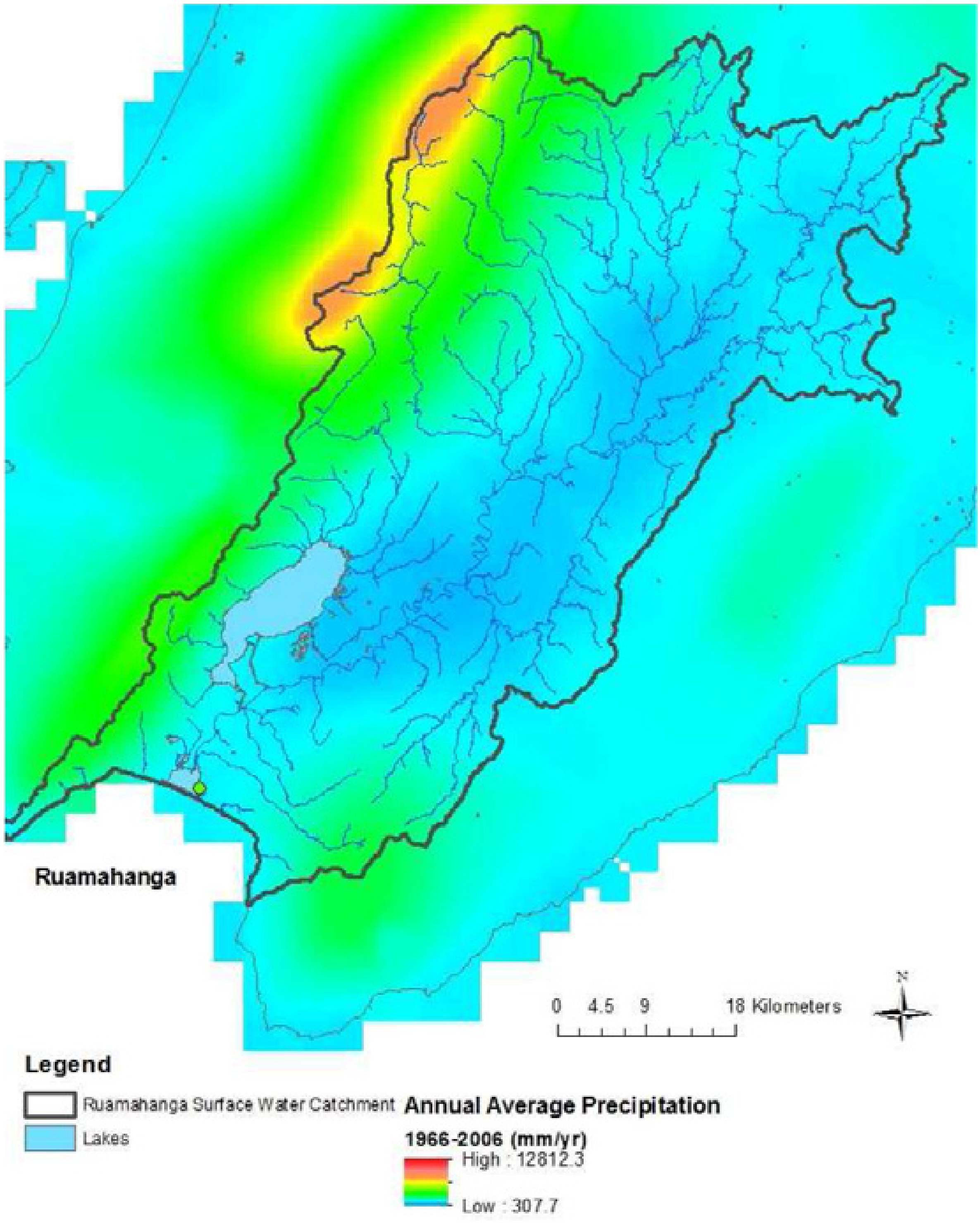


Figure 3-4: Annual precipitation across the period 1966-2006.

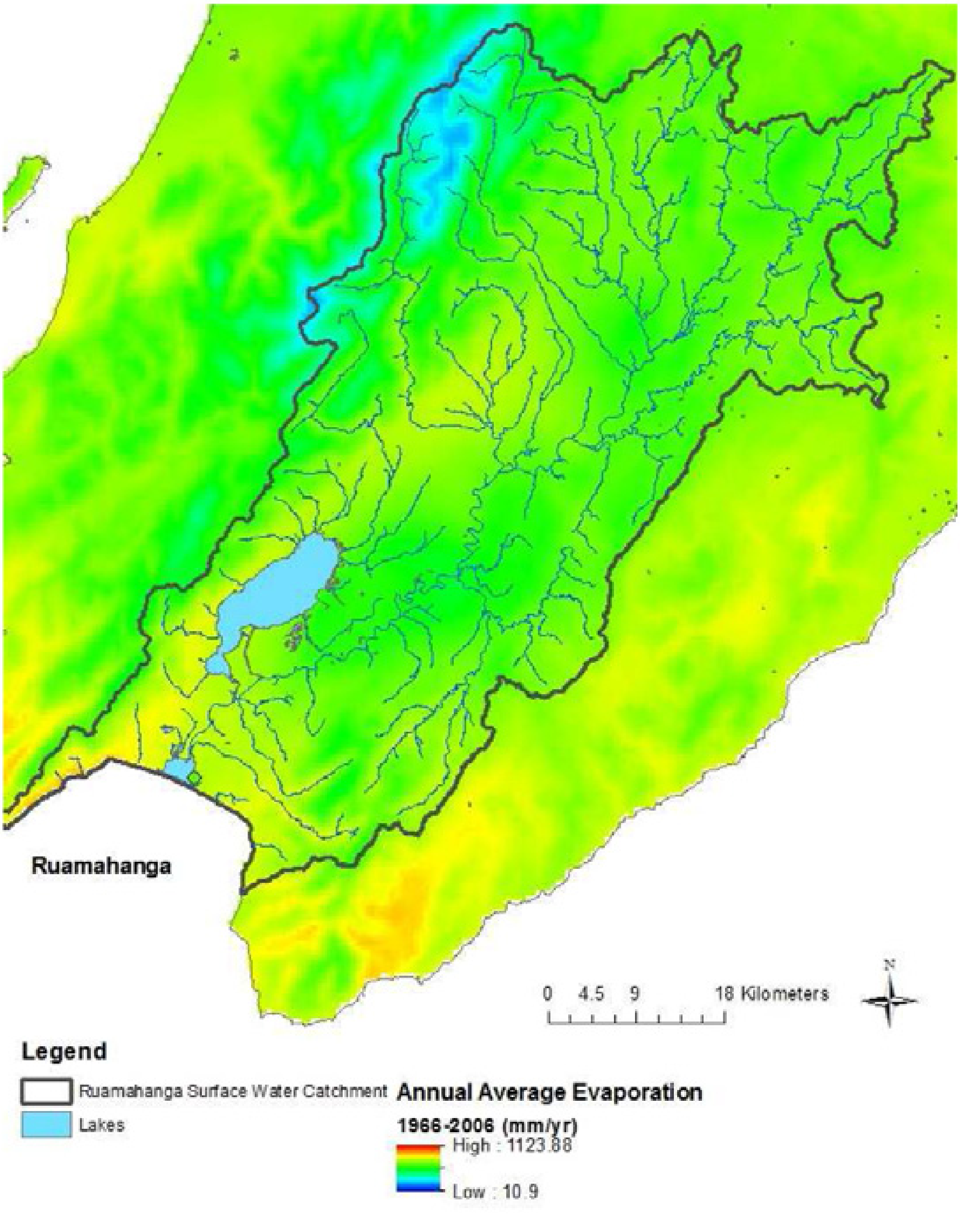


Figure 3-5: Annual evaporation across the period 1966-2006

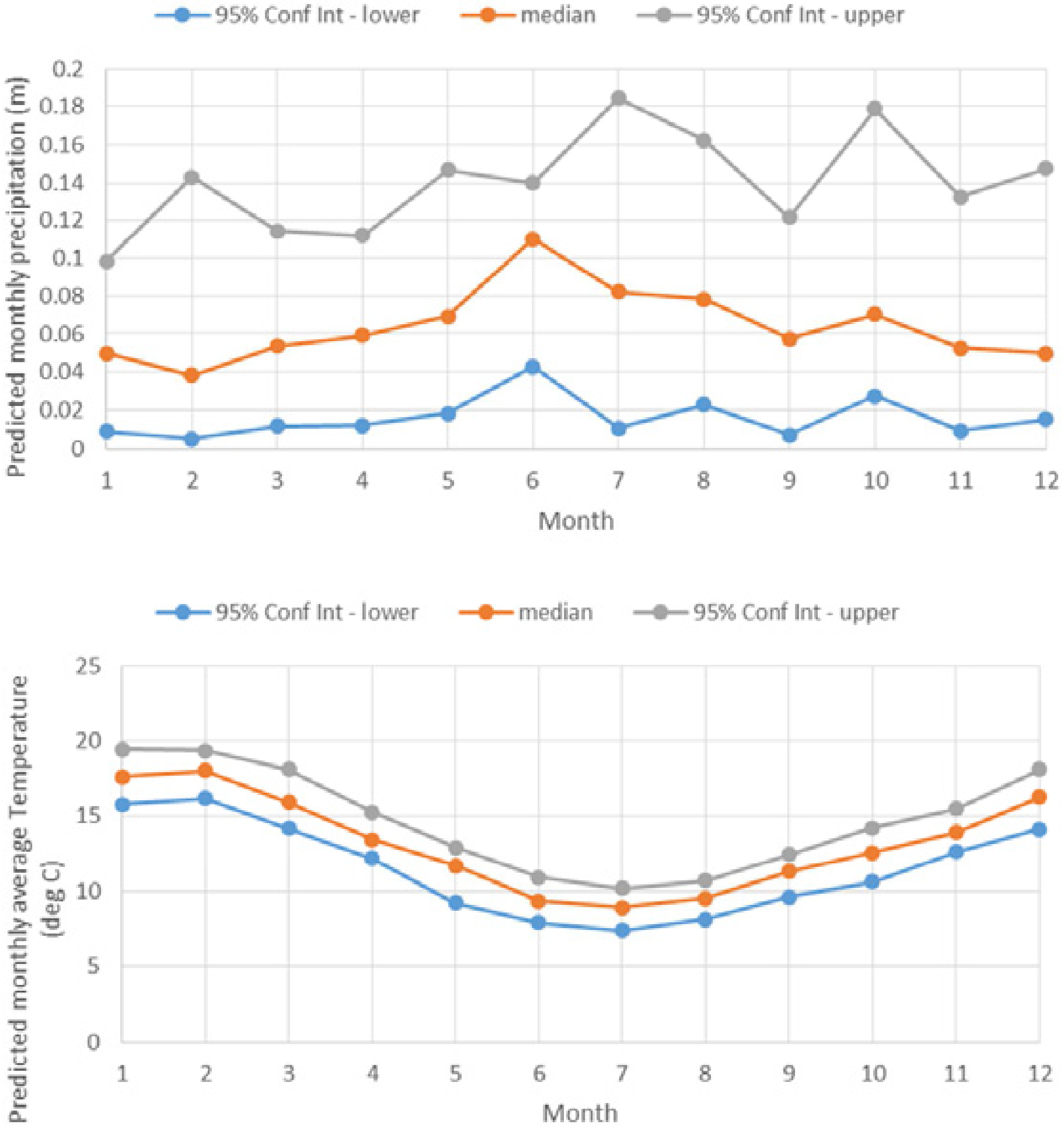


Figure 3-6: Monthly median simulated catchment average precipitation (top) and temperature (bottom) for the Ruamahanga surface water catchment over the period 1972-2014

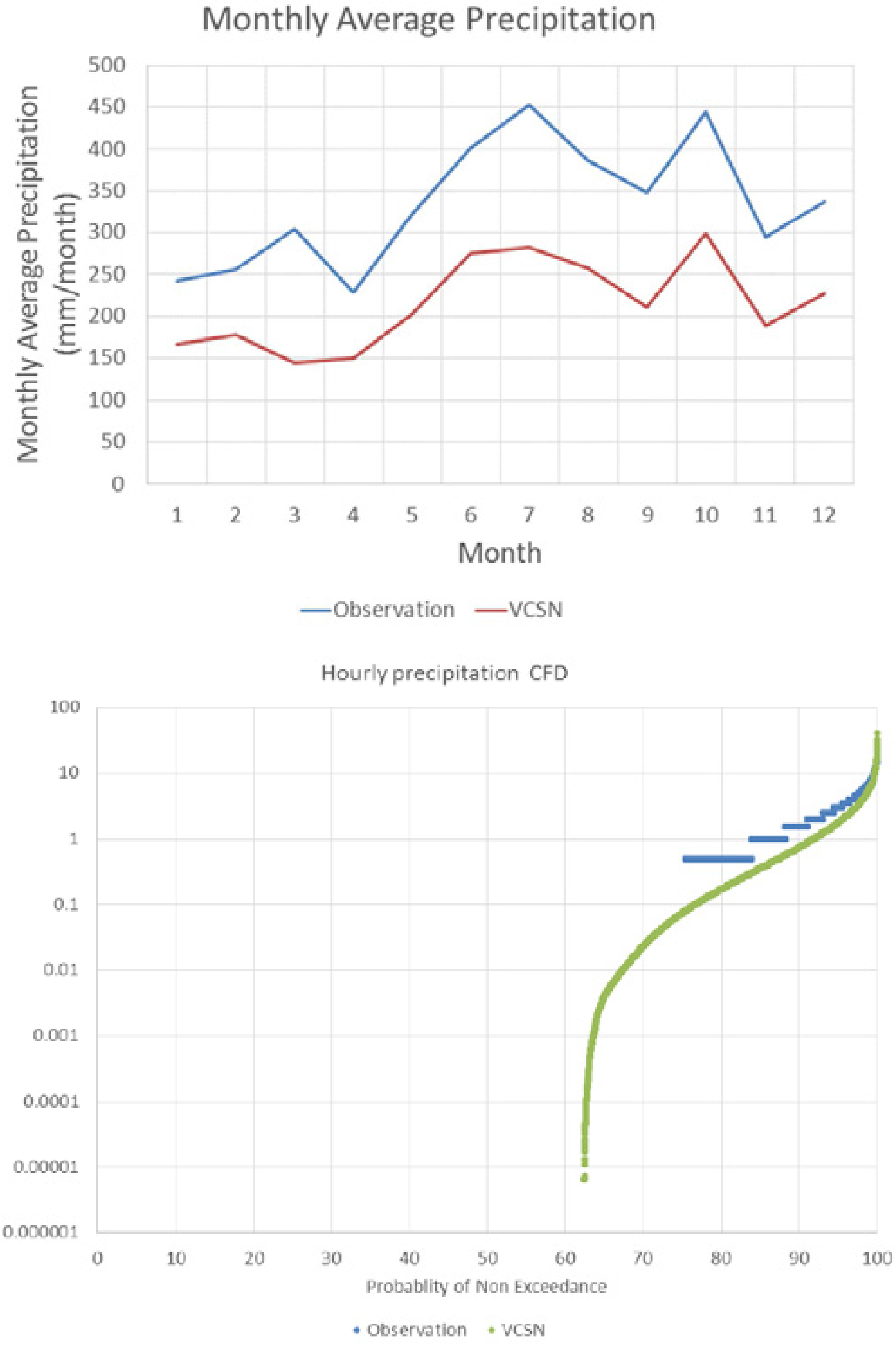


Figure 3-7: Observed monthly precipitation at Tauherenikau at Bull Mound (Tideda ID 59310) and corresponding catchment average precipitation simulated by TopNet (reach ID 09256528) over the simulation period 2001-2013 (Top). Observed and simulated precipitation frequency distribution at the same location over the same time period (Bottom).

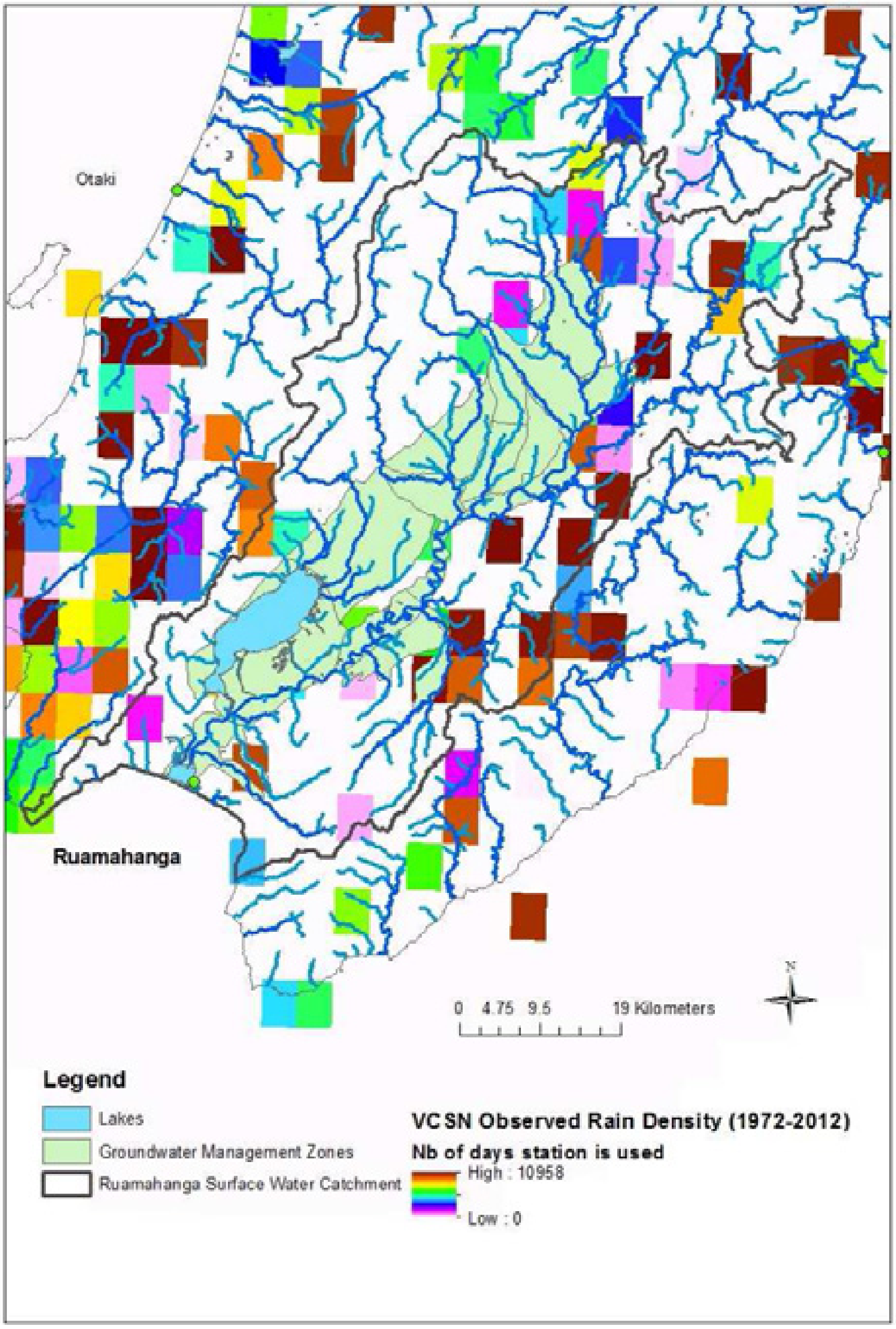


Figure 3-8: Location of the observed precipitation gauge used to derive the daily VCSN precipitation gridded information. The colour scheme represents the number of days (over a 40 year period) a particular station is used.

3.3 Water consenting

An interrogation of the GWRC consents databases showed that there are no significant abstraction, damming or diversion activities upstream of the nine gauging stations. As a result observed streamflows at those sites are assumed to be in a naturalized 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 9 locations listed in Table 3-2 and their locations are presented in Figure 3-9 together with their corresponding draining watersheds

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

Watershed	Site	Tideda ID	REC2 reach ID	Area (km^2)
Tauherenikau	Tauherenikau at Gorge	29251	9259046	114.21
Waiohine	Waiohine at Gorge(new site)	29224	9257741	177.89
Waingawa	Waingawa at Upper Kaituna	29246	9254309	76.50
Waipoua	Waipoua at Mikimiki	29257	9253108	79.84
Ruamahanga	Ruamahanga at Mt Bruce	29254	9250417	78.70
Kopuaranga	Kopuaranga at Palmers Br	29230	9252319	100.63
Whangaehu	Whangaehu at Waihi	29244	9252727	36.80
Taueru	Taueru at Te Weraiti	29231	9257216	391.19
Huangarua	Huangarua at Hautotara	29222	9265072	139.23

Most 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. However, three of the nine sites (Taueru at Te Weraiti, Huangarua at Hautotara and Waipoua at Mikimiki) have for long periods in their history been maintained as flood warning sites only and low flow record during these periods is unreliable. This has been taken in to account during the model calibration/validation.

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

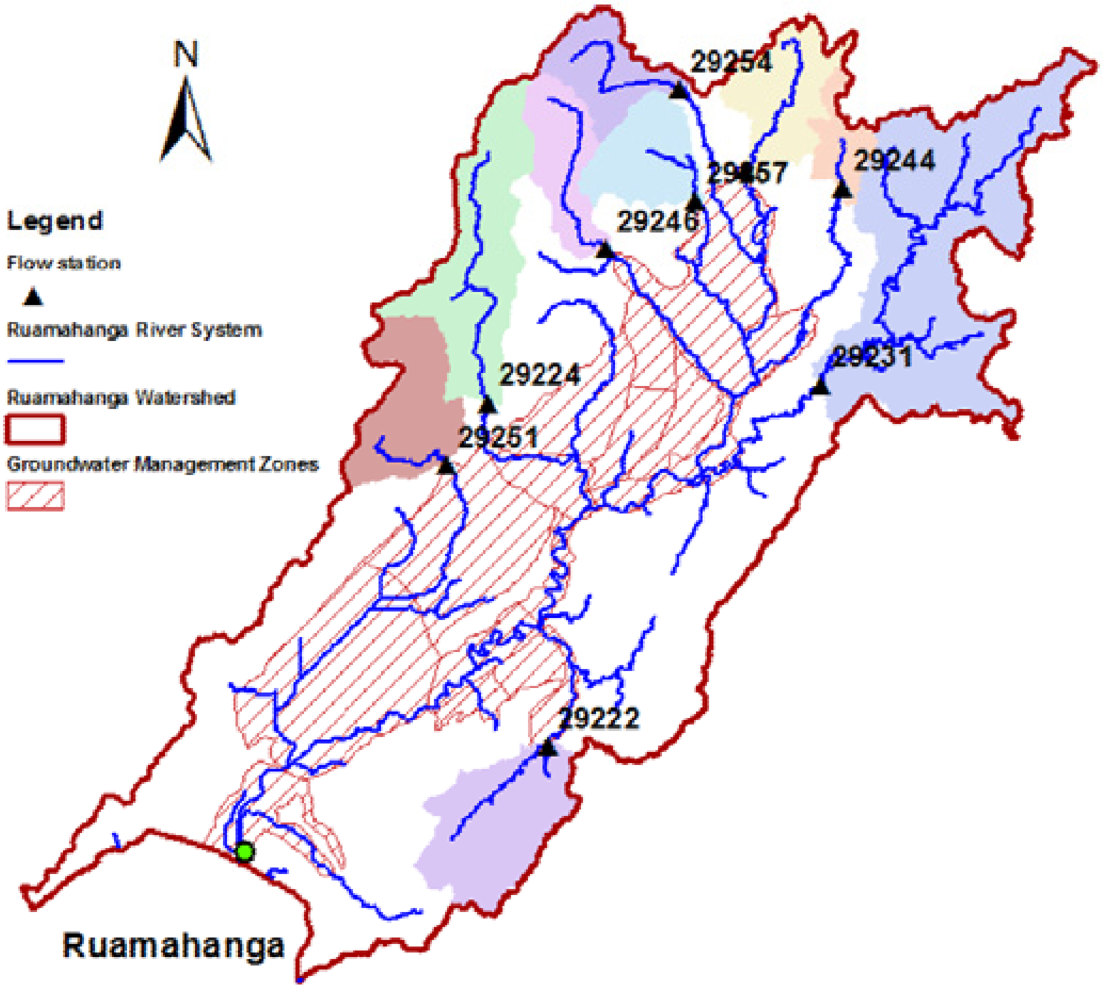


Figure 3-9: Location of the nine calibrated sub-watersheds and associated flow station sites (represented by their Tideda ID) for model calibration in the Ruamahanga watershed.

3.4.2 Precipitation

Analysis of the current network of VCSN rainfall gauges over the Upper Ruamahanga indicates that the density of the network is not homogenous across the different catchments (only limited VCSN precipitation gauges are located within the extent of the surface water catchments- see Figure 3-8). As a result it was decided to use the VCSN information as a driver of the hydrological model. However daily precipitation was temporally disaggregated to hourly time steps, using temporal precipitation information provided by the existing GWRC 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 Parameter regionalisation

The identified 9 surface water catchments do not cover the entire area discharging to the GWZ zone. As a result the TopNet parameters, calibrated for those 9 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
2. Soil type
3. Climate range input

Figure 3-10 presents the soil drainage capability map based on FSL information, while Figure 3-11 presents the soil type map based on the FSL, while Figure 3-4 presents the annual average precipitation experienced by the Ruamahanga surface water catchment.

Figure 3-12 presents the regionalisation of the calibrated TopNet parameter that was applied to the lower Ruamahanga to generate inflows discharge time series to the GWZ.

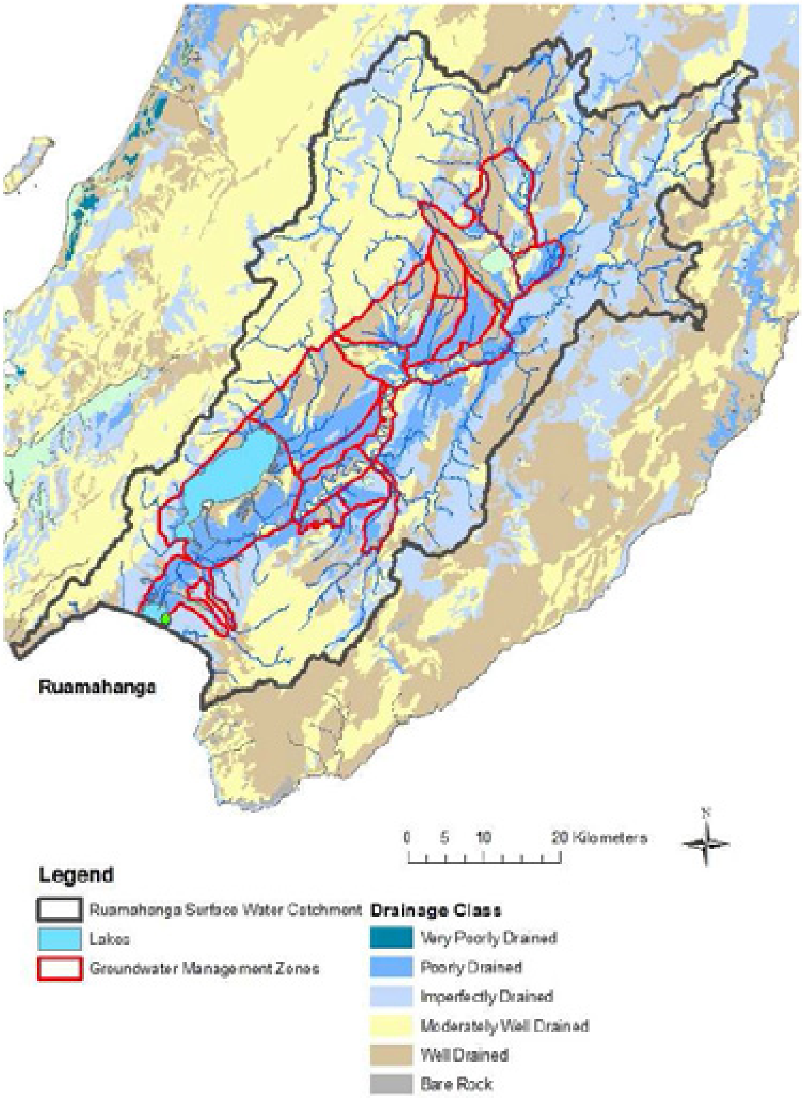


Figure 3-10: FSL soil drainage classes for the Ruamahanga watershed.

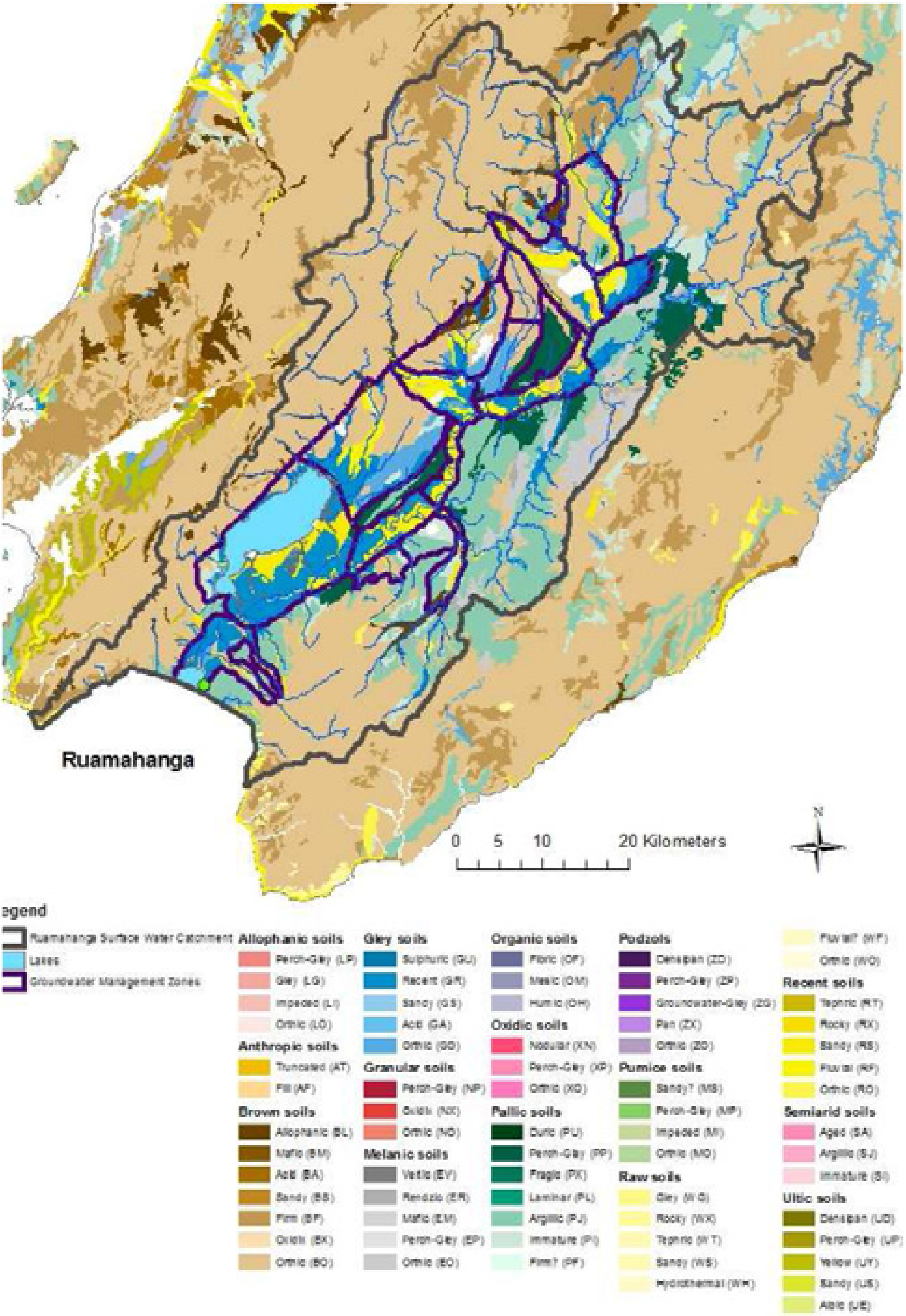


Figure 3-11: FSL soil drainage classes for the Ruamahanga watershed.

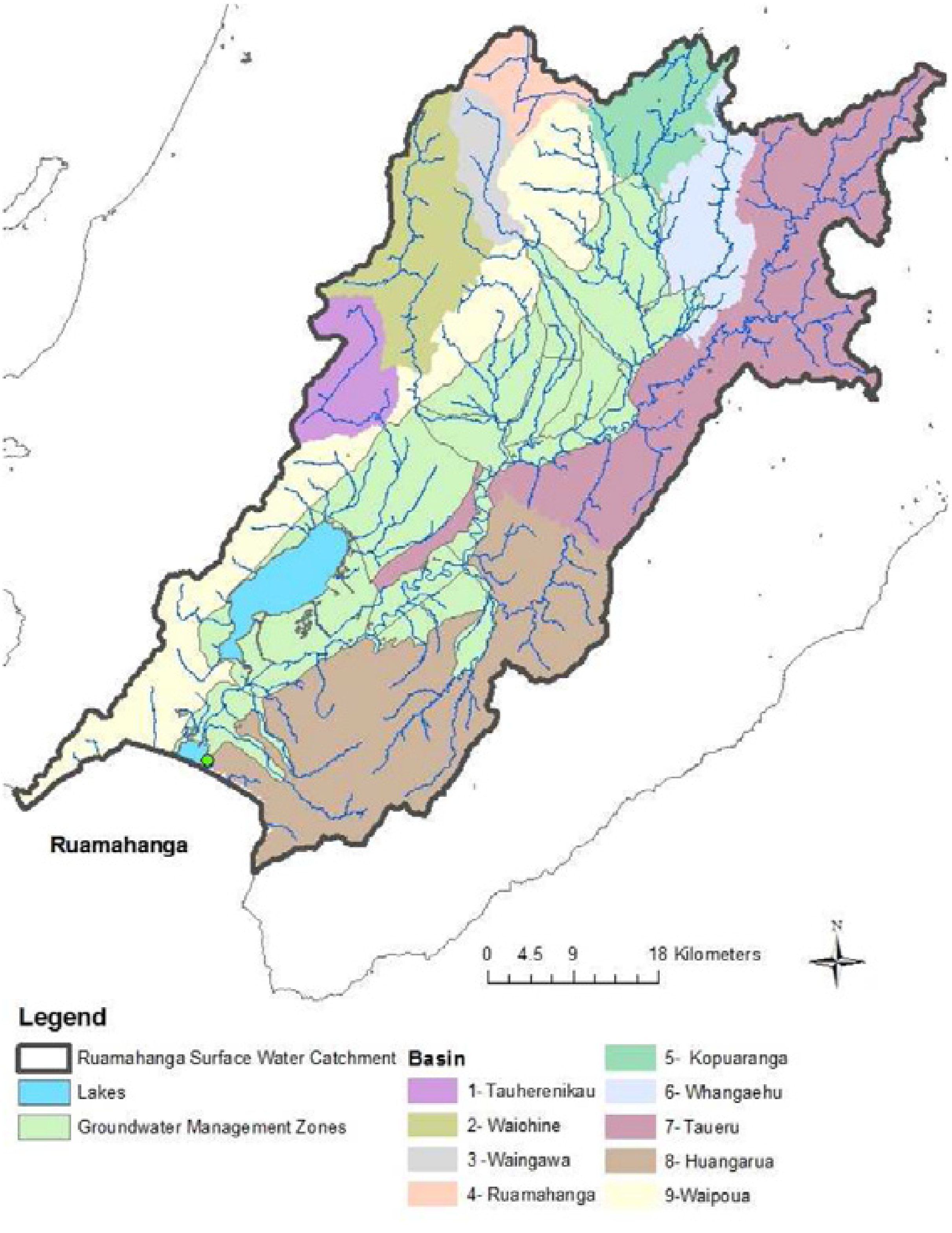


Figure 3-12: TopNet basin identifier for TopNet modelling of the Ruamahanga watershed.

4 Model calibration

4.1 Calibration methodology

TopNet calibration requires the calibration of parameter multipliers, as 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 above. TopNet requires the calibration 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 (2001-2003) has been chosen to represent diverse water resource hydrological conditions (e.g. annual flow below and above the observed mean annual flow at each of the gauging station) while validation was carried out over the 2003-2010 time period. In this application the calibration parameter set mainly represented low flow periods at each gauging station. 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 that aim to better represent low flow conditions. In addition further care was taken to ensure that the model parameters remained between physically reasonable limits.

For these nine watersheds, as no consented activities are impacting observed discharge at the gauging sites, calibration was carried out over both high peak 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 mode, 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 mismatch 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 Annual Flow (MAF) and 7 days Mean Annual Low Flow (7days MALF) characteristic 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 decile presented hereafter is 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. (to come)

The calibration/validation results and associated analysis is presented hereafter for each watershed.

4.2 Parameter sensitivity

The sensitivity analysis associated with the TopNet parameters reported for each catchment hereafter is not completed at this stage in the project. As a result the sensitivity analysis reported in this section is for the previous set of calibrated parameters and is used as a demonstration of the outputs of such a study.

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:

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

Where $d_i\left(X\right)$ is the local sensitivity measure at the random point $X = \left(x_1,\ldots,x_{i-1},x_i,\cdots,x_n\right)$, and Δ =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: one is the sample mean of absolute values of the elementary effects (μ^*) measuring the degree of parameter sensitivity, and the other is 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 calibrated catchment discharging to the GWZ area. Table 4-2 presents the TopNet parameters considered during the sensitivity analysis as well as their range.

Table 4-2: 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		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		0.05	10
canscap		0.1	15

Parameter name (internal name)	Parameter description	Minimum	Maximum
canenhf		0.1	15
salbedo		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.

Table 4-3 presents the result of the sensitivity analysis, in term of local sensitivity ranking, carried out for each catchment (identified by its most downstream reachID) 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 4-3: Local sensitivity ranking for each TopNet parameter. Catchment identified by their reach ID (Table 3.2)

Parameter name (internal name)	9259046	9257741	9254309	92553108	9250417	9252319	9252727	9257216	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

Analysis of the sensitivity results indicates that:

- Notwithstanding the extreme sensitivity of the model outputs to gucatch, in general sensitivity ranking indicates the saturated store sensitivity (topmodf) is the most sensitive parameter 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 parameter group is swater2 and dthetat. Swater2 controls the "soil depth" hydraulically active in TopNet, while dthetat controls the amount of soil moisture available in each subcatchment.
- The third group of parameters are 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, which control the reflectance of the land surface, r_man_n, which control the surface rugosity in the river system, and overvel, that controls the amount of Hortonian type surface runoff experienced by each subcatchment.

The sensitivity ranking obtained in Table 4-3 is compatible to the sensitivity ranking expected for any TopNet calibration. However it is important to stress that any sensitivity analysis is subject to model setup (e.g., climate information input), parameter range, and the chosen objective function. As a result it is expected that the sensitivity analysis outcome is dependant of the objective function used to calibrate the model.

4.3 Tauherenikau watershed

The accuracy of the streamflow model prediction is presented in Table 4-4 for the calibration phase and the validation phase. The final values of parameters are provided in Table 4-5. Table 4-6 provides the simulated water balance. Table 4-7 provides the simulated and observed MAF and 7 day MALF, while Table 4-8 presents the observed and simulated monthly average flows over the period of simulation.

Figures 4-1 and 4-2 present the simulation results at the streamflow gauging station in term 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 (ie for discharge below MAF) 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 4-4: Calibration- Validation statistics for Tauherenikau watershed.

	Calibration (2001-2003)		Validation (2004-2012)	
Location	NSlog	NS	NSlog	NS
Tauherenikau at Gorge	0.614	0.438	0.754	0.444

Table 4-5: TopNet parameters for Tauherenikau watershed.

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 4-6: Simulated water balance by TopNet for Tauherenikau watershed over the period 2003-2012

Annual Average Flux	TopNet (2004-2012) (mm/yr)	GWRC (2004-2012) (mm/yr)	GWRC (1976-2015) (mm/yr)	VCSN (1972-2014) (mm/yr)
Mean annual precipitation	3148	NA	NA	
Mean annual evaporation	494	NA	NA	
Mean annual runoff	2560	2514	2365	

Table 4-7: Simulated and Observed flow characteristics for Tauherenikau watershed over the period 2003-2012

Annual Average hydrological characteristics	TopNet (2004-2012) (m3/s)	GWRC (2004-2012) (m3/s)	GWRC (1976-2015) (m3/s)
Mean Annual Flow	8.606	8.529	9.100
7 days Mean Annual Low Flow	1.506	1.365	1.321

Table 4-8: **Simulated and Observed monthly average flows for Tauherenikau watershed over the period 2003-2012**

Annual Monthly Flows	Observed (2013-2012) (m3/s	TopNet (2003-2012) (m3/s))	Observed (1976-2015) (m3/s)
January	4.872	4.627	5.624
February	6.455	8.496	6.183
March	5.470	5.061	6.233
April	5.913	6.547	5,830
May	9.062	10.066	8.916
June	10.174	10.273	10.196
July	14.774	13.630	14.599
August	12.109	12.385	11.878
September	8.581	8.166	8.705
October	12.482	11.999	11.924
November	6.663	6.192	6.287
December	5.469	5.525	5.690

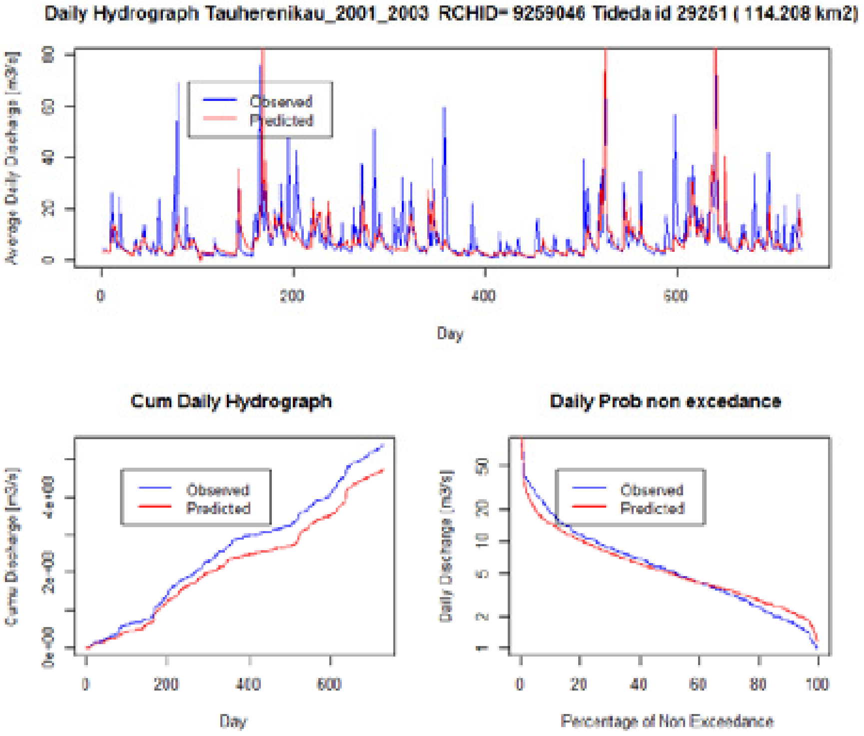


Figure 4-1: **Calibrated daily hydrograph-cumulative hydrograph and flow duration curve of Tauherenikau at Gorge over the calibration period 2001-2003. Flow duration curve flows are plotted in log scale.**

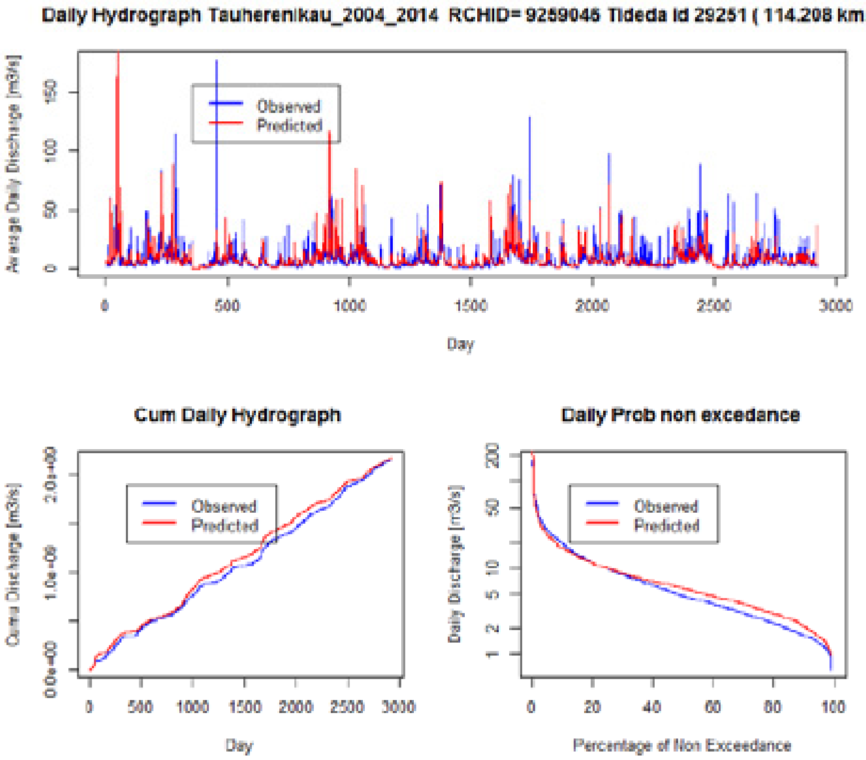


Figure 4-2: Simulated daily hydrograph-cumulative hydrograph and flow duration curve of Tauherenikau at Gorge over the validation period 2003-2010. Flow duration curve flows are plotted in log scale.

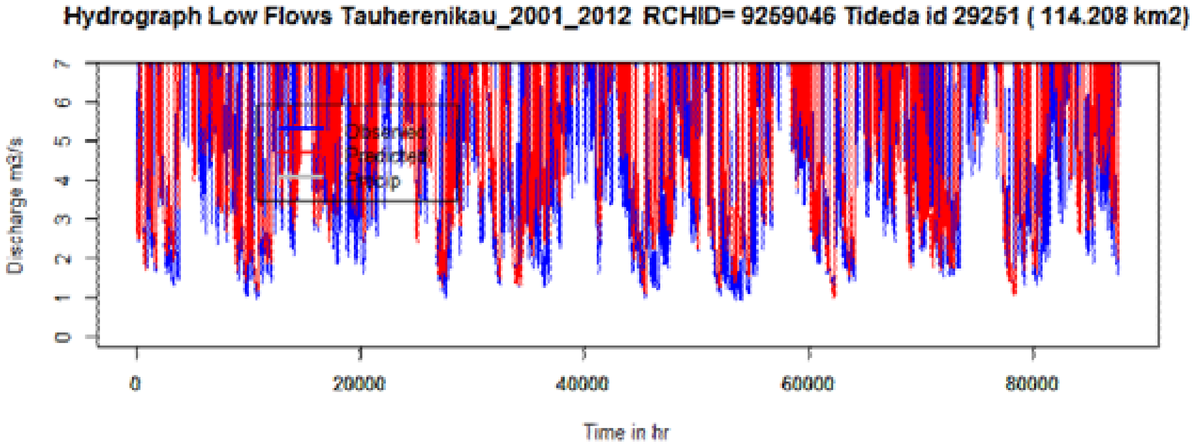


Figure 4-3: Observed and simulated hourly low flow hydrograph (i.e. flow below MAF) for Tauherenikau at Gorge over the calibration period and validation period.

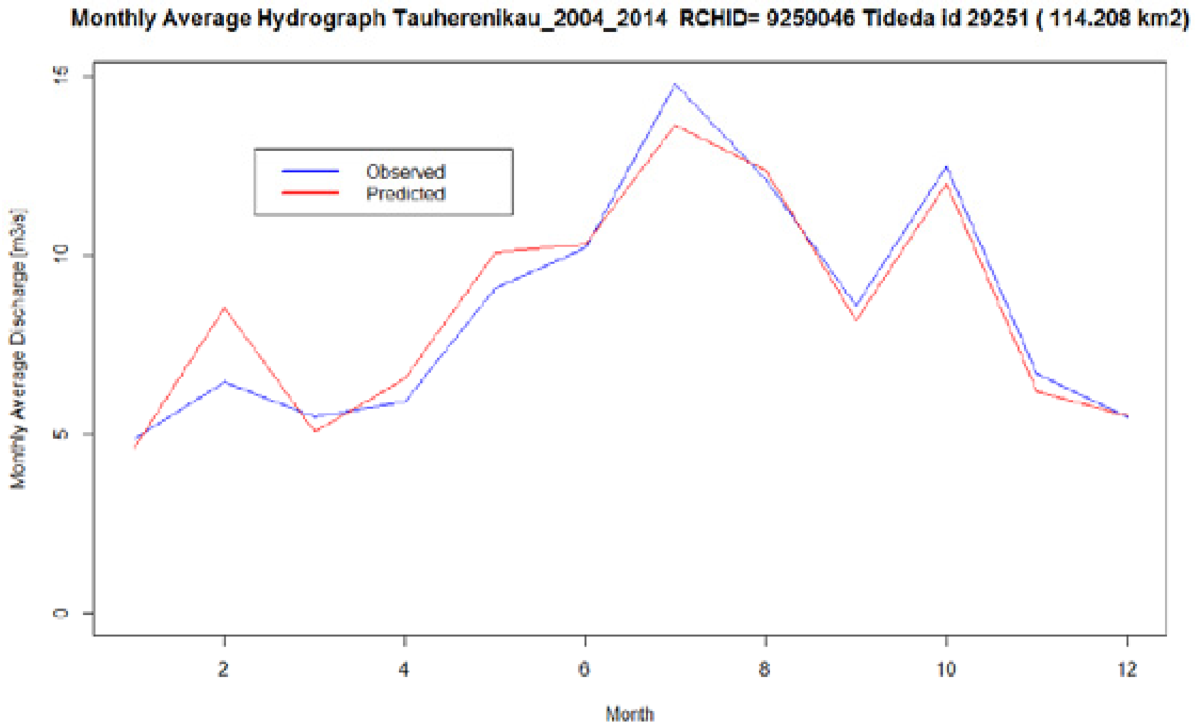


Figure 4-4: **Observed and simulated monthly average flow for Tauherenikau at Gorge over the period 2004-2012.**

Analysis of the simulations indicates:

- Analysis by GWRC of observed flow time series indicates that low flow measurements are subject to caution.
- The relatively low 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).
- The calibrated model is able to reproduce the hydrological behaviour (in term of MAF and 7 days MALF) encountered during simulation and validation periods. Hence timing and magnitude of seasonal change are correctly reproduced by the calibrated model.
- Low flow hydrological conditions tend to be slightly over-predicted (Figures 4-2to 4-3), especially in the flow recession component of the hydrographs (i.e. flows under 10 m^3/s). This is likely to be associated with the misrepresentation of subsurface soil processes, 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 MAF is correctly represented over the time of the model validation
- Seasonal flows are correctly reproduced except for February where larger errors 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 (Figure 4-2)

4.4 Waiohine watershed

The accuracy of the streamflow model prediction is presented in Table 4-9 for the calibration phase and the validation phase. The final values of parameters are provided in Table 4-10. Table 4-11 provides the simulated water balance. Table 4-12 provides the simulated and observed MAF and 7 day MALF, while Table 4-13 presents the observed and simulated monthly average flows over the period of simulation.

Figures 4-5 and 4-6 present the simulation results at the streamflow gauging station in term 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 MAF) 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 4-9: Calibration- validation statistics for Waiohine watershed.

	Calibration (2001-2003)		Validation (2004-2012)	
Location	NSlog	NS	NSlog	NS
Waiohine at Gorge	0.554	0.372	0.784	0.501

Table 4-10: TopNet parameters for Waiohine watershed.

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

Parameter name (internal name)	Parameter description	Calibrated value
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

Table 4-11: Simulated water balance by TopNet for Waiohine watershed over the period 2003-2012

Annual Average Flux	TopNet (2004-2012) (mm/yr)	GWRC (2004-2012) (mm/yr)	GWRC (1954-2015) (mm/yr)	VCSN (1972-2014) (mm/yr)
Mean annual precipitation	4297	NA	NA	
Mean annual evaporation	249	NA	NA	
Mean annual runoff	4009	4158	4348	

Table 4-12: Simulated and Observed flow characteristics for Waiohine watershed over the period 2003-2012

Annual Average hydrological characteristics	TopNet (2004-2012) (m3/s)	GWRC (2004-2012) (m^3/s)	GWRC (1954-2015) (m^3/s)
Mean Annual Flow	21.592	23.439	24.510
7 days Mean Annual Low Flow	6.000	3.603	7.601

Table 4-13: Simulated and Observed monthly average flows for Waiohine watershed over the period 2003-2012

Annual Monthly Flows	Observed (2004-2012) (m^3/s)	TopNet (2004-2012) (m^3/s)	Observed (1954-2015) (m^3/s
January	17.211	18.612	17.309
February	21.631	22.085	20.571
March	14.834	12.939	16.645
April	16.191	15.071	15.362
May	23.176	21.497	22.009
June	25.268	21.576	24.247
July	35.893	26.030	35.130
August	29.786	27.791	28.651
September	27.585	23.035	24.472

Annual Monthly Flows	Observed (2004-2012) (m³/s)	TopNet (2004-2012) (m³/s)	Observed (1954-2015) (m³/s
October	35.344	32.478	33.370
November	23.368	21.453	21.530
December	19.823	20.201	19.531

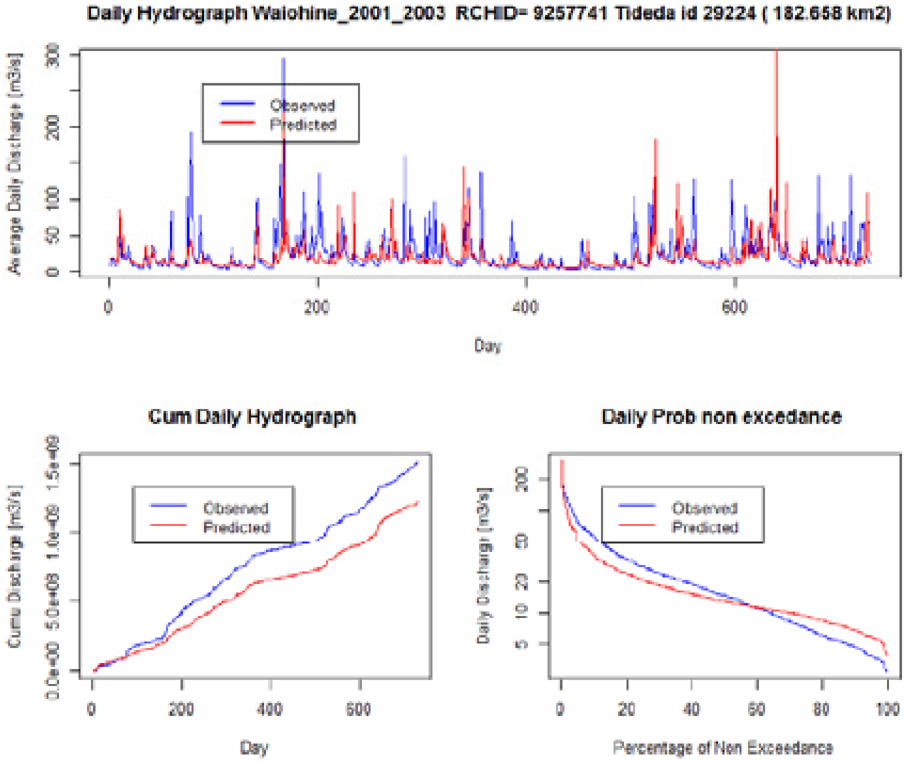


Figure 4-5: Calibrated hourly hydrograph of Waiohine at Gorge (new site) over the calibration period 2001-2003. Flows are plotted in log scale.

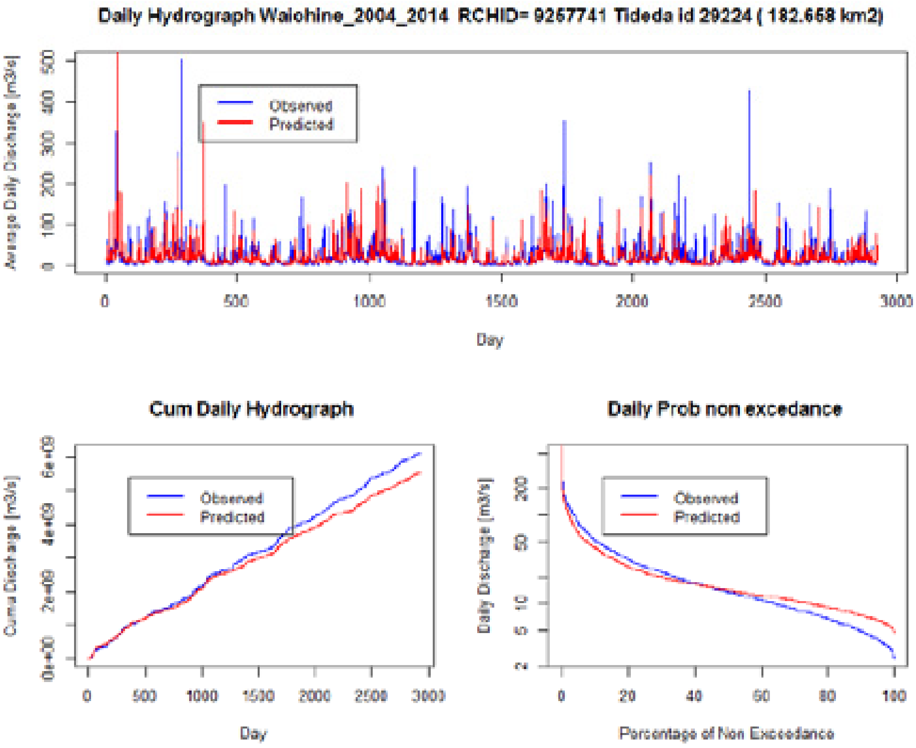


Figure 4-6: Simulated hourly hydrograph of Waiohine at Gorge(new site) Branch over the validation period 2008-2010. Flows are plotted in log scale.

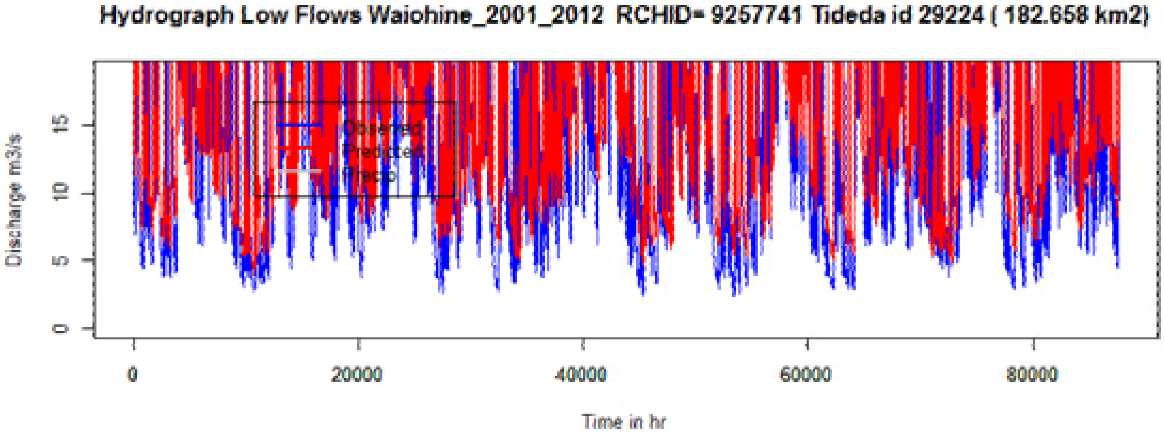


Figure 4-7: Observed and simulated hourly flow duration curve of Waiohine at Gorge(new site) Branch over the calibration period and validation period. Flows are plotted in log scale.

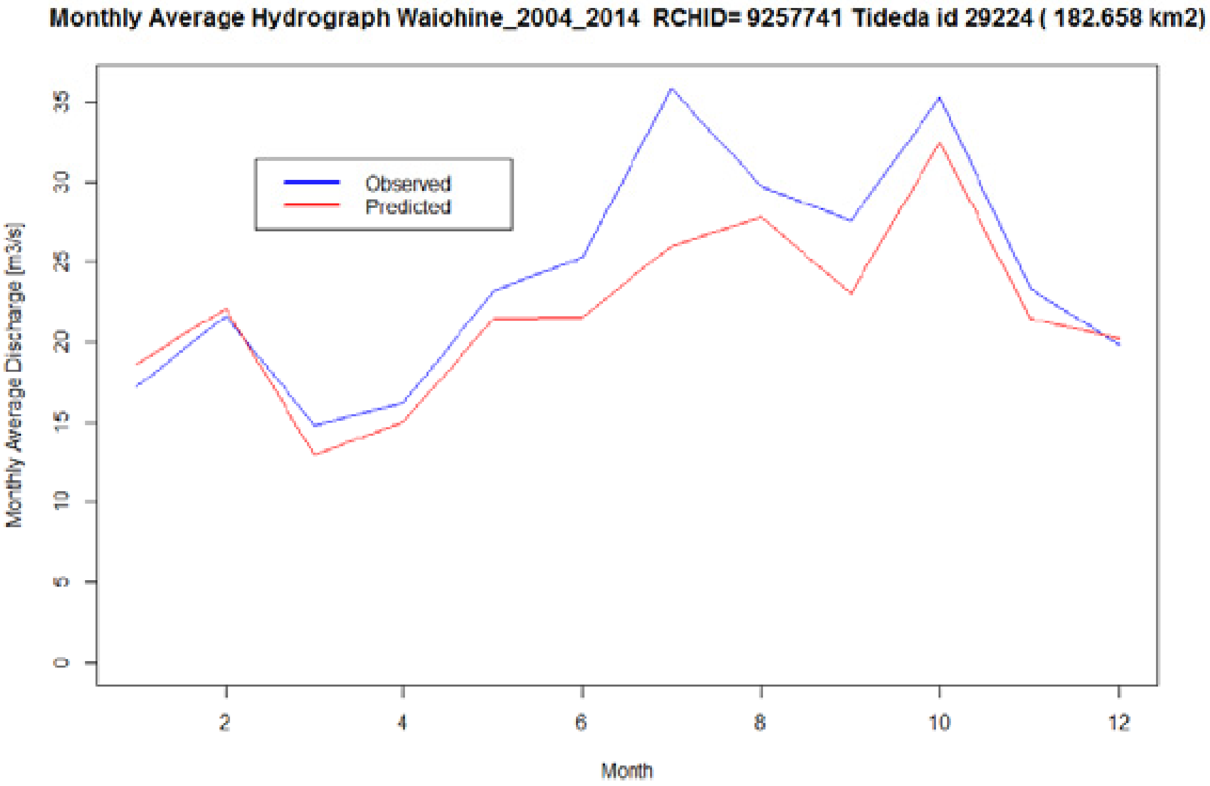


Figure 4-8: Observed and simulated monthly average flow for Waiohine at Gorge(new site) Branch over the validation period.

Analysis of the simulations indicates:

- Analysis by GWRC of observed flow time series indicates that high flow rating curve might have large uncertainties in high flow (following rating done in October 2000), but the current rating is considered to be of excellent quality at low flow conditions.
- The relatively low 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 underestimation of daily VCSN in the upper Waiohine catchment during winter 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 further analysis indicates that the TopNet model is consistently overestimating observed low flows.
- 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 in order to be able to reproduce correctly the average annual flow and the annual average catchment water balance.

- Low flow hydrological conditions tend to be over-predicted (Figures 4-7) by around 2m^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 processes, which are related to the soil and geological data used in this study.
- Seasonal flows are correctly reproduced (magnitude and timing) during the summer months. Magnitudes of the winter flows are largely under-predicted and this is thought to be associated with an under-representation of the winter precipitation magnitude in the upper Waiohine catchment.

4.5 Waingawa watershed

The accuracy of the streamflow model prediction is presented in Table 4-14 for the calibration phase and the validation phase. The final values of parameters are provided in Table 4-15. Table 4-16 provides the simulated water balance. Table 4-17 provides the simulated and observed MAF and 7 day MALF, while Table 4-18 presents the observed and simulated monthly average flows over the period of simulation.

Figures 4-9 and 4-10 present the simulation results at the streamflow gauging station in term 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 4-11 presents the observed and simulated hourly low flows hydrograph (i.e., for discharge below MAF) 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 4-14: Calibration- validation statistics for Waingawa watershed.

	Calibration (2001-2003)		Validation (2004-2012)	
Location	NSlog	NS	NSlog	NS
Waingawa at Upper Kaituna Branch	0.554	0.437	0.661	0.443

Table 4-15: TopNet parameters for Waingawa watershed.

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

Parameter name (internal name)	Parameter description	Calibrated value
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 4-16: Simulated water balance by TopNet for Waingawa watershed over the period 2003-2012

Annual Average Flux	TopNet (2004-2012) (mm/yr)	GWRC (2004-2012) (mm/yr)	GWRC (1976-2015) (mm/yr)	VCSN (1972-2014) (mm/yr)
Mean annual precipitation	4075	NA	NA	
Mean annual evaporation	123	NA	NA	
Mean annual runoff	3856	3917	4160	

Table 4-17: Simulated and Observed flow characteristics for Waingawa watershed over the period 2003-2012

Annual Average hydrological characteristics	TopNet (2004-2012) (m^3/s)	GWRC (2004-2012) (m^3/s)	GWRC (1976-2012) (m^3/s)
Mean Annual Flow	8.703	9.496	10.084
7 days Mean Annual Low Flow	1.489	1.362	1.405

Table 4-18: Simulated and Observed monthly average flows for Waingawa watershed over the period 2003-2012

Annual Monthly Flows	Observed (2004-2012) (m^3/s)	TopNet (2003-2012) (m^3/s)	Observed (1976-2015) (m^3/s)
January	6.136	6.907	6.392
February	8.533	8.788	8.221
March	5.915	5.563	6.705
April	6.390	6.541	6.230
May	9.850	8.923	9.553
June	10.984	8.738	10.624
July	14.400	10.714	14.377

Annual Monthly Flows	Observed (2004-2012) (m³/s)	TopNet (2003-2012) (m³/s)	Observed (1976-2015) (m³/s)
August	12.406	10.801	12.249
September	10.811	9.139	10.892
October	13.522	12.922	13.110
November	8.593	7.910	7.983
December	7.464	8.453	7.434

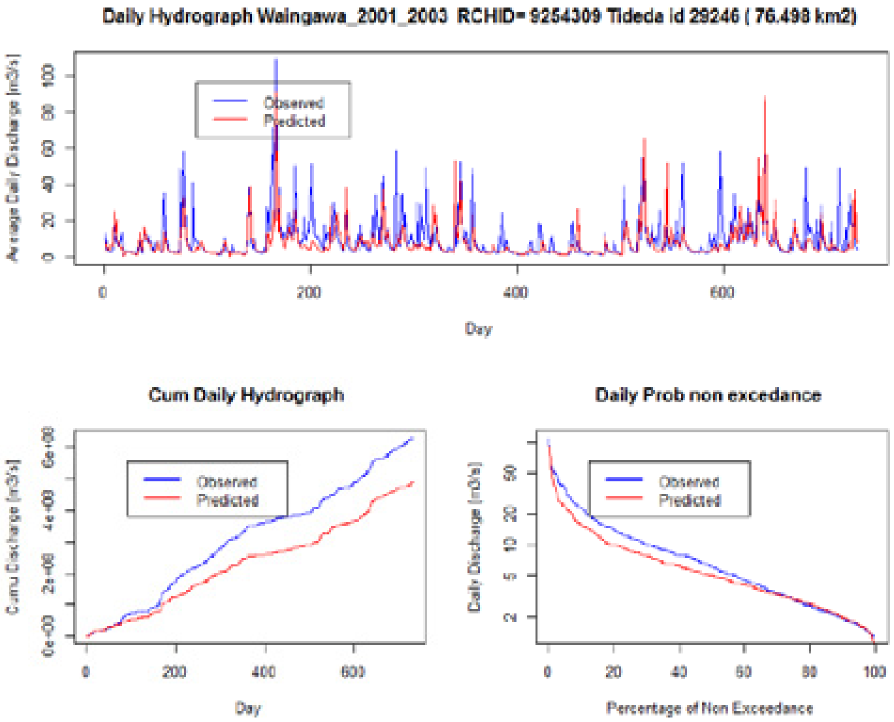


Figure 4-9: Calibrated hourly hydrograph of Waingawa at Upper Kaituna Branch over the calibration period 2001-2003. Flows are plotted in log scale.

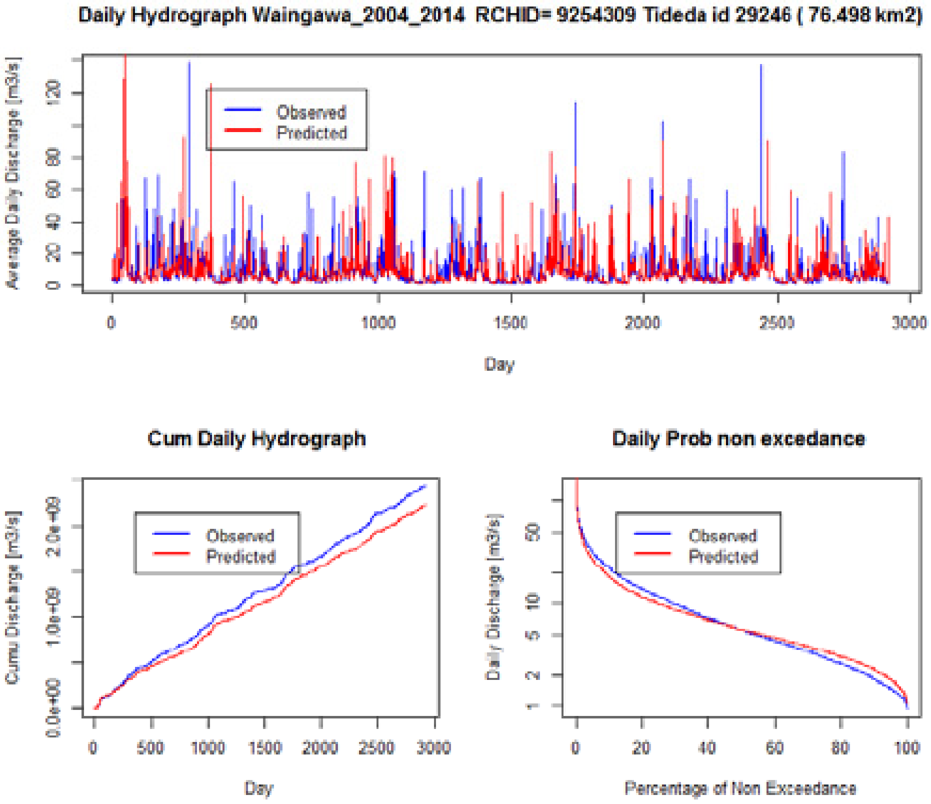


Figure 4-10: Simulated hourly hydrograph of Waingawa at Upper Kaituna Branch over the validation period 2008-2010. Flows are plotted in log scale.

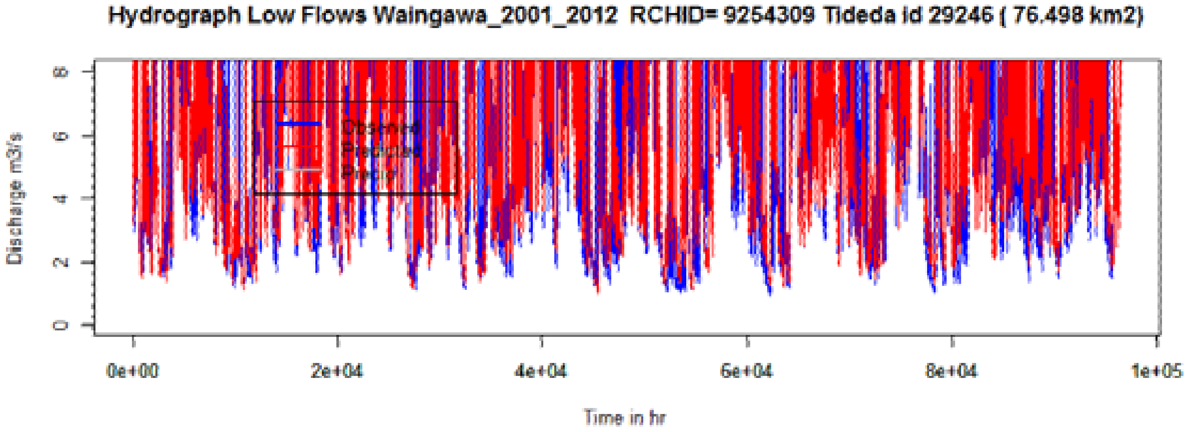


Figure 4-11: Observed and simulated hourly flow duration curve of Waingawa at Upper Kaituna Branch over the calibration period and validation period. Flows are plotted in log scale.

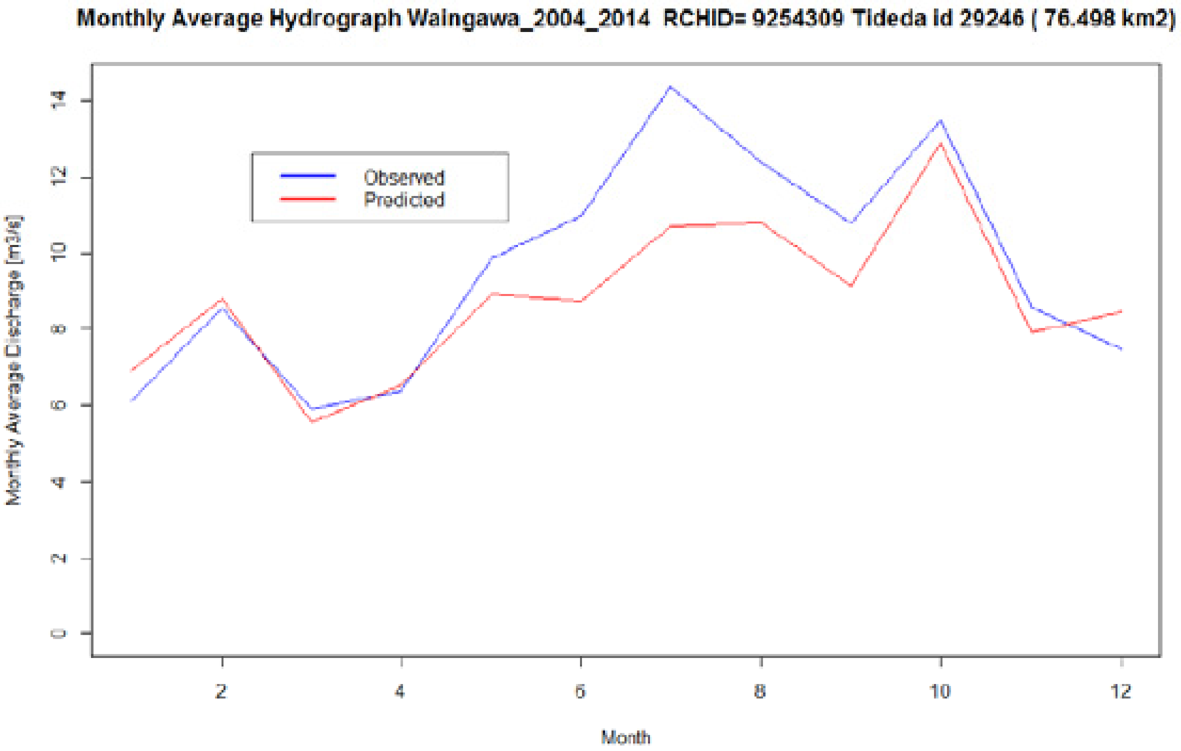


Figure 4-12: Observed and simulated monthly average flow for Waingawa at Upper Kaituna Branch over the validation period

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 relatively low NS score obtained during the calibration and validation period is linked to the underestimation of the peak discharges across all seasons (Figure 4-9-4-10). This can be seen on Figure 4-9 where observed discharge below 5 m^3/s are consistently underestimated.
- 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.
- The calibrated model is able to reproduce the hydrological behaviour (MAF and 7 days MALF) encountered during simulation and validation periods. Hence timing and magnitude of seasonal change are correctly reproduced by the calibrated model. The current underestimation of the MAF is linked to the underestimation of the winter precipitation and corresponding winter discharge(Figure 4-12- Appendix A-XX)
- 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 in order to be able to

reproduce correctly the average annual flow and the annual average catchment water balance.

- 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 watershed

The accuracy of the streamflow model prediction is presented in Table 4-19 for the calibration phase and the validation phase. The final values of parameters are provided in Table 4-20. Table 4-21 provides the simulated water balance. Table 4-22 provides the simulated and observed MAF and 7 day MALF, while Table 4-23 presents the observed and simulated monthly average flows over the period of simulation.

Figures 4-13 and 4-14 present the simulation results at the streamflow gauging station in term 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 (ie for discharge below MAF) 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

Table 4-19: Calibration- validation statistics for Waipoua watershed.

	Calibration (2007-2009)		Validation (2004-2012)	
Location	NSlog	NS	NSlog	NS
Waipoua at Mikimiki	0.571	0.520	0.572	0.604

Table 4-20: TopNet parameters for Waipoua watershed.

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

Parameter name (internal name)	Parameter description	Calibrated value
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 4-21: Simulated water balance by TopNet for Waipoua watershed over the period 2010-2012

Annual Average Flux	TopNet (2010-2012) (mm/yr)	GWRC (2010-2012) (mm/yr)	GWRC (1979-2015) (mm/yr	VCSN (1972-2014) (mm/yr)
Mean annual precipitation	2497	NA	NA	
Mean annual evaporation	1120	NA	NA	
Mean annual runoff	1304	1407	2143	

Table 4-22: Simulated and Observed flow characteristics for Waipoua watershed over the period 2010-2012

Annual Average hydrological characteristics	TopNet (2010-2012) (m3/s)	GWRC (2010-2012) (m3/s)	GWRC (1979-2015) (m3/s
Mean Annual Flow	3.208	3.562	5.423
7 days Mean Annual Low Flow	0.250	0.449	1.129

Table 4-23: Simulated and Observed monthly average flows for Waipoua watershed over the period 2010-2012

Annual Monthly Flows	Observed (2010-2012) (m3/s)	TopNet (2010-2012) (m3/s)	GWRC (2007-2015) (m3/s
January	2.202	1.190	2.234
February	1.498	0.850	1.520
March	2.224	1.586	2.190
April	1.479	2.549	1.494
May	3.157	4.718	3.143
June	4.110	5.469	4.097
July	7.848	7.458	7.759
August	6.492	5.269	6.419
September	4.930	2.966	4.864

Annual Monthly Flows	**Observed (2010-2012) (m3/s)**	**TopNet (2010-2012) (m3/s)**	**GWRC (2007-2015) (m3/s**
October	5.799	3.013	5.683
November	1.617	0.918	1.771
December	1.194	0.637	1.424

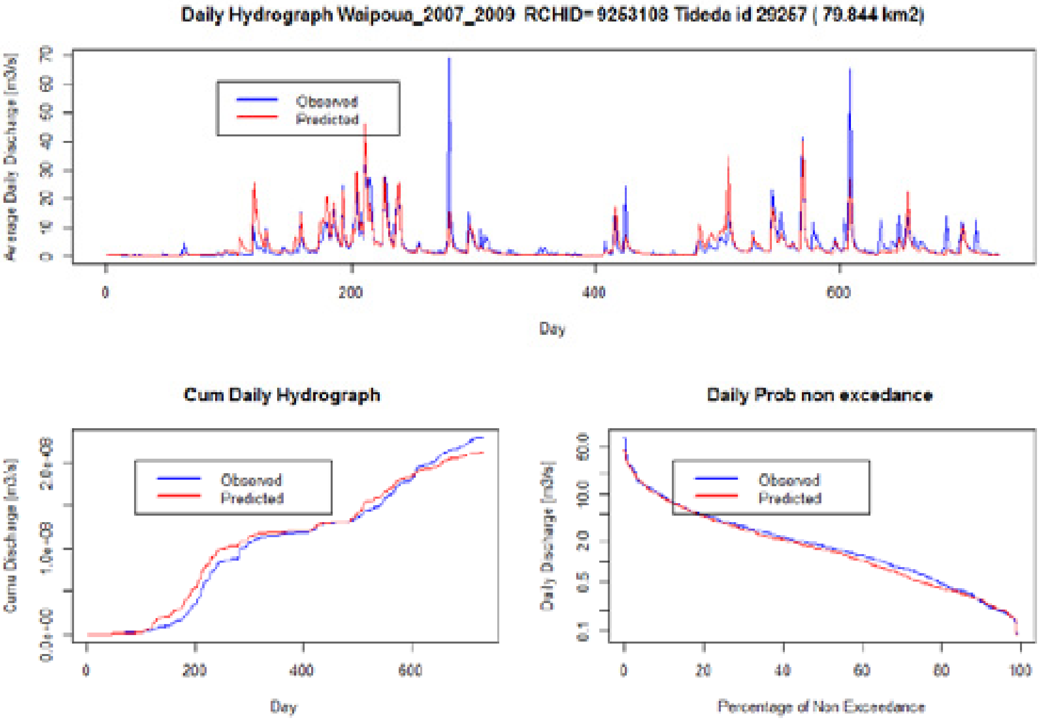


Figure 4-13: Calibrated hourly hydrograph of Waipoua at Mikimiki over the calibration period 2001-2003. Flows are plotted in log scale.

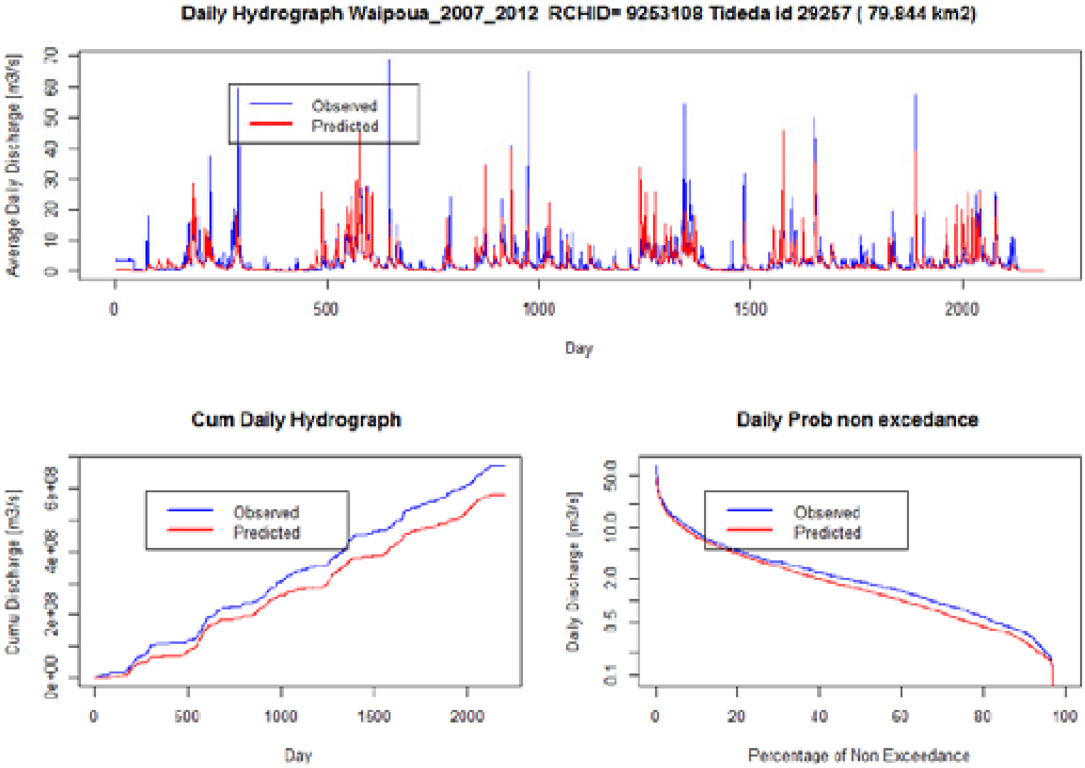


Figure 4-14: Simulated hourly hydrograph of Waipoua at Mikimiki over the validation period 2008-2010. Flows are plotted in log scale.

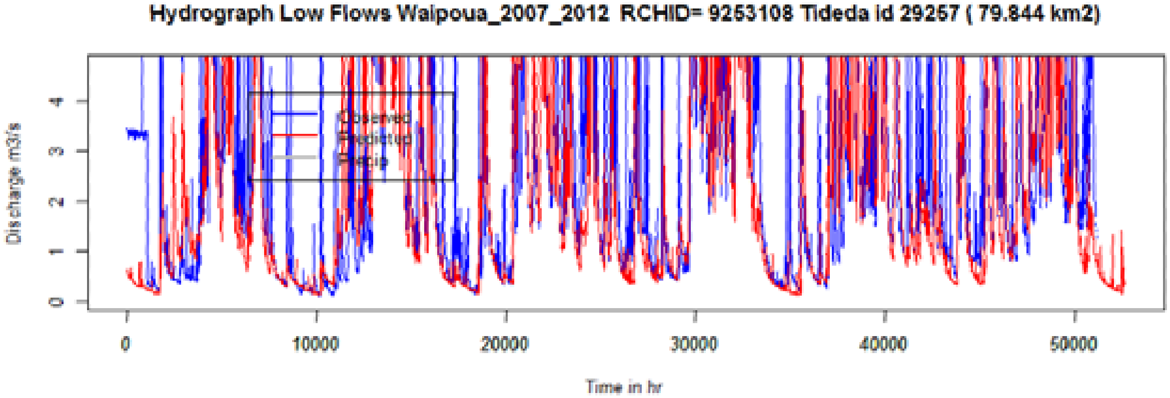


Figure 4-15: Observed and simulated hourly flow duration curve of Waipoua at Mikimiki over the calibration period and validation period. Flows are plotted in log scale.

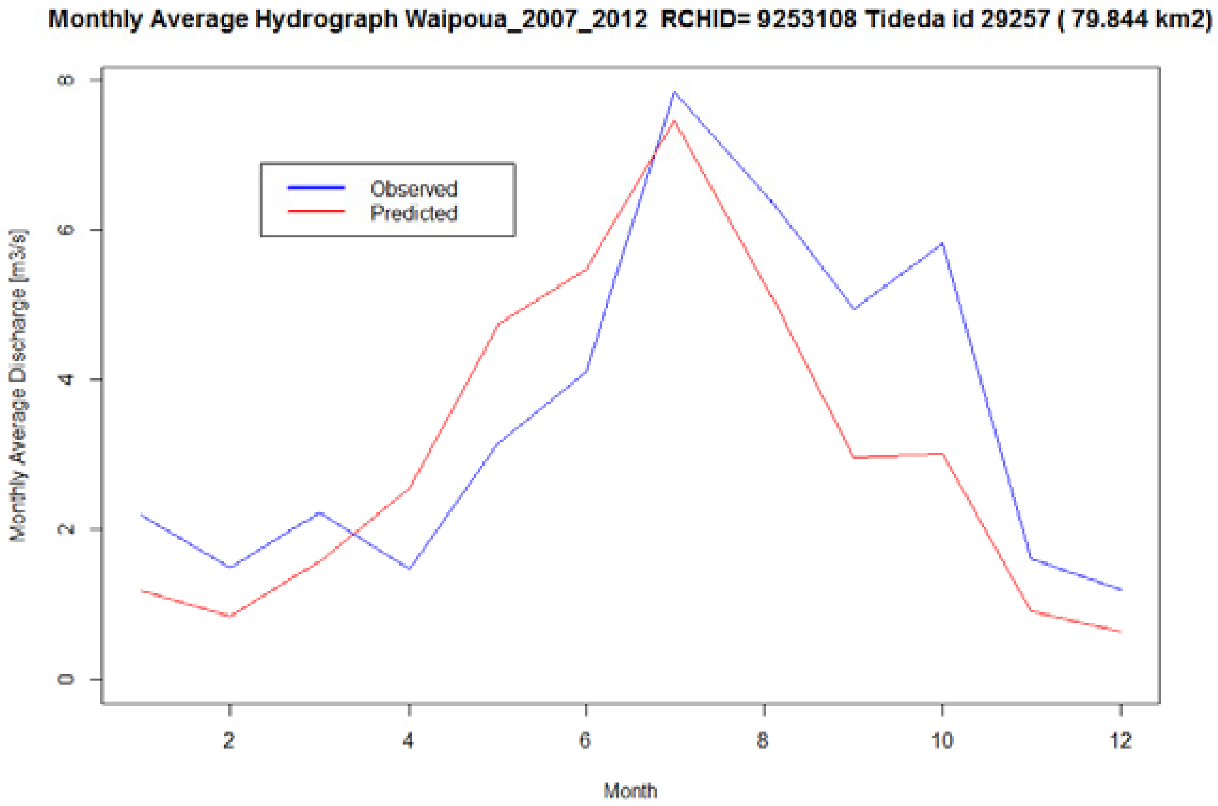


Figure 4-16: Observed and simulated monthly average flow for Waipoua at Mikimiki over the validation period

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 2007 to record both high and low flows. However marked degradation is still occurring during high flood events. In addition low flow statistics were derived from a correlation between 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.
- The relatively reasonable NS score obtained during the calibration and validation period is linked to the relative 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 daily VCSN in the upper Waipoua catchment over the period simulated, but cannot be verified as no GWRC precipitation gauge are present in the catchment.
- 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 low flow are reproduced as well as high glows

by TopNet. However further analysis indicates that the TopNet model is consistently underestimating observed low flows (Figure 4-14).

- Annual average evaporation estimated by TopNet is higher than the expected long term average annual evaporation across the catchment
- Low flow hydrological conditions tend to be correctly reproduced (Figure 4-15). However small discharge event occurring around low flow conditions are not correctly reproduced. This is thought to be associated with a misrepresentation in TopNet of the sub-daily precipitation.
- Seasonal flows are correctly reproduced (timing) all year around, however large errors are present in the magnitude of the discharge.

4.7 Ruamahanga Mt Bruce watershed

The accuracy of the streamflow model prediction is presented in Table 4-23 for the calibration phase and the validation phase. The final values of parameters are provided in Table 4-24. Table 4-25 provides the simulated water balance. Table 4-26 provides the simulated and observed MAF and 7 day MALF, while Table 4-27 presents the observed and simulated monthly average flows over the period of simulation.

Figures 4.17 and 4.18 present the simulation results at the streamflow gauging station in term 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 (ie for discharge below MAF) 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 4-24: Calibration- Validation statistics for Ruamahanga watershed.

	Calibration (2001-2003)		Validation (2004-2012)	
Location	NSlog	NS	NSlog	NS
Ruamahanga at Mt Bruce	0.501	0.318	0.630	0.427

Table 4-25: TopNet parameters for Ruamahanga watershed.

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

Parameter name (internal name)	Parameter description	Calibrated value
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 4-26: Simulated water balance by TopNet for Ruamahanga watershed over the period 2003-2012

Annual Average Flux	TopNet (2004-2012) (mm/yr)	GWRC (2004-2012) (mm/yr)	GWRC (1975-2012) (mm/yr)	VCSN (1972-2014) (mm/yr)
Mean annual precipitation	4994	NA		
Mean annual evaporation	161	NA		
Mean annual runoof	4746	4086	4013	

Table 4-27: Simulated and Observed flow characteristics for Ruamahanga watershed over the period 2003-2012

Annual Average hydrological characteristics	TopNet (2004-2012) (m3/s)	GWRC (2004-2012) (m3/s)	GWRC (1975-2015) (m3/s)
Mean Annual Flow	9.371	10.192	10.010
7 days Mean Annual Low Flow	1.194	1.245	1.315

Table 4-28: Simulated and Observed monthly average flows for Ruamahanga Mt Bruce watershed over the period 2003-2012

Annual Monthly Flows	Observed (1976-2012) (m3/s)	TopNet (2003-2012) (m3/s)	GWRC (1975-2015) (m3/s
January	6.022	7.275	6.866
February	10.260	11.089	9.163
March	6.430	5.859	6.728
April	6.238	6.257	6.485
May	9.842	8.785	9.544
June	12.216	8.538	11.590
July	15.277	12.995	14.313
August	14.891	12.413	12.824

Annual Monthly Flows	Observed (1976-2012) (m3/s)	TopNet (2003-2012) (m3/s)	GWRC (1975-2015) (m3/s
September	10.226	7.924	12.199
October	17.126	14.221	14.612
November	10.600	8.317	9.262
December	9.255	8.696	8.590

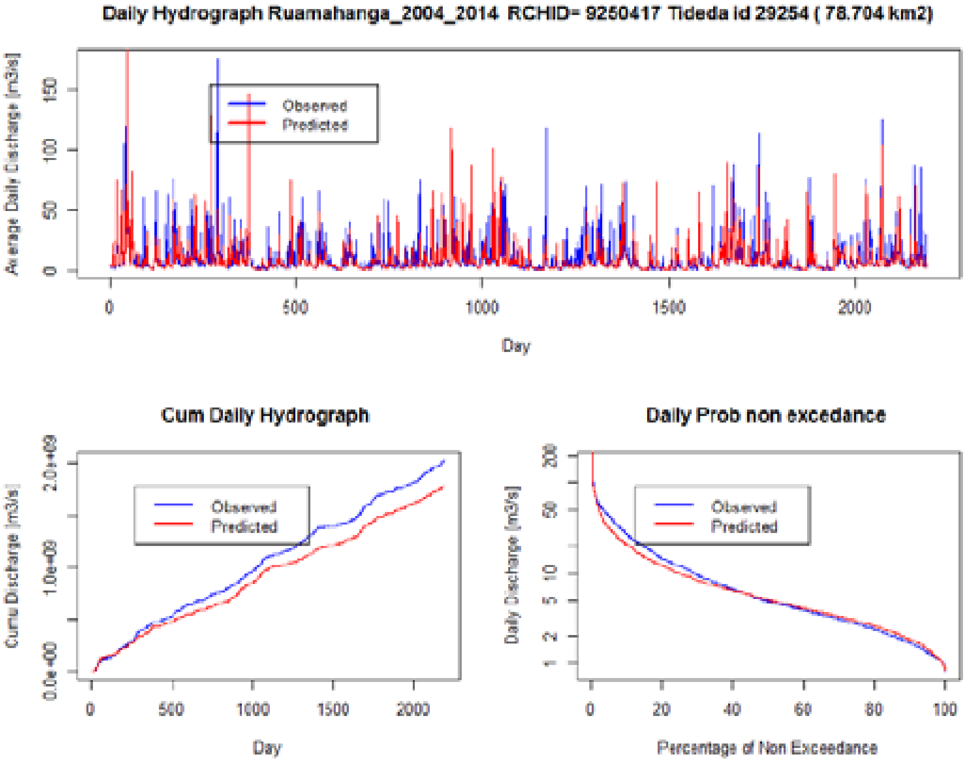


Figure 4-17: Calibrated hourly hydrograph of Ruamahanga at Mt Bruce over the calibration period 2001-2003. Flows are plotted in log scale.

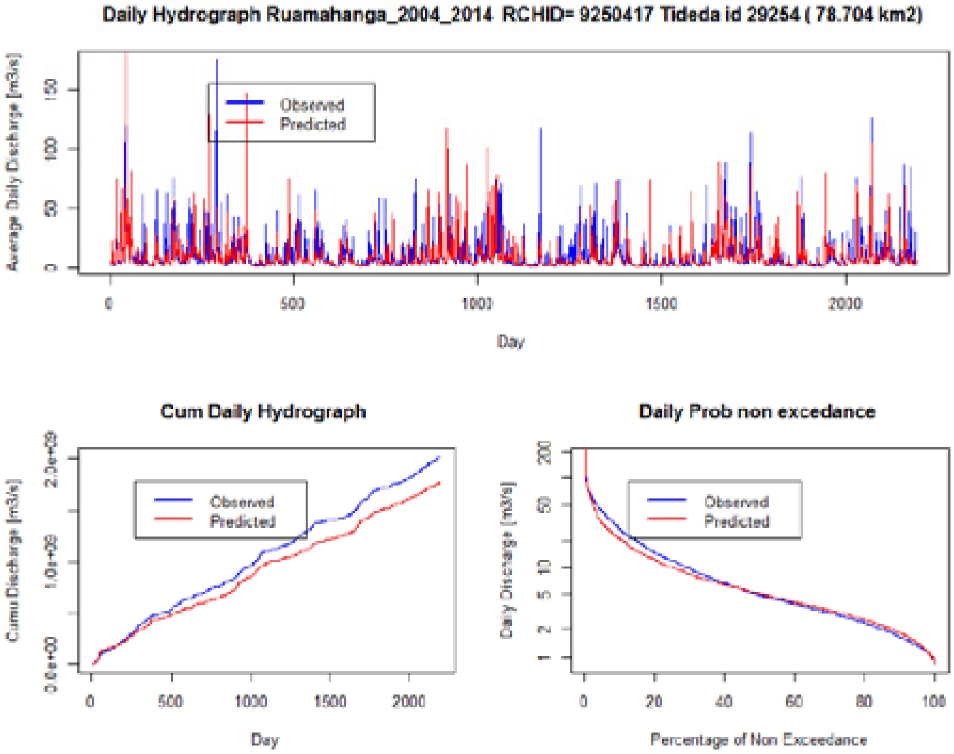


Figure 4-18: Simulated hourly hydrograph of Ruamahanga at Mt Bruce over the validation period 2008-2010. Flows are plotted in log scale.

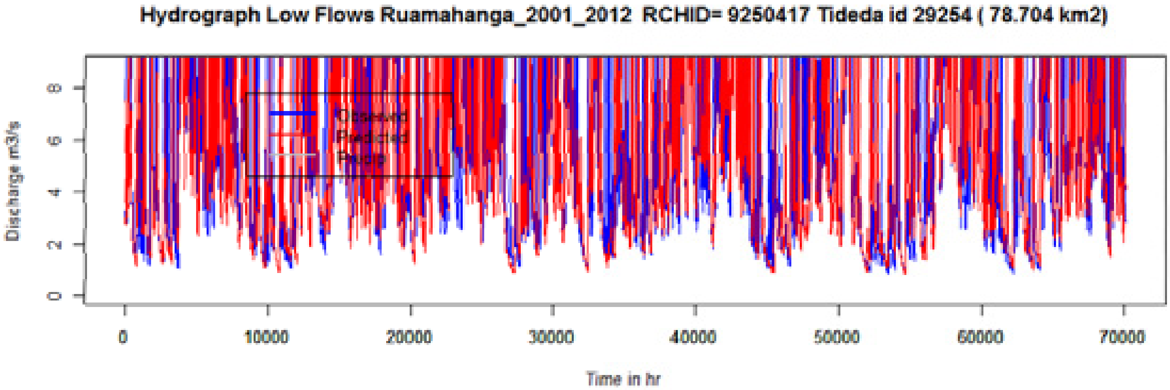


Figure 4-19: Observed and simulated hourly flow duration curve of Ruamahanga at Mt Bruce UpperStem over the calibration period and validation period. Flows are plotted in log scale.

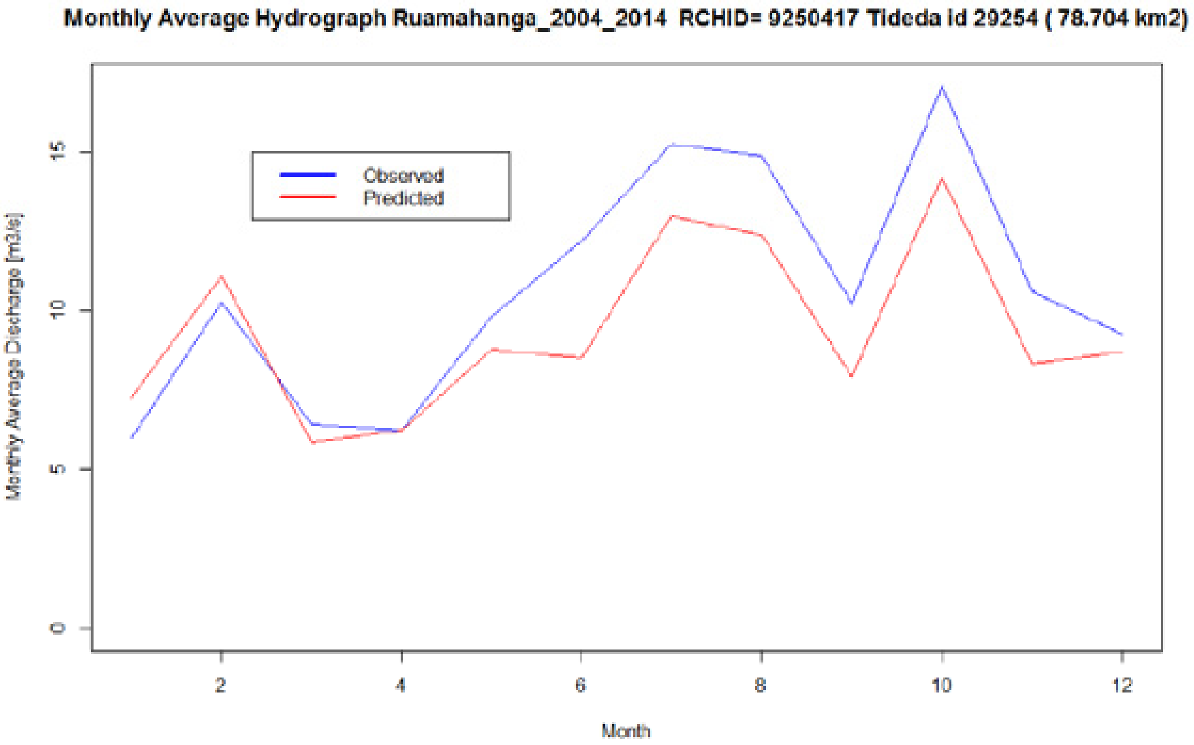


Figure 4-20: Observed and simulated monthly average flow for Ruamahanga at Mt Bruce UpperStem over the validation period

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 relatively low NS score obtained during the calibration and validation period is linked to the underestimation of the high flows (i.e. flow having a probability of exceedance of less than 40%- (Figure 4-17 and Figure 4-18*)*
- Analysis by GWRC of observed flow time series indicates that high flow rating curve might have large uncertainties in high flow (following rating done in October 2000), but the current rating is considered to be of excellent quality at low flow conditions.
- The calibrated model is able to reasonably reproduce observed low flows (based on NS Log score) for most of the time during the calibration and validation period. However further analysis indicates that the TopNet model is consistently overestimating observed low flows.
- 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 in order to be able to

reproduce correctly the average annual flow and the annual average catchment water balance.

- Seasonal flows are correctly reproduced (magnitude and timing) during the summer months. Magnitude of the winter flows are largely under-predicted and this is thought to be associated with an underrepresentation of the winter precipitation magnitude in the Ruamahanga Mt Bruce catchment.

4.8 Kopuaranga watershed

The accuracy of the streamflow model prediction is presented in Table 4-28 for the calibration phase and the validation phase. The final values of parameters are provided in Table 4-29. Table 4-30 provides the simulated water balance. Table 4-31 provides the simulated and observed MAF and 7 day MALF, while Table 4-32 presents the observed and simulated monthly average flows over the period of simulation.

Figures 4.21 and 4.22 present the simulation results at the streamflow gauging station in term 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 4-23 presents the observed and simulated hourly low flows hydrograph (ie for discharge below MAF) 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 4-29: Calibration- Validation statistics for Kopuaranga watershed.

	Calibration (2001-2003)		Validation (2004-2012)	
Location	NSlog	NS	NSlog	NS
Kopuaranga at Palmers Br	0.665	0.740	0.620	0.571

Table 4-30: TopNet parameters for Kopuaranga watershed.

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

Parameter name (internal name)	Parameter description	Calibrated value
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 4-31: Simulated water balance by TopNet for Kopuaranga watershed over the period 2003-2012

Annual Average Flux	TopNet (2004-2012) (mm/yr)	GWRC (2004-2012) (mm/yr)	GWRC (1985-2015) (mm/yr)	VCSN (1972-2014) (mm/yr)
Mean annual precipitation	2076	NA		
Mean annual evaporation	737	NA		
Mean annual runoof	1297	899	807	

Table 4-32: Simulated and Observed flow characteristics for Kopuaranga watershed over the period 2003-2012

Annual Average hydrological characteristics	TopNet (2004-2012) (m3/s)	GWRC (20042012) (m3/s)	GWRC (1985-2015) (m3/s)
Mean Annual Flow	3.208	2.868	2.575
7 days Mean Annual Low Flow	0.197	0.316	0.317

Table 4-33: Simulated and Observed monthly average flows for Kopuaranga watershed over the period 2003-2012

Annual Monthly Flows	Observed (1976-2012) (m3/s	) TopNet (2003-2012) (m3/s)	GWRC (1985-2015) (m3/s)
January	1.188	1.005	1.678
February	2.371	2.929	2.041
March	1.050	1.373	1.323
April	1.147	1.945	1.268
May	2.550	4.117	2.512
June	4.533	5.158	4.269
July	5.101	7.194	5.518
August	5.449	5.265	4.954
September	2.370	1.994	3.260

Annual Monthly Flows	Observed (1976-2012) (m3/s	) TopNet (2003-2012) (m3/s)	GWRC (1985-2015) (m3/s)
October	5.227	4.281	4.419
November	1.835	1.659	1.670
December	1.505	1.470	1.209

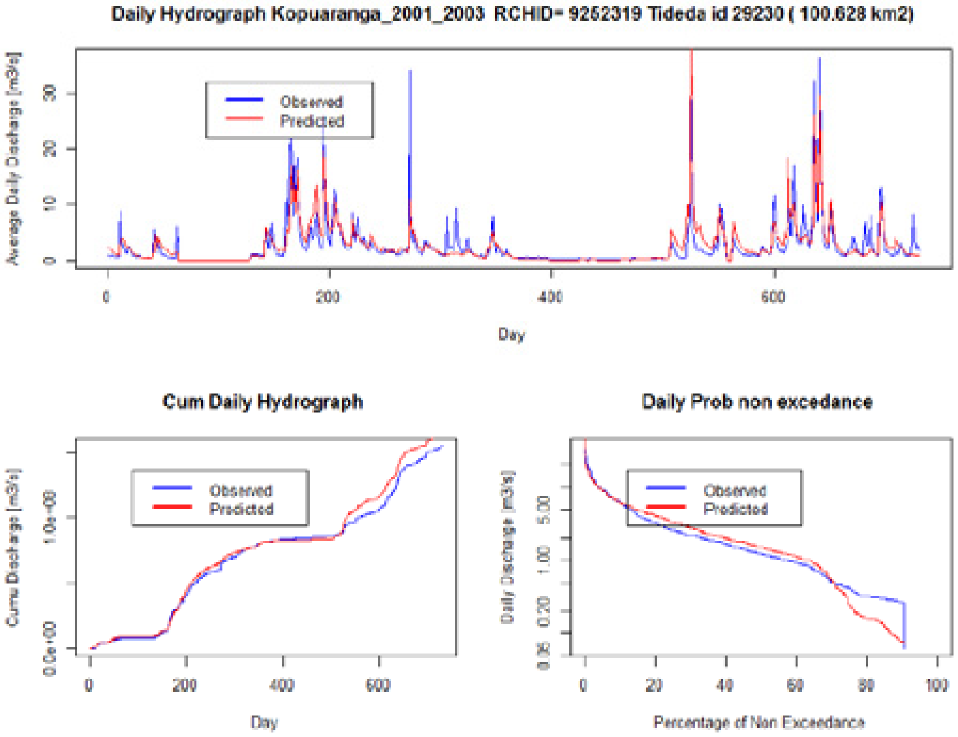


Figure 4-21: Calibrated hourly hydrograph of Kopuaranga at Palmers Br over the calibration period 2001-2003. Flows are plotted in log scale.

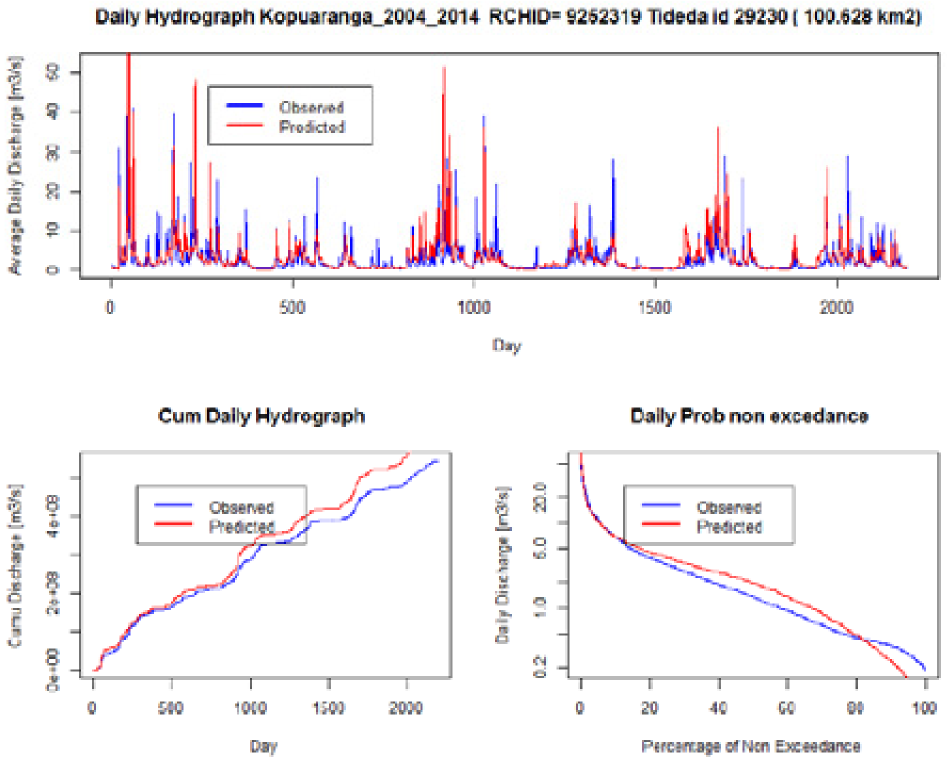


Figure 4-22: Simulated hourly hydrograph of Kopuaranga at Palmers Br over the validation period 2008-2010. Flows are plotted in log scale.

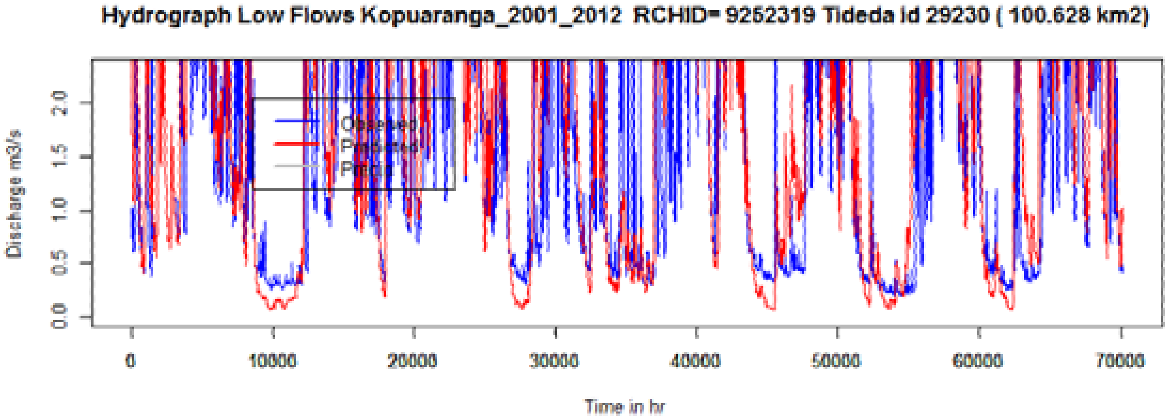


Figure 4-23: Observed and simulated hourly flow duration curve of Kopuaranga at Palmers Br Branch over the calibration period and validation period. Flows are plotted in log scale.

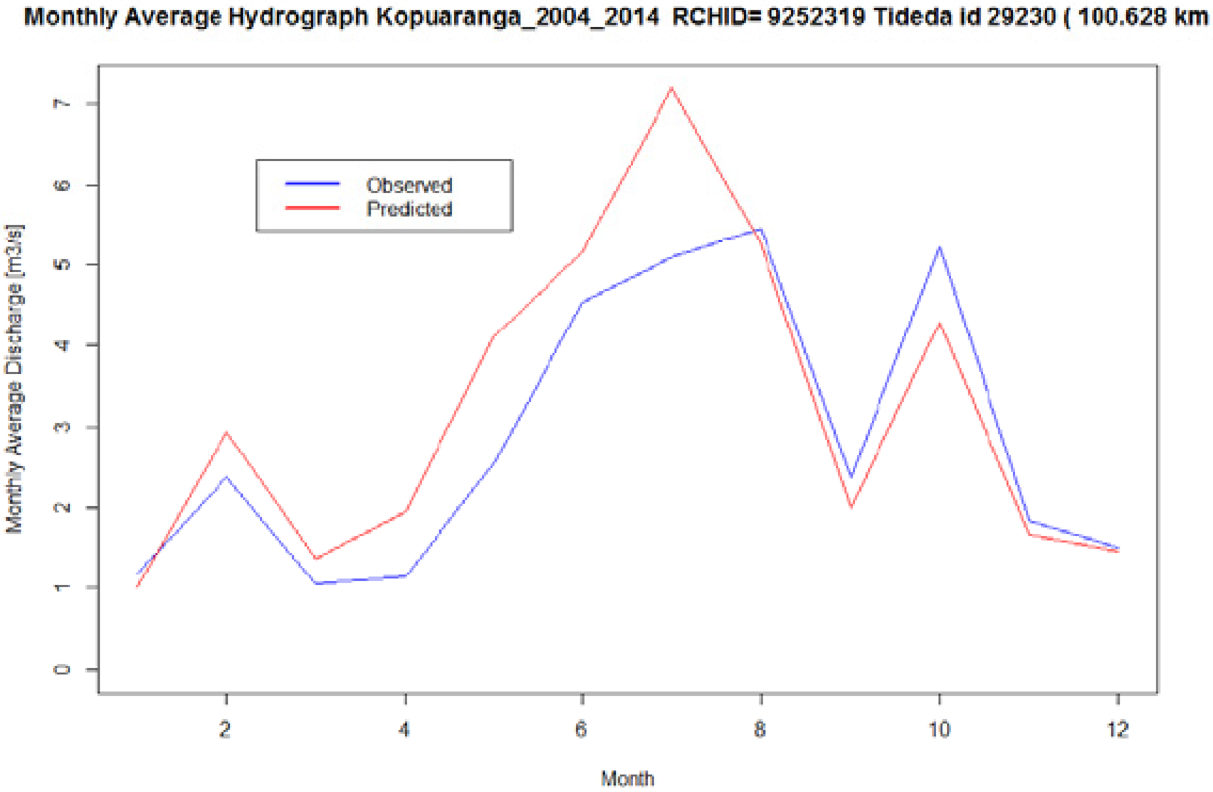


Figure 4-24: Observed and simulated monthly average flow for Kopuaranga at at Palmers Br Branch over the validation period

Analysis of the simulations indicates:

- The relatively high NZ and NS Log scores during the calibration period indicate that the hydrological model is correctly mimicking the catchment hydrological behaviour across flood and recession characteristics. However these flood characteristics tend to be reduced during the validation period and this is thought to be linked with over-prediction of the discharge in the mid to high range (Figure 4-22)
- Analysis by GWRC of observed flow time series indicates that high flow rating curve might have large uncertainties in high flow (following rating done in October 2000), but the current rating is considered to be of excellent quality at low flow conditions.
- The calibrated model is able to reasonably reproduce observed low flows (based on NS Log 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.
- 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 in order to be able to reproduce correctly the average annual flow and the annual average catchment water balance.

- Seasonal flows are correctly reproduced (magnitude and timing) during the summer months. Magnitude of the winter flows are largely under-predicted and this is thought to be associated with an underrepresentation of the winter precipitation magnitude in the upper Kopuaranga catchment.

4.9 Whangaehu watershed

The accuracy of the streamflow model prediction is presented in Table 4-33 for the calibration phase and the validation phase. The final values of parameters are provided in Table 4-34. Table 4-35 provides the simulated water balance. Table 4-36 provides the simulated and observed MAF and 7 day MALF, while Table 4-37 presents the observed and simulated monthly average flows over the period of simulation.

Figures 4.25 and 4.26 present the simulation results at the streamflow gauging station in term 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 (ie for discharge below MAF) 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 4-34: Calibration- Validation statistics for Whangaehu watershed.

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

Table 4-35: TopNet parameters for Whangaehu watershed.

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

Parameter name (internal name)	Parameter description	Calibrated value
Gauge Undercatch (gucatch)	Adjustment for non-representative precipitation	0.907* default

Table 4-36: Simulated water balance by TopNet for Whangaehu watershed over the period 2003-2012

Annual Average Flux	TopNet (2004-2012) (mm/yr)	GWRC (2004-2012) (mm/yr)	GWRC (2008-2016) (mm/yr	VCSN (1972-2014) (mm/yr)
Mean annual precipitation	1410			
Mean annual evaporation	734			
Mean annual runoof	636	509	451	

Table 4-37: Simulated and Observed flow characteristics for Whangaehu watershed over the period 2003-2012

Annual Average hydrological characteristics	TopNet (2004-2012) (m3/s)	GWRC (2004-2012) (m3/s)	GWRC (2008-2016) (mm/yr
Mean Annual Flow	0.571	0.617	0.526
7 days Mean Annual Low Flow	0.031	0.028	0.024

Table 4-38: Simulated and Observed monthly average flows for Whangaehu watershed over the period 2003-2012

Annual Monthly Flows	Observed (1976-2012) (m3/s)	TopNet (2003-2012) (m3/s)	
January	0.132	0.156	0.559
February	0.588	0.572	0.193
March	0.117	0.130	0.470
April	0.145	0.230	0.217
May	0.495	0.856	0.414
June	1.136	1.224	1.021
July	1.685	1.733	1.699
August	1.320	1.051	1.072
September	0.452	0.243	0.896
October	0.969	0.400	0.694

Annual Monthly Flows	Observed (1976-2012) (m3/s)	TopNet (2003-2012) (m3/s)	
November	0.190	0.159	0.203
December	0.153	0.085	0.109

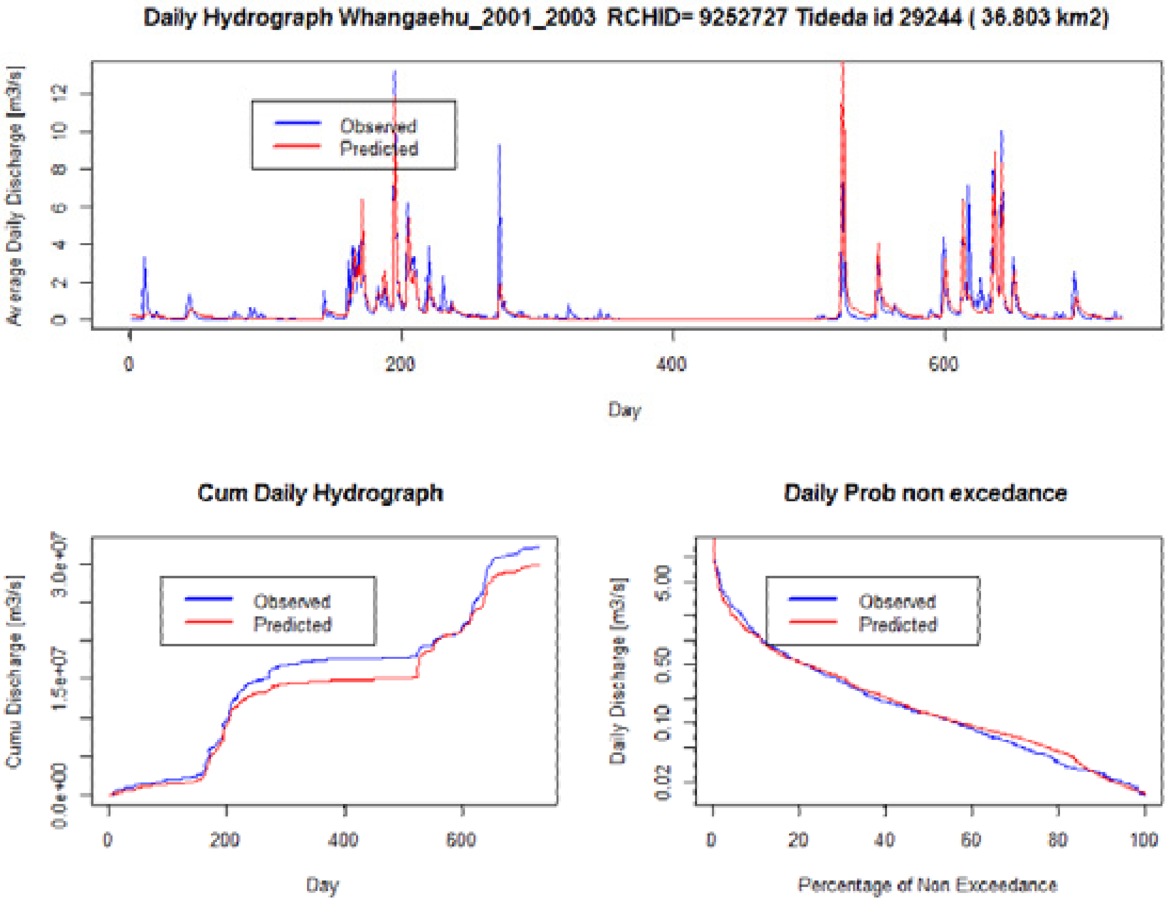


Figure 4-25: Calibrated hourly hydrograph of Whangaehu at Waihi over the calibration period 2001-2003. Flows are plotted in log scale.

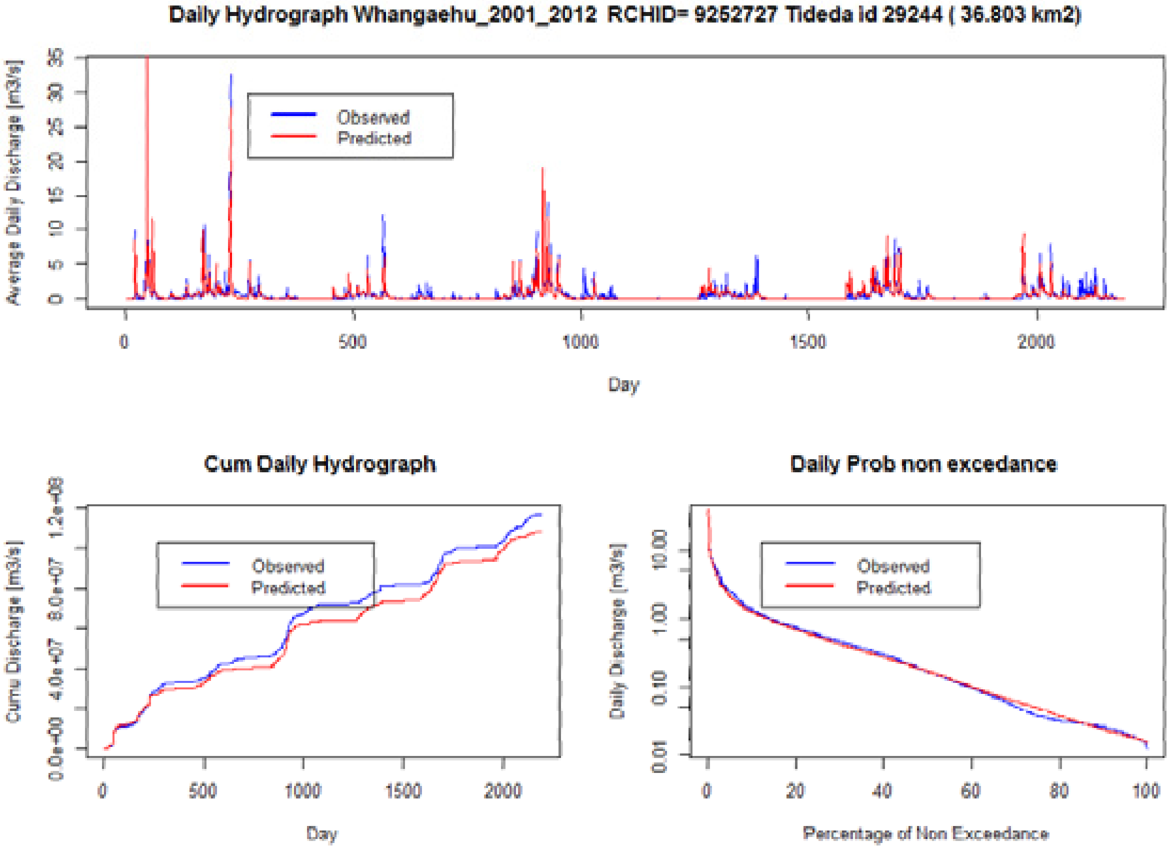


Figure 4-26: Simulated hourly hydrograph of Whangaehu at Waihi over the validation period 2008-2010. Flows are plotted in log scale.

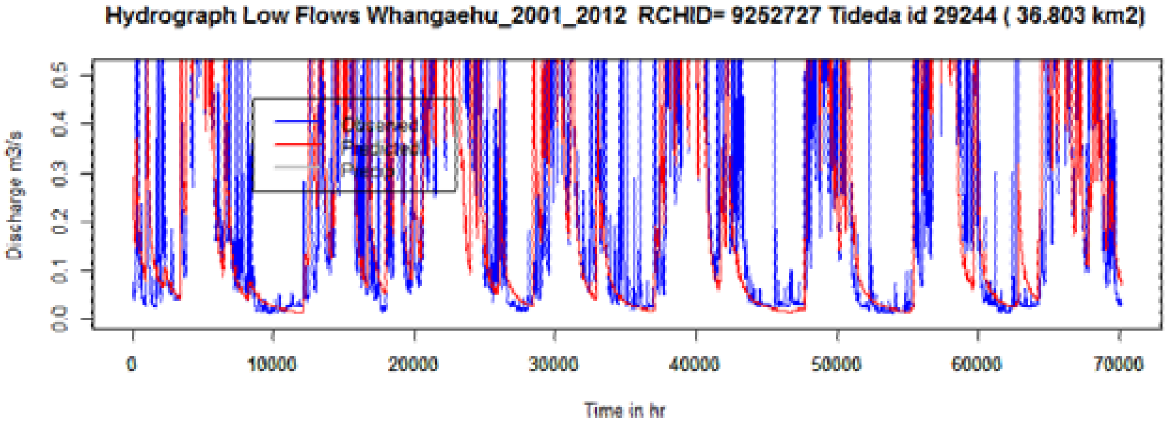


Figure 4-27: Observed and simulated hourly flow duration curve of Whangaehu at Waihi over the calibration period and validation period. Flows are plotted in log scale.

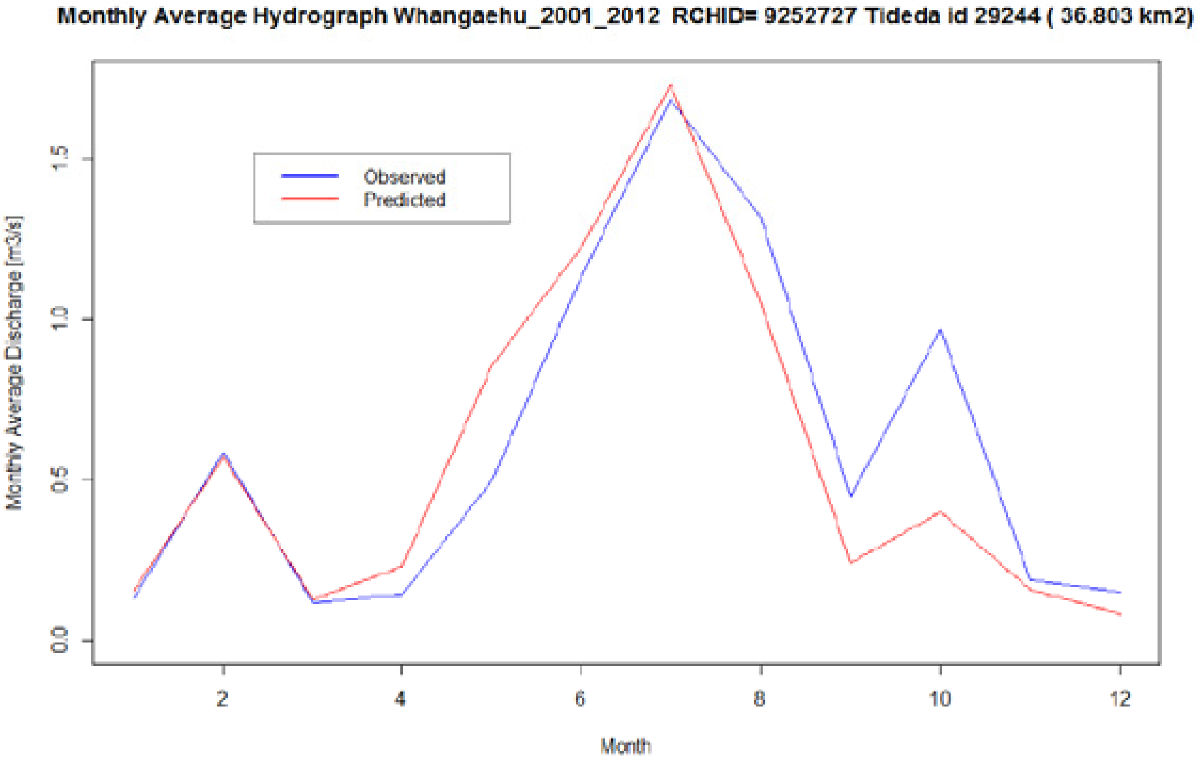


Figure 4-28: Observed and simulated monthly average flow for Whangaehu at Waihi over the validation period

Analysis of the simulations indicates:

- Analysis by GWRC of observed flow time series indicates that high flow rating curve might have large uncertainties in high flow (following rating done in October 2000), but the current rating is considered to be of excellent quality at low flow conditions.
- The calibrated model is able to reasonably reproduce observed low flows (based on NS Log 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.
- 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 in order to be able to reproduce correctly the average annual flow and the annual average catchment water balance.
- Seasonal flows are correctly reproduced (magnitude and timing) during the summer months. Magnitude of the winter flows are largely under-predicted and this is thought to be associated with an underrepresentation of the winter precipitation magnitude in the upper Whangaehu catchment.

4.10 Taueru watershed

The accuracy of the streamflow model prediction is presented in Table 4-39 for the calibration phase and the validation phase. The final values of parameters are provided in Table 4-40. Table 4-41 provides the simulated water balance. Table 4-42 provides the simulated and observed MAF and 7 day MALF, while Table 4-43 presents the observed and simulated monthly average flows over the period of simulation.

Figures 4.29 and 4.30 present the simulation results at the streamflow gauging station in term 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 MAF) 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 4-39: Calibration- Validation statistics for Taueru watershed.

	Calibration (2001-2003)		Validation (2004-2012)	
Location	NSlog	NS	NSlog	NS
Taueru at Te Weraiti	0.815	0.645	0.738	0.711

Table 4-40: TopNet parameters for Taueru watershed.

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 4-41: Simulated water balance by TopNet for Taueru watershed over the period 2003-2012

Annual Average Flux	TopNet (2004-2012) (mm/yr)	GWRC (2004-2012) (mm/yr)	GWRC (1969-2015) (mm/yr
Mean annual precipitation	1515		
Mean annual evaporation	564		
Mean annual runoof	898	465	485

Table 4-42: Simulated and Observed flow characteristics for Taueru watershed over the period 2003-2012

Annual Average hydrological characteristics	TopNet (2004-2012) (m3/s)	GWRC (2004-2012) (m3/s)	GWRC (1969-2015) (mm/yr
Mean Annual Flow	8.770	9.878	6.022
7 days Mean Annual Low Flow	1.358	0.139	0.433

Table 4-43: Simulated and Observed monthly average flows for Taueru watershed over the period 2003-2012

Annual Monthly Flows	Observed (1976-2012) (m3/s)	TopNet (2003-2012 (m3/s)	Observed (1969-2015)
January	3.579	3.243	2.604
February	6.409	6.147	3.672
March	4.551	5.453	3.302
April	4.324	6.097	1.951
May	9.043	11.595	4.299
June	13.966	13.662	8.630
July	27.641	25.334	20.174
August	18.126	14.510	12.897
September	8.120	5.071	4.613
October	11.927	6.368	4.862
November	5.504	3.788	1.029
December	4.791	3.536	0.742

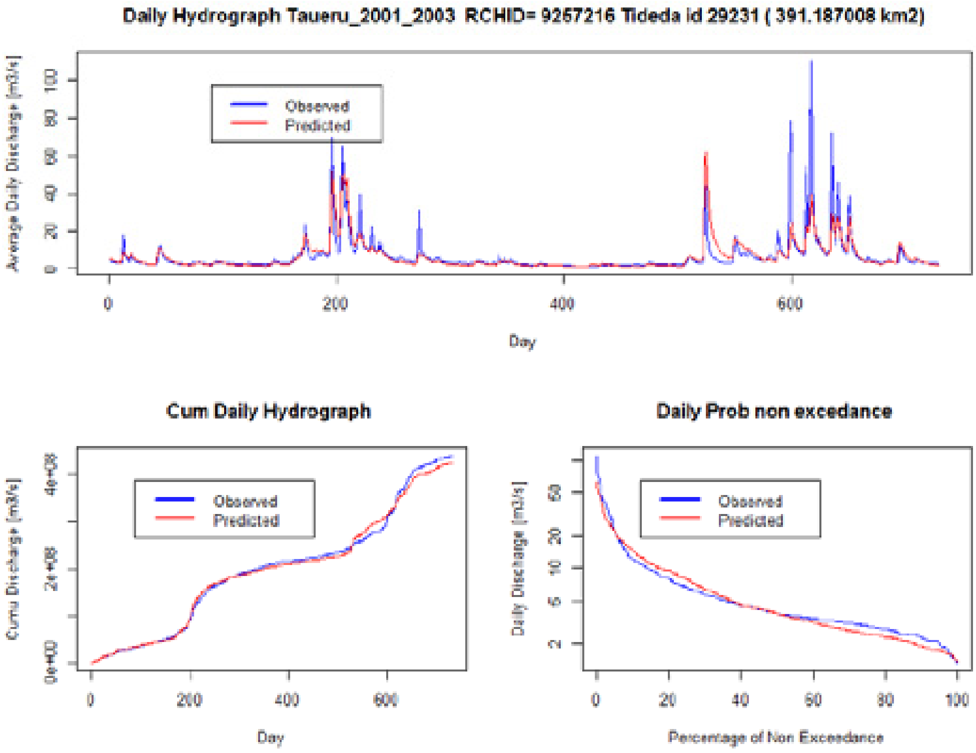


Figure 4-29: Calibrated hourly hydrograph of Taueru at Te Weraiti over the calibration period 2001-2003. Flows are plotted in log scale.

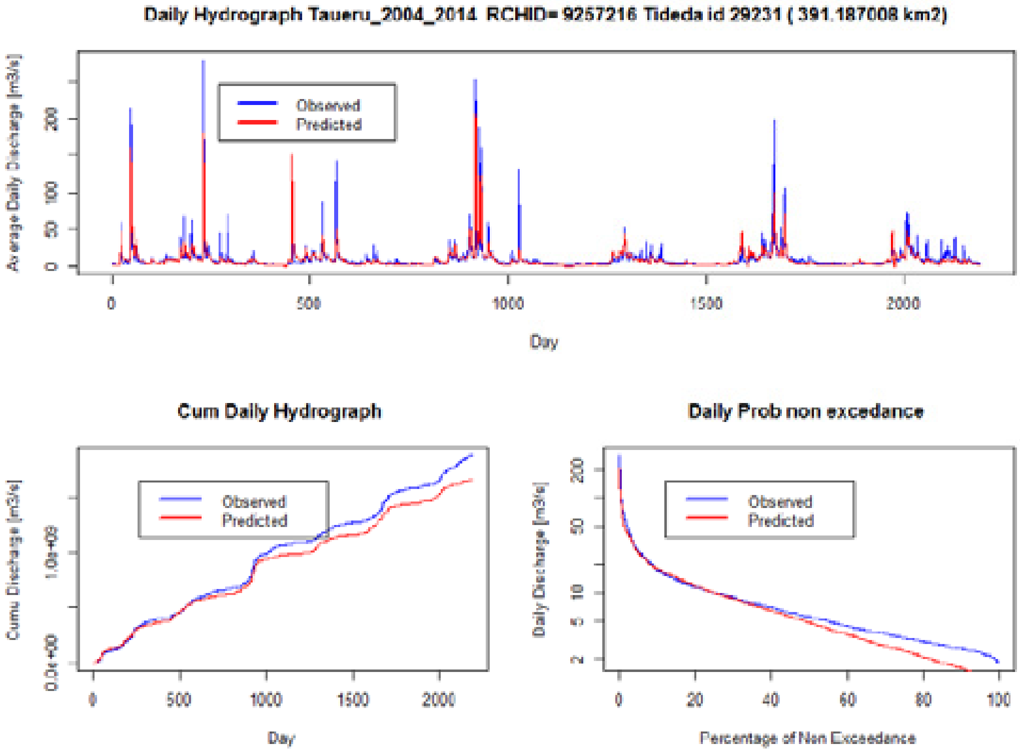


Figure 4-30: Simulated hourly hydrograph of Taueru at Te Weraiti over the validation period 2008-2010. Flows are plotted in log scale.

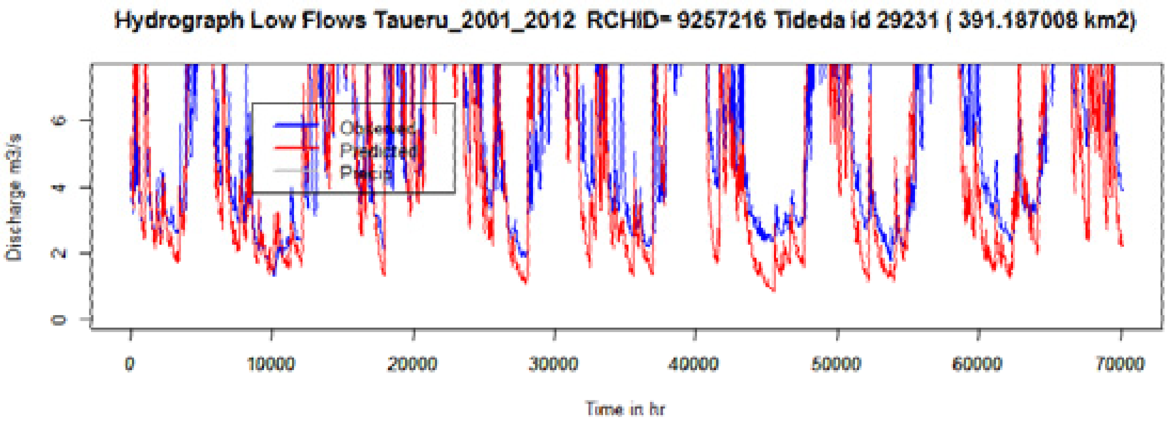


Figure 4-31: Observed and simulated hourly flow duration curve of Taueru at Te Weraiti over the calibration period and validation period. Flows are plotted in log scale.

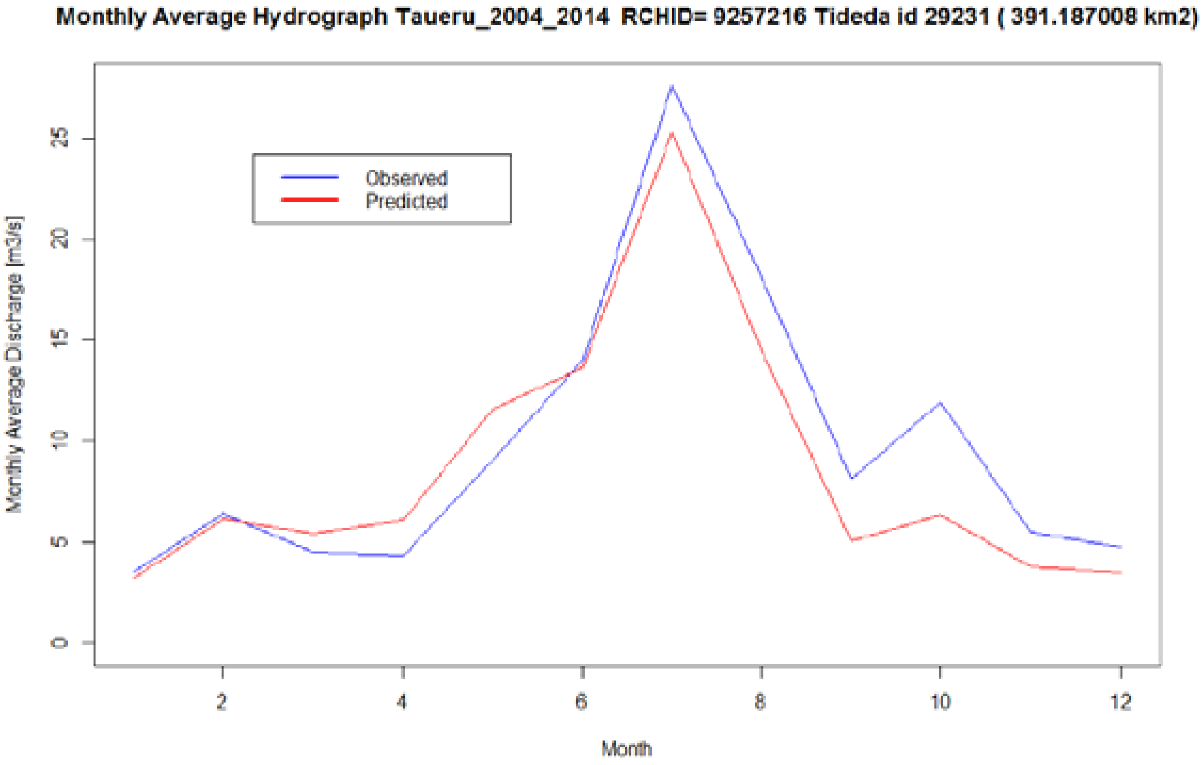


Figure 4-32: Observed and simulated monthly average flow for Taueru at Te Weraiti over the validation period

Analysis of the simulations indicates:

- The calibrated model correctly reproduces the hydrological behaviour encountered during simulation and validation periods.

4.11 Huangarua watershed

The accuracy of the streamflow model prediction is presented in Table 4-244 for the calibration phase and the validation phase. The final values of parameters are provided in Table 4-45. Table 4-46 provides the simulated water balance. Table 4-47 provides the simulated and observed MAF and 7 day MALF, while Table 4-48 presents the observed and simulated monthly average flows over the period of simulation.

Figures 4.33 and 4.34 present the simulation results at the streamflow gauging station in term 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 (ie for discharge below MAF) 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 4-44: Calibration- Validation statistics for Huangarua watershed.

	Calibration (2001-2003)		Validation (2004-2012)	
Location	NSlog	NS	NSlog	NS
Huangarua at Hautotara Branch	0.798	0.814	0.657	0.837

Table 4-45: TopNnet parameters for Huangarua watershed.

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 4-46: Simulated water balance by TopNet for Huangarua watershed over the period 2003-2012

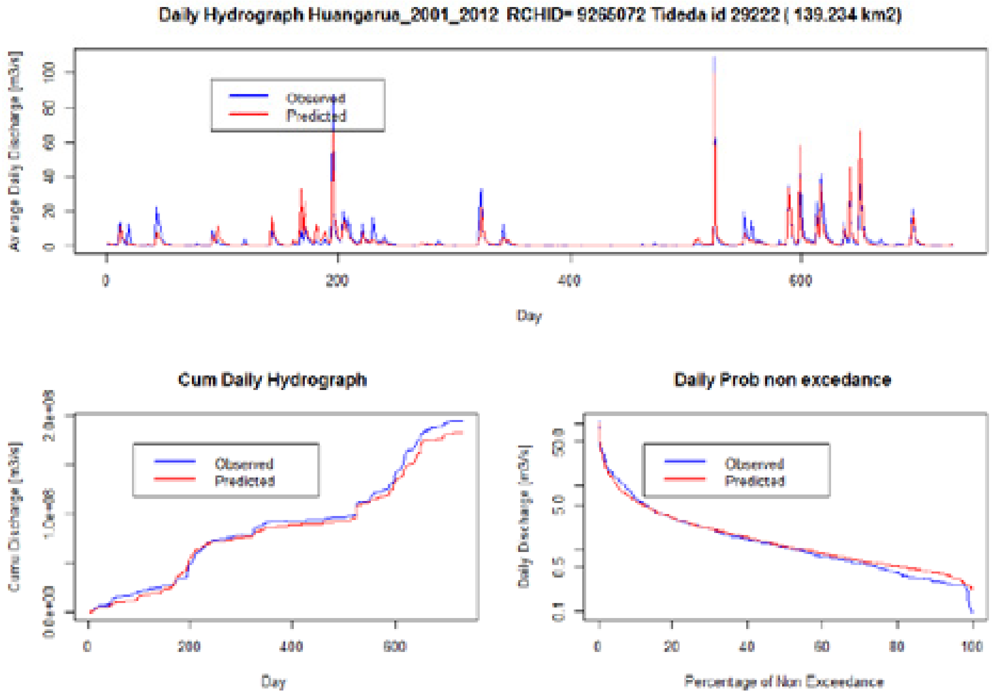
Annual Average Flux	TopNet (2003-2012) (mm/yr)	GWRC (1976-2012) (mm/yr)		VCSN (1972-2014) (mm/yr)
Mean annual precipitation	1736			
Mean annual evaporation	552			
Mean annual runoff	1132	1368	1187	

Table 4-47: Simulated and Observed flow characteristics for Huangarua watershed over the period 2003-2012

Annual Average hydrological characteristics	TopNet (2003-2012) (m3/s)	GWRC (1976-2012) (m3/s)	GWRC (1970-2015) (m3/s
Mean Annual Flow	4.010	6.036	5.240
7 days Mean Annual Low Flow	0.271	2.779	1.850

Table 4-48: Simulated and Observed monthly average flows for Huangarua watershed over the period 2003-2012

Annual Monthly Flows	Observed (1976-2012 (m3/s)	TopNet (2003-2012) (m3/s)	Observed (1970-2010) (m3/s)
January	1.085	1.408	3.488
February	3.327	2.393	4.846
March	1.949	3.199	4.275
April	1.564	1.690	3.847
May	2.086	2.724	6.851
June	3.645	3.164	6.837
July	6.564	6.300	13.034
August	3.864	3.407	10.353
September	0.742	0.958	4.289
October	1.558	1.606	5.931
November	0.131	0.169	3.789
December	1.478	1.066	4.609

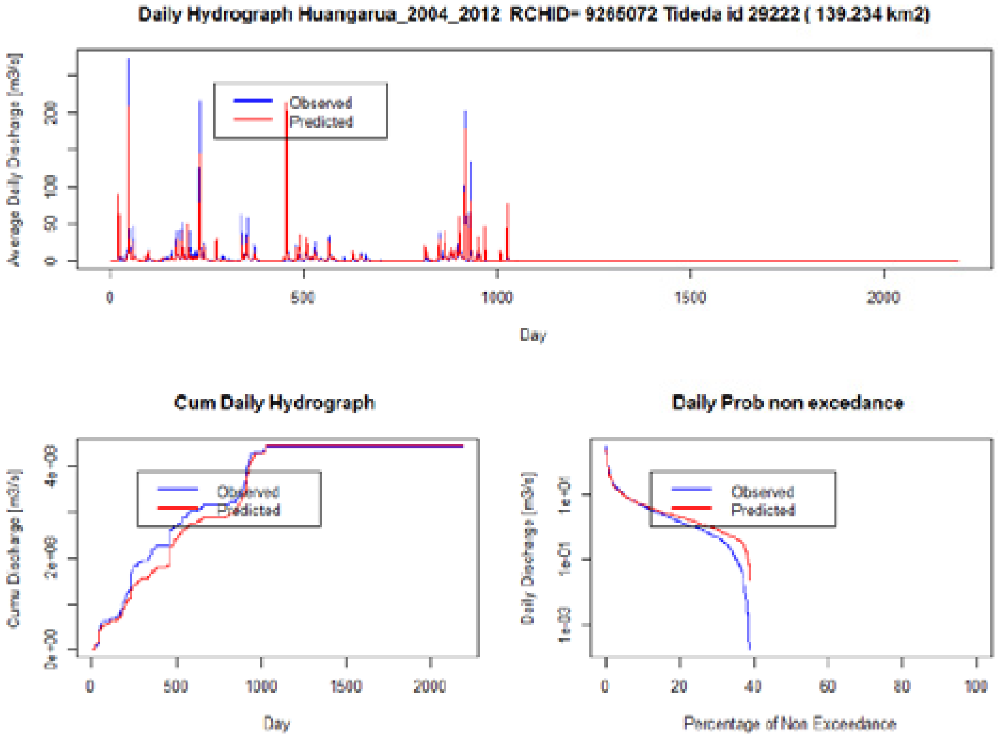


Daily Hydrograph Huangarua_2001_2012 RCHID= 9265072 Tideda id 29222 (139.234 km2)

Cum Daily Hydrograph

Daily Prob non excedance

Figure 4-33: Calibrated hourly hydrograph of Huangarua at Hautotara Branch over the calibration period 2001-2003. Flows are plotted in log scale.



Daily Hydrograph Huangarua_2004_2012 RCHID= 9265072 Tideda id 29222 (139.234 km2)

Cum Daily Hydrograph

Daily Prob non excedance

Figure 4-34: Simulated hourly hydrograph of Huangarua at Hautotara Branch over the validation period 2008-2010. Flows are plotted in log scale.

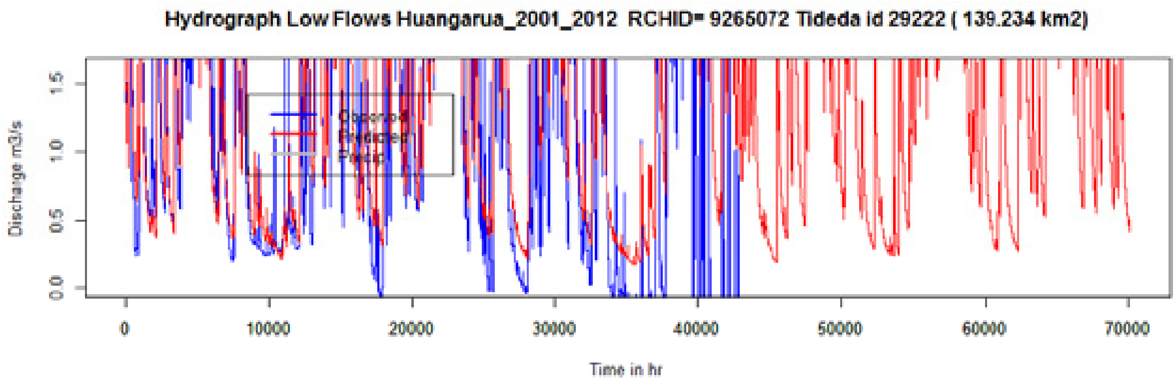


Figure 4-35: Observed and simulated hourly flow duration curve of Huangarua at Hautotara Branch over the calibration period and validation period. Flows are plotted in log scale.

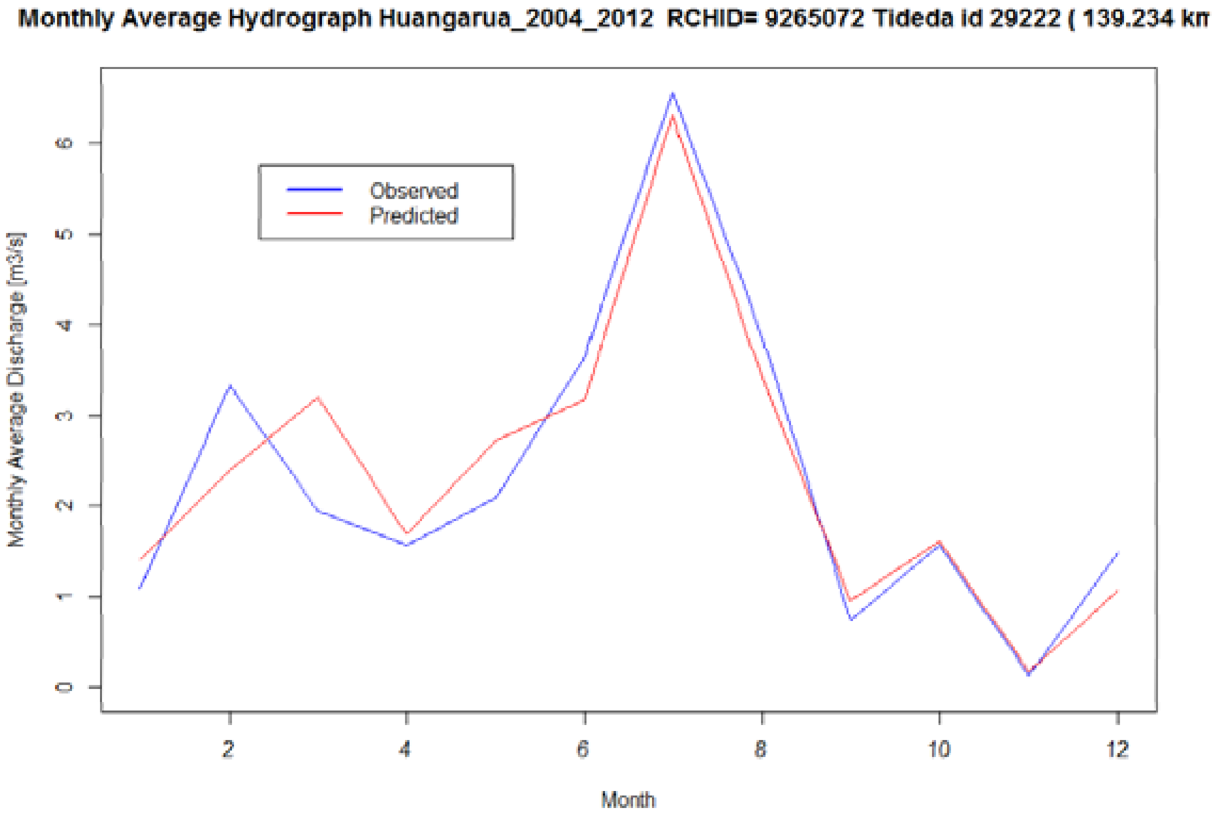


Figure 4-36: Observed and simulated monthly average flow for Huangarua at Hautotara Branch over the validation period.

Analysis of the simulations indicates:

- The calibrated model correctly reproduces the hydrological behaviour encountered during simulation and validation periods as shown by NS and NS Log values.

- Analysis by GWRC of observed flow time series indicates that high flow rating curve might have large uncertainties in high flow (following rating done in October 2000), but the current rating is considered to be of excellent quality at low flow conditions.
- The calibrated model is able to reasonably reproduce observed low flows (based on NS Log 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.
- 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 in order to be able to reproduce correctly the average annual flow and the annual average catchment water balance.
- Seasonal flows are correctly reproduced (magnitude and timing) during the summer months. Magnitude of the winter flows are largely under-predicted and this is thought to be associated with an underrepresentation of the winter precipitation magnitude in the upper Huangarua catchment.

5 Uncertainty analysis

Due to "curse of dimensionality" (e.g., number of parameters and rivers) in distributed hydrological modelling, sophisticated uncertainty analysis techniques such as Generalized **likelihood uncertainty estimation (**GLUE) (Beven and Binley 1992) and Bayesian framework are not applicable to our study. Instead, a simplified approach below was adopted:

- First, model calibration is performed to obtain an optimal parameter set.
- Second, parameters are set to be variable (-10%, 10%) around the optimal parameter set.
- Finally, draw random parameter sets, run the hydrologic model, and obtain model prediction uncertainty

At the time of this draft report the uncertainty simulations have not been completed yet due to large computing load requirement necessary to conduct such an analysis.

6 Model limitations

The above model simulations are subject to TopNet assumptions and limitations in the validity/uncertainties associated with climate inputs. The 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). As a result larger uncertainties exist in the dataset where large areas affected by orographic effects are covered without observations located across the mountain ranges. 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. Due to the paucity of the network within the Ruamahanga catchment, especially at higher elevations large biases are expected in terms of the correct representation of the timing of specific events.

2) **Current understanding of soil, geological information and landuse information**. In the upper catchment land use 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 has been recently updated through the development of the QMaps product (GNS) and SMaps (Landcare). Any misrepresentation of either geological or soil classification will impact surface water/groundwater interaction and evaporation processes and streamflow discharge.

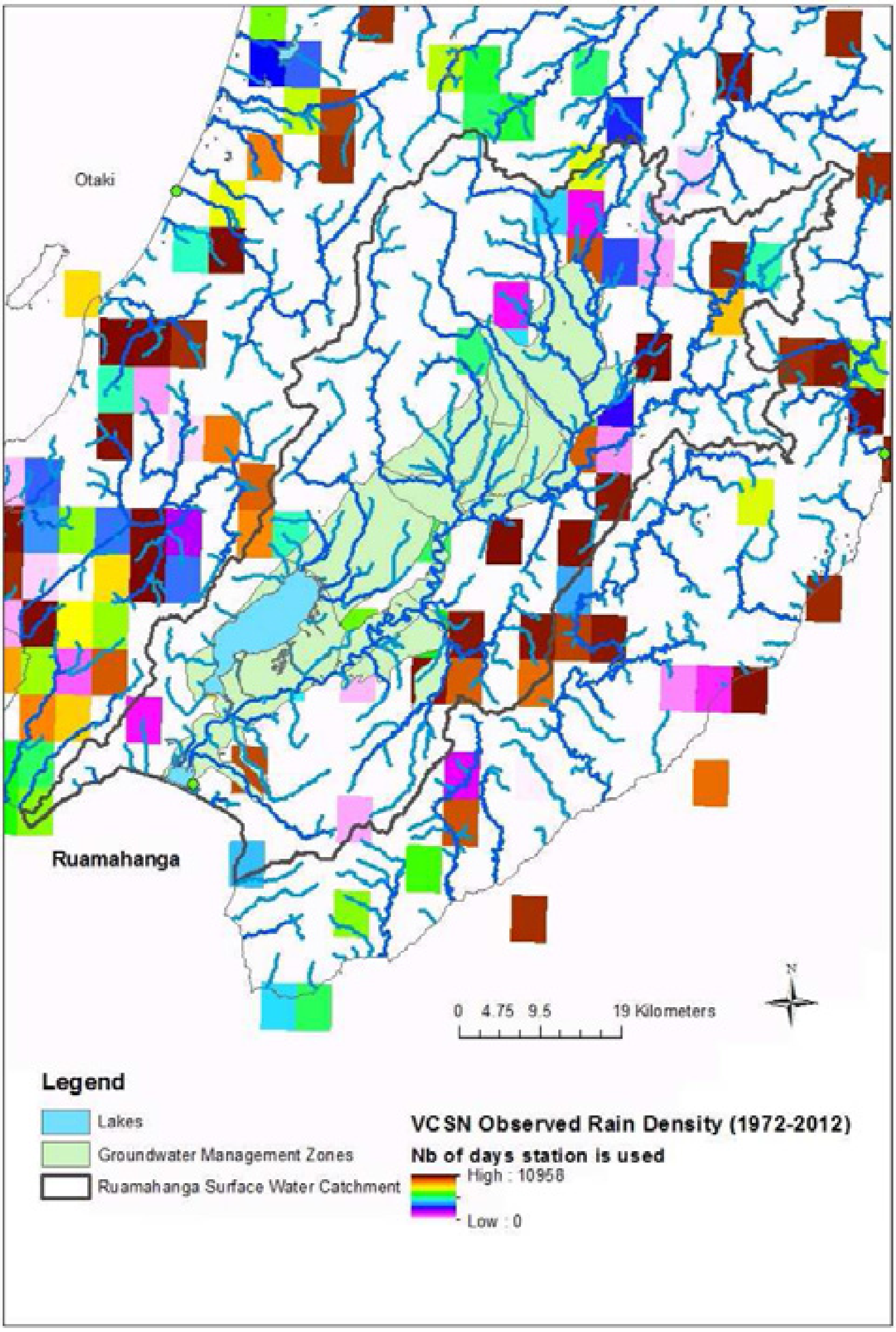


Figure 6-1: Location of the observed precipitation gauge used to derive the daily VCSN precipitation gridded information. The colour scheme represents the number of days (over a 40 year period) a particular station is used.

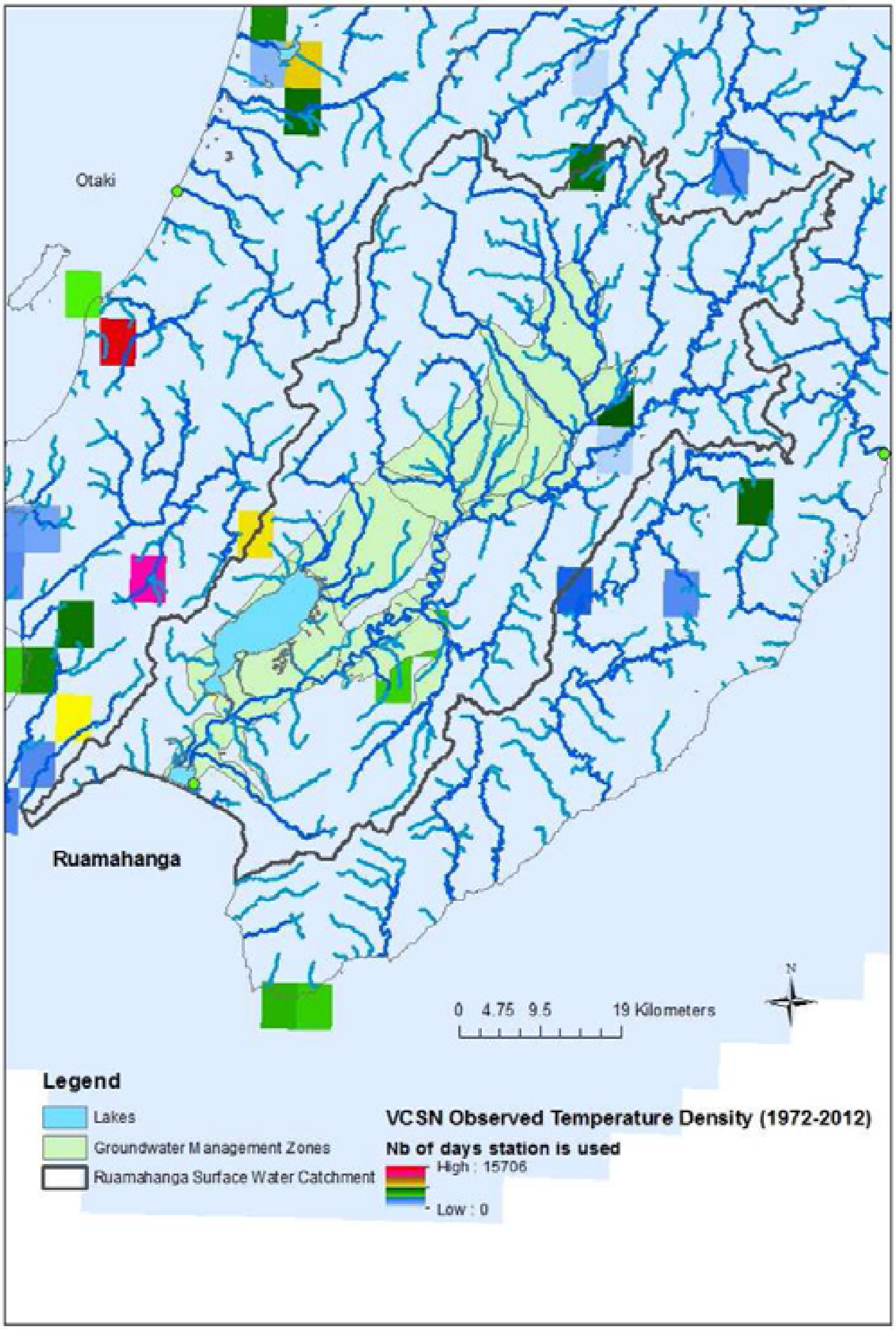


Figure 6-2: Location of the observed temperature gauge used to derive the daily VCSN precipitation gridded information. The colour scheme represents the number of days (over a 40 year period) a particular station is used.

7 Summary

To be completed for final report

8 Glossary of abbreviations and terms

GWZ	Ruamahanga Groundwater Management Zone
Strahler order	**Strahler Stream 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.

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Appendix A <Type the Appendix heading>type in the heading of the App A to come

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