# GROUNDWATER RECHARGE TO GEOTHERMAL SYSTEMS IN THE TAUPO VOLCANIC ZONE ASSESSED WITH WATER BUDGETS AND THREE-DIMENSIONAL GEOLOGICAL MODELS

P.A. White [1], C. Tschritter [1], and R. D. Henderson [2]

[1]GNS Science, Private Bag 2000, Taupo, New Zealand

[2] National Institute of Water and Atmospheric Research, P.O. Box 8602, Riccarton, Christchurch, New Zealand

p.white@gns.cri.nz

**Keywords:** *Water budgets, groundwater recharge, stream baseflow, Tauranga, Upper Waikato River, geothermal system recharge.*

## ABSTRACT

Surface and groundwater budgets in the Taupo Volcanic Zone (TVZ) are developed at the sub-regional scale using hydrological observations and three-dimensional geological models to assess groundwater recharge to geothermal systems. Observations of rainfall, evapotranspiration, rainfall recharge to groundwater and surface flows (baseflow and runoff) show key features of surface and groundwater flows associated with volcanogenic units.

Firstly, rainfall recharge to groundwater is typically a large percentage of rainfall. Rainfall recharge measurements with lysimeters at Kaharoa north of Rotorua show that rainfall recharge is approximately 50% of rainfall which is consistent with a surface water and groundwater budget study of the western Mamaku Plateau. Secondly, most rainfall recharge to groundwater discharges at the ground surface as baseflow in streams. Surface flows are dominated by baseflow and runoff is a small proportion of surface flow as demonstrated by field measurements and analysis of surface water hydrographs. For example, surface baseflow is typically 94% of total surface water flows in the Waikato River catchment between Karapiro Dam and Lake Taupo as demonstrated by an analysis of surface water hydrographs.

Groundwater recharge to deep TVZ systems (including geothermal fields) is a small proportion of total rainfall recharge to groundwater. Groundwater recharge rates to the deep TVZ systems are possibly an important control on the location of geothermal activity as demonstrated in Ohakuri hydropower dam sub-catchments. In this area, many geothermal systems (e.g., Waiotapu, Te Kopia and Reporoa) are located in northern and western sub-catchments where deep groundwater recharge is relatively high. In contrast, few geothermal systems are located in eastern sub-catchments where water budget equations estimate no deep groundwater recharge from the ground surface.

## 1. INTRODUCTION

Groundwater recharge in the Taupo Volcanic Zone (TVZ) is important to cold groundwater and geothermal systems. Groundwater is a water source for agriculture, industry and municipal supply in the TVZ that regional councils aim to manage sustainably. The groundwater system supports flow in many TVZ springs and baseflow in rivers and streams. Regional councils also aim to manage groundwater sustainably to maintain baseflow in rivers and streams (White et al., 2008a; Waikato Regional Council, 2012). Groundwater recharge also supplies geothermal systems. This water is important because heat may be transported to and from geothermal systems by groundwater convection (Kissling and Weir, 2005), groundwater flow supports geothermal springs and geysers (White and Hunt, 2005); and geothermal fluids flowing to the ground surface may be a mix of water from hot (deep) and shallow (cold) sources (White and Hunt, 2005). However, the groundwater inflow into the deep TVZ geothermal system (approximately 27 mm/year; from Kissling and Weir, 2005) is small in terms of the water budget with average rainfall of 1643 mm/year estimated in the TVZ model area (Figure 1).

This paper presents the development of water budgets for the TVZ area using environmental observations (i.e., rainfall, evapotranspiration, rainfall recharge to groundwater and surface flows) and three dimensional geological models to estimate flows in aquifers. These aquifers are defined either as 'shallow' (groundwater flow supports flow to cold springs and seeps) or 'deep' (groundwater flow potentially travels to the geothermal systems). This approach is demonstrated by application to the Tauranga and Upper Waikato model areas.

## 2. WATER BUDGET

A general water budget equation describes the relationships between water inflow, water outflow and water storage within a defined area of a catchment in steady-state conditions assuming water inflow equals water outflow (Scanlon et al., 2002):

$$P + Q_{IN} = AET + Q_{OUT} \quad (1)$$

Water inflows include:

P precipitation,

$Q_{IN}$ water flow into the area which is the sum of $Q^{SW}_{IN}$ (surface water inflow, i.e., baseflow, interflow and runoff) and $Q^{GW}_{IN}$ (groundwater flow).

Water outflows include:

AET actual evapotranspiration

$Q_{OUT}$ water flow from the area which is the sum of surface water outflow, $Q^{SW}_{BF}$ (surface water baseflow generated in the area), $Q^{SW}_{QU}$ (quick flow, or interflow plus runoff from the area) and $Q^{GW}_{OUT}$ (groundwater outflow from the area including consumptive groundwater use), i.e.:

$$P + Q_{IN} = AET + Q^{SW}_{BF} + Q^{SW}_{QU} + Q^{GW}_{OUT} \quad (2)$$

Water budgets are assessed for surface and groundwater catchments within TVZ sub-regions, and for layers in the geological models assuming groundwater use is zero. 'Shallow' groundwater recharge is used here as the component of groundwater recharge that flows to surface water baseflow ($Q^{SW}_{BF}$). 'Deep' groundwater recharge is used here as the component of groundwater recharge that flows across the catchment boundary ($Q^{GW}_{OUT}$). The distinction of 'shallow' and 'deep' groundwater recharge is useful as regional councils aim to manage groundwater use to control effects on stream baseflow (Waikato Regional Council, 2012) and the sources of geothermal systems are typically deep. However, identification of the groundwater flow paths for 'shallow' and 'deep' groundwater recharge requires physical and chemical measurements and modelling, that are beyond the scope of the water budgets derived in this paper.

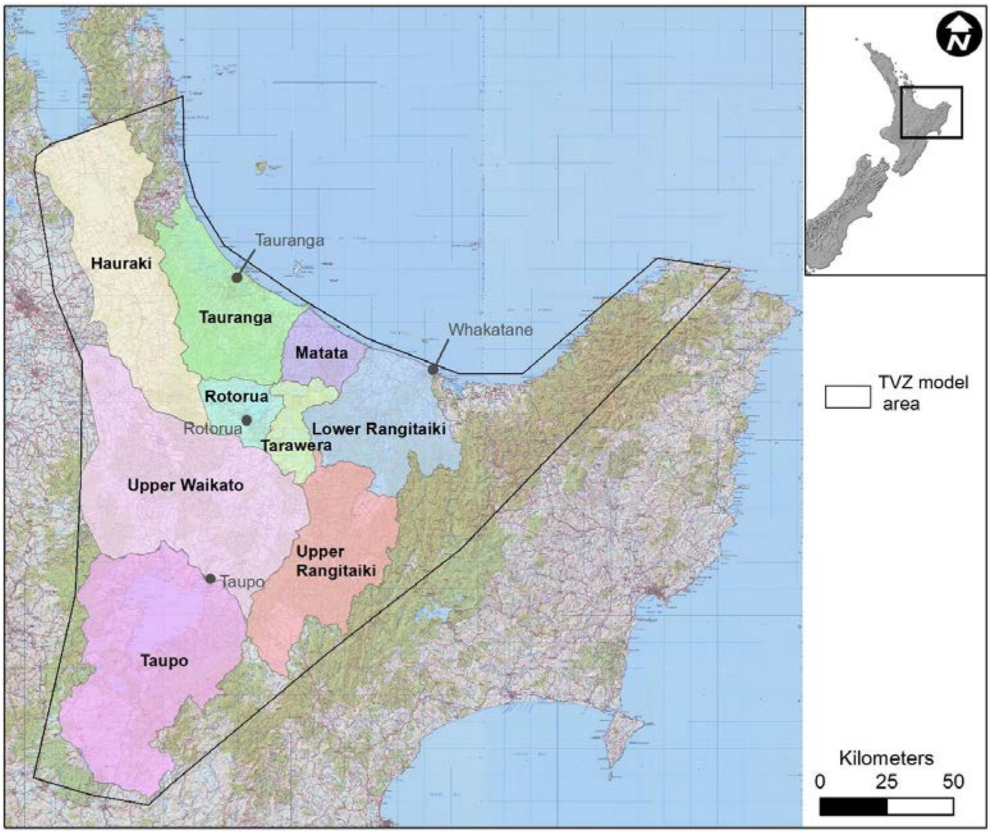


**Figure 1: Sub-regions of the Taupo Volcanic Zone.**

Observations of rainfall, evapotranspiration, rainfall recharge to groundwater and surface flows show two key features of groundwater and surface water flows associated with volcanogenic units in the TVZ. Firstly, rainfall recharge to groundwater is typically a large percentage of rainfall. Rainfall recharge measurements with lysimeters at Kaharoa north of Rotorua show that rainfall recharge is approximately 50% of rainfall which is consistent with surface water and groundwater budgets of the western Mamaku Plateau (White et al., 2007; Dell, 1982a and 1982b). Most rainfall recharge is associated with higher intensity rainfall events. For example, 71% of rainfall recharge at Kaharoa in the period 1st August 2005 to 31st July 2006 occurs where rainfall intensity is greater than 25 mm/day (White et al., 2007). Secondly, surface flows are dominated by baseflow whereas quickflow (interflow and runoff) is a small proportion of surface flow, as demonstrated by surface water hydrographs and field observations. For example, a baseflow analysis of Upper Waikato surface water hydrographs shows that baseflow is typically 91% of total surface water flow. Surface runoff has not been observed at the Kaharoa rainfall recharge site with rainfall intensities up to approximately 22 mm/hr in weather at the time described as "a torrential gale with wind-blown rain" (Reeves, GNS Science, pers. comm.). Most rainfall recharge to groundwater in the TVZ discharges at the ground surface as baseflow in streams. For example, an estimated 76% of rainfall recharge in the Lake Rotorua catchment discharges to surface water baseflow (White et al., 2007).

Baseflow and quick flow are calculated with available surface flow data, which includes surface flow gaugings and continuous flow measurements from rated stage recorder sites. Surface flow gauging data has a greater geographic spread than continuous flow measurements; however, collection of surface flow gauging measurements is typically not systematic. Therefore baseflow is generally calculated as the median surface water flow from gaugings whereas quickflow is calculated as the difference between mean surface water flow and median surface water flow from gaugings, with removal of outliers (e.g., flood gaugings). This approach using gauging data estimates that baseflow is 79% of total surface water flow in the Upper Waikato, which is a little less than the estimate from baseflow analysis of the continuous flow hydrographs.

Rainfall, evapotranspiration and surface water flows are the largest components of the water budget that are used to estimate groundwater flow and recharge to geothermal systems. Rainfall and evapotranspiration in the TVZ area (Figure 1) are estimated as the equivalent of 1039 $m^3/s$ and 497 $m^3/s$, respectively, from national-scale models (Tait et al., 2006; Woods et al., 2006). These models are based on 500 m by 500 m grids for the 1960 – 2006 time period. Surface water flows from the TVZ sub-regions are an estimated 514 $m^3/s$ with the balance of inflows and outflows (28 $m^3/s$) associated with groundwater outflow from the area (i.e., through the coastal boundary) or uncertainty in water budget estimates.

## 2. THREE-DIMENSIONAL GEOLOGICAL MODELS AND GROUNDWATER BUDGETS

Three-dimensional (3D) geological models have been derived for most sub-regions of the TVZ including: Hauraki, Tauranga, Matata, Rangitaiki Plains, Rotorua, Upper Waikato and Taupo with models of other sub-regions under development; Figure 1. These models were derived with EarthVision® software using relevant information including digital terrain maps, geological maps, well log and well depth data collected by Bay of Plenty Regional Council and Waikato Regional Council and available geophysical data. A 3D geological model is generally composed of a series of units (layers) that are assembled with respect to their chronology and structural relationships. These units are defined by a set of boundary surfaces. The number, and nature, of layers and boundary surfaces relevant to groundwater flow are defined and positioned in 3D space. Generally, only the surface for the top of each geological layer is defined; the bottom of each geological layer is then represented by the top surface of the underlying layer. The 3D models are used to represent key geological formations for groundwater flow, and the following summarises the results of some of the TVZ geological and water budget models.

### 3.1 Hauraki

The Hauraki 3D model is comprised of Holocene and Pleistocene sediments, Pleistocene ignimbrites, including the Waiteariki Ignimbrite, Pakaumanu Group ignimbrites and Mamaku Plateau Formation ignimbrites, a greywacke gravel fan derived from the erosion of the Hapukakohe Range in the northern Hauraki Plains and basement consisting of Jurassic greywacke and Tertiary volcanics. Pleistocene Hinuera and Karapiro formation sediments are the main aquifers in the Hauraki Plains. The groundwater budget for this area suggests that Hauraki Plains Pleistocene sediments are recharged from rainfall on the Hauraki Plains. However, the calculations also demonstrate that a significant proportion of the groundwater recharge to the Pleistocene sediments is derived from groundwater recharge to Hauraki Plains ignimbrite aquifers, e.g. recharge to Waiteariki Ignimbrite in the Kaimai Range. In contrast, the groundwater budget suggests that all groundwater recharge to the Mamaku Plateau Formation discharges to surface water.

### 3.2 Tauranga

The geological model of the Tauranga area (White et al., 2008a) includes key aquifers such as Tauranga Group Sediments, Mamaku Plateau Formation, Waiteariki Ignimbrite and Aongatete Ignimbrite. Tauranga Group Formation includes Quaternary sediments near the coast, whereas Mamaku Plateau Formation is sourced from the Rotorua caldera area and forms an important aquifer in the headwaters of this area. The Waiteariki Ignimbrite (erupted from near the Kaimai Range) and Aongatete Ignimbrite (a volcanic unit with considerable thickness that is not exposed at the ground surface) aquifers are important in the area because they are used for municipal water supply and contain the Tauranga low-temperature geothermal system. $Q^{GW}_{OUT}$ in the Tauranga area is estimated as 13.7 $m^3/s$ using a water budget that includes: rainfall (113 $m^3/s$), actual evaporation (60 $m^3/s$) surface water baseflow (64 $m^3/s$); groundwater discharge to the Lake Rotorua catchment (2.7 $m^3/s$); surface water inflow to the Tauranga area from the Kaituna River; and groundwater inflows to the Tauranga area, possibly from the Matata model area.

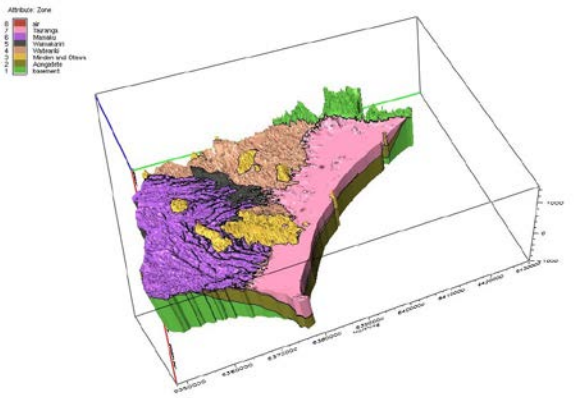

**Figure 2: Three-dimensional geological model of the Tauranga area (White et al., 2008a); view to the west.**

### 3.3 Matata

The Matata model (White et al., 2008b) describes a late Pliocene to Holocene sequence of volcanic rocks and volcanogenic sediments overlying Mesozoic greywacke basement. Pleistocene sediments and Mamaku Plateau Formation are the most commonly used geological units for groundwater in the area. Groundwater available for allocation is an estimated 1.4 $m^3/s$ with a water balance model based on estimates of rainfall recharge to groundwater and estimates of stream baseflow considering possible groundwater recharge from lakes and catchments of Rotoehu and Rotoma in the Tarawera model area.

### 3.4 Rotorua

The 3D geological model of the Lake Rotorua catchment (White et al., 2007) incorporates the key units in the Lake Rotorua Caldera including alluvial sediments, Huka Formation sediments and Mamaku Plateau Formation. Huka Formation has partially water-bearing sediments above an elevation of 280 m and water-bearing sediments between an elevation of 280 m and 230 m. The main water-bearing unit in Mamaku Plateau Formation is in the depth range 65 m to 110 m below ground level. The model indicates that approximately 76% of water inflows to the lake from the catchment are from the surface water and approximately 24% are from groundwater.

### 3.5 Upper Waikato

The Upper Waikato 3D model (White et al., 2011) is developed in the area between Karapiro Dam and Lake Taupo as part of project to assess the relationships between land use, groundwater quality and surface water quality. The geology of this area is summarised as 18 groupings of geological layers including Permian - Jurassic basement at approximately 4 km below sea level in the centre of the rift and a depth of approximately 3 km below sea level the Taupo-Reporoa Depression. Pleistocene volcanics, Holocene volcanics and Holocene Tauranga Group sediments fill the TVZ graben with largest-volume deposits associated with the Mangakino and Whakamaru eruptive sequences. Rainfall and actual evapotranspiration are an estimated 198 $m^3/s$ and 108 $m^3/s$, respectively. The water budget indicates that all groundwater recharge in the area discharges through the Waikato River at Karapiro. Recharge to groundwater is an estimated 86 $m^3/s$ with the majority (approximately 70 $m^3/s$) flowing to sub-catchments of the Waikato River to become baseflow. The balance ($Q^{GW}_{OUT}$, approximately 16 $m^3/s$) discharges from sub-catchments via direct groundwater inflow to the Waikato River.

## 4. GROUNDWATER RECHARGE AND GEOTHERMAL SYSTEMS

Water budget calculations are summarised in this paper for two representative sub-regions in the TVZ: 1) the Tauranga sub-region has $Q^{GW}_{OUT}$ greater than zero and therefore groundwater discharges to the sea through the coastal boundary, and 2) the Upper Waikato sub-region where $Q^{GW}_{OUT}$ is equal to zero, i.e. water discharge from the sub-region is only via surface water.

### 4.1 Tauranga

The rate of groundwater recharge that provides flow across the coastal boundary and flow to the Lake Rotorua catchment (i.e., $Q^{GW}_{OUT}$ over the Tauranga model area) is equivalent to approximately 230 mm/year. However, part of the area (on the Mamaku Plateau) is within the groundwater catchment of Lake Rotorua and supports flow in Hamurana and Awahou springs on the northern shores of the lake. The component of $Q^{GW}_{OUT}$ in this part of the model area is approximately 1000 mm/year. Outside the Lake Rotorua groundwater catchment, $Q^{GW}_{OUT}$ is in the range -579 to 834 mm/year with negative values indicating that approximately 50% of the catchments, by area, gain groundwater from adjacent catchments. The balance of the model area has a positive $Q^{GW}_{OUT}$ that indicates groundwater discharge across the coastal boundary. Flow in the Waiteariki and Aongatete ignimbrite aquifers probably intersects the Tauranga low-temperature geothermal field and groundwater inflow to the field is an estimated 1.0 $m^3/s$. Therefore groundwater inflow to the Tauranga low-temperature geothermal field is likely to be a small proportion of rainfall and rainfall recharge in the Tauranga area.

### 4.2 Upper Waikato

$Q^{GW}_{OUT}$ from the entire model area is zero as all groundwater recharge flows to the Waikato River within the area. However, groundwater discharges from sub-catchments to the Waikato region within the model area. This is because average $Q^{GW}_{OUT}$ from eight hydropower dam catchments in the model area is equivalent of 113 mm/year. $Q^{GW}_{OUT}$ is largest in the Karapiro (4.9 $m^3/s$) and Ohakuri (5.7 $m^3/s$) hydropower dam catchments. Equivalent $Q^{GW}_{OUT}$ is also largest in the Karapiro (186 mm/year) and Ohakuri (121 mm/year) catchments.

Sub-catchments within hydropower dam catchments show considerable variation in $Q^{GW}_{OUT}$. For example the Ohakuri hydropower dam catchment, largely coincident with the Reporoa basin, includes six sub-catchments between Ohakuri dam and Aratiatia dam. $Q^{GW}_{OUT}$ from sub-catchments on the north and west of the Ohakuri hydropower dam catchment are in the range 186 - 289 mm/year, however $Q^{GW}_{OUT}$ from sub-catchments in the east (i.e., Kaingaroa Plateau) are in the range -61 to -176 mm/year. This indicates that groundwater recharge to the deep groundwater system may come from rainfall recharge in the north and west of the Ohakuri hydropower dam catchment, which is consistent with higher rainfall in this area. For example, average annual rainfall in northern and western sub-catchments averages approximately 1378 mm/year whereas average annual rainfall in eastern sub-catchments average 1253 mm/year.

### 4.3 Implications for geothermal systems

$Q^{GW}_{OUT}$ is a small proportion of the water budget in the Tauranga and Upper Waikato areas with average estimates of 230 mm/year and 113 mm/year for the Tauranga and Upper Waikato areas, respectively. These estimates are equivalent to 12% and 8% of average rainfall in the Tauranga and Upper Waikato areas, respectively, and they are greater than the estimate of groundwater inflow into the deep TVZ geothermal system (approximately 27 mm/year; from Kissling and Weir, 2005). Therefore the full fraction of $Q^{GW}_{OUT}$ may not all travel to the deep geothermal systems.

The distribution of geothermal systems in the Ohakuri hydropower dam catchment seems broadly related to sub-catchment estimates of $Q^{GW}_{OUT}$. Many geothermal systems (Waikite, Waiotapu, Te Kopia, Reporoa, Orakei Korako and Nga Tamariki) occur in western and northern sub-catchments where $Q^{GW}_{OUT}$ is relatively high. In contrast, few geothermal systems are associated with sub-catchments in the east where $Q^{GW}_{OUT}$ is less than zero, i.e., no deep groundwater recharge occurs from the ground surface. Two geothermal systems (Ohaaki and Rotokawa) that overlap western and eastern catchments are associated with the Waikato River and areas where $Q^{GW}_{OUT}$ possibly discharges to the river.

## 5. CONCLUSIONS

Groundwater recharge to deep TVZ systems (including geothermal fields) is a small proportion of total rainfall recharge to groundwater, consistent with Kissling and Weir (2005). For example, deep groundwater recharge is equivalent to 12% and 8% of average rainfall in the Tauranga and Upper Waikato model areas, respectively. The rates of deep groundwater recharge, and flow, may influence the location of geothermal fields. For example, many geothermal systems (e.g., Waiotapu, Te Kopia and Reporoa) are located in the northern and western Ohakuri hydropower dam sub-catchments where deep groundwater recharge is relatively high. However few geothermal systems occur in the eastern Ohakuri hydropower dam sub-catchments where water budgets estimate that no deep groundwater recharge occurs from the ground surface.

## 5. REFERENCES

Dell, P.M. 1982a. The effect of afforestation on the water resources of the Mamaku Plateau region. A thesis submitted in partial fulfilment of the requirements for the degree Master of Science in Earth Science, University of Waikato. 319p.

Dell, P.M. 1982b. The water resource of the Mamaku Plateau region. New Zealand Hydrological Society Annual Symposium, Auckland.

Kissling, W.M. and Weir, G.J. 2005. The spatial distribution of geothermal fields in the Taupo Volcanic Zone, New Zealand. Journal of Volcanology and Geothermal Research, 145: 136-150.

Scanlon, B.R., Healy, R.W., Cook, P.G. 2002. Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeology Journal, 10: 18-39.

Tait, A., Henderson, R.D., Turner, R., Zheng, X. 2006. Spatial interpolation of daily rainfall for New Zealand. International Journal of Climatology, 26(14): 2097-2115.

Waikato Regional Council, 2012. Proposed Waikato Regional Plan Variation 6 – water allocation operative (10 April 2012). Waikato Regional Council document number 2141102, 80p.

White, P.A. Hunt, T.M. 2005. Simple models of the effects of exploitation on hot springs, Geyser Valley, Wairakei, New Zealand. Geothermics 34(2) Special Issue: Environmental aspects of geothermal energy. 184- 204.

White, P.A. Meilhac, C., Zemansky, G., Kilgour, G. 2008a. Groundwater resource investigations of the Western Bay of Plenty area stage 1 – conceptual geological and hydrological models and preliminary allocation assessment. GNS Client report 2008/240 to Environment Bay of Plenty.

White, P.A., Meilhac, C., Della Pasqua, F. 2008b. Groundwater resource investigations of the Paengaroa-Matata area stage 1 – conceptual geological and hydrogeological models and preliminary allocation assessment. GNS Science Consultancy Report 2008/134.

White, P.A, Zemansky, G., Hong, T., Kilgour, G., Wall, M., 2007. Lake Rotorua groundwater and Lake Rotorua nutrients – phase 3 science programme technical report. GNS Client report 2007/220 to Environment Bay of Plenty. 402p.

White, P.A., Tschritter, C., Cameron, S. 2011. A 3D geological model of the Upper Waikato River catchment with associated hydrogeological parameters. New Zealand Hydrological Society Conference, Wellington.

Woods, R.A., Hendrikx, J., Henderson, R.D., Tait, A.B. 2006. Estimating mean flow of New Zealand rivers. Journal of Hydrology (NZ), 45(2): 95-110.