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Modelling groundwater abstraction scenarios using a groundwater–river interaction model of the Upper Motueka River catchment

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Abstract

The effects of various groundwater abstraction scenarios on stream flow and groundwater levels in the Upper Moteuka River catchment have been investigated using a groundwater–river interaction model. The model operated on a daily time step and had two components: a FEFLOW groundwater model to simulate groundwater losses and gains from the river, and a custom-built river model to route river flow and to calculate river water levels using Manning's equation. For the 'base case', the model input included climate and abstraction data for the period 1 July 2001 to 30 June 2003, and the model was calibrated by adjusting hydraulic conductivity and streambed conductance to achieve a good match to observed groundwater levels, river flows and river water levels measured in this same time period. Thereafter the calibrated model was then used to predict groundwater levels, river flows and river water levels for six different scenarios: 1) actual groundwater abstraction at the end of 2008; 2) groundwater abstraction assuming the maximum take specified on each existing water permit; 3) groundwater abstraction assuming additional permitted takes sufficient to allow complete irrigation over all potentially irrigable land; 4) actual groundwater abstraction at the end of 2008 in roughly half of the model area combined with complete irrigation of all potentially irrigable land in the remainder of the model area; and 5) actual groundwater abstraction at the end of 2008 assuming river bed elevations were 0.3 m higher or lower than current elevations. For all scenarios, modelled mean and median river flows during the irrigation season were at most 5% less than for the base case, and differences outside the irrigation season were even smaller. Only the third of the tested scenarios resulted in modelled river flows that may breach minimum flow requirements at

some locations. For all scenarios, modelled groundwater levels were no more than 1 m below the base case, with the largest drops occurring at four locations along the margins of the catchment and near pumping centres. The results suggest that a groundwater pumping scheme could incorporate existing and new abstraction while still ensuring that estimated low flow conditions are not breached during the irrigation season, and the scenario modelling results can be used by Tasman District Council for groundwater allocation management.

Keywords

FEFLOW, river flow routing, Manning equation

Introduction

The Motueka River is located in the northwest part of the South Island of New Zealand (Fig. 1). The Upper Motueka River catchment receives flow contributions from the Upper Motueka, Tadmor and Motupiko headwater tributaries. The area upstream of the Wangapeka confluence has a sizeable area of fertile alluvial river terrace land that is suitable for irrigated agriculture. Since the mid-1990s there has been an increasing demand for irrigation water, especially from groundwater in these alluvial terraces. Water concerns in the Motueka catchment have gained international attention and the Motueka catchment was selected to be a pilot catchment for the UNESCO Hydrology for the Environment, Life and Policy (HELP) programme to demonstrate Integrated Catchment Management practices in New Zealand (Fenemor *et al.*, 2006; 2008; 2011).

Tasman District Council, water users and stakeholders with in-stream interests are confronting questions about the effects of increasing groundwater abstraction on groundwater levels and stream flow in the Upper Motueka River catchment. Due to strong aquifer–surface water interactions in this

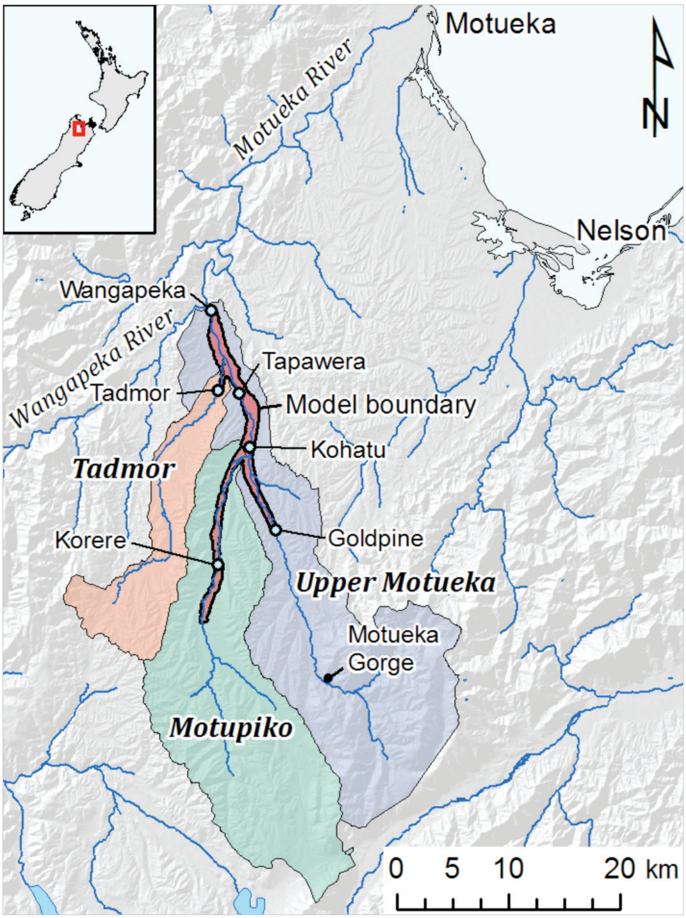


Figure 1 – Location of study area in the Motueka River Catchment, highlighting contributing surface water catchments. The model domain is shown by the red shaded area and locations of river gauging stations are shown by circles.

region, abstraction of more groundwater for irrigation may lower groundwater levels and consequently reduce the baseflow of streams during the summer season to unacceptable levels. Increased groundwater abstraction could therefore reduce the availability and life-supporting capacity of surface water for aquatic life, recreation and other uses. It could also add extra pressure in terms of water allocation and maintenance of minimum flows downstream for the Motueka River and tributaries. Fenemor *et al.* (2006) provide a full description of water use and policy trends in the Motueka catchment.

The purpose of this study was to gain a better understanding of the effects of water allocation schemes on the shallow aquifer and surface water systems in the Upper Motueka River catchment. A groundwater–river interaction model was developed using FEFLOW software linked with a custom-built river model. FEFLOW employs a finite element modelling approach, which allows mesh refinement in areas where intensive interactions were expected between streams and shallow aquifers. The river model was used to calculate river flow routing, using the simulated groundwater losses and gains from the FEFLOW model on a daily time step. In the river model, the river water levels were estimated using rating curves obtained with Manning's equation, in combination with river cross-section profiles developed in MIKE 11. The linked groundwater–river model was calibrated to groundwater level and river flow measurements for the period from 1 July 2001 to 30 June 2003, which was one of drier periods on record for the catchment. The calibrated model was then used to simulate the effects of six different groundwater allocation scenarios selected in consultation with Tasman District Council. Modelled groundwater and river flows for each scenario were used to identify pinch-point areas that were the most affected by groundwater abstraction. The results of this study will be used to plan defensible water management policies for the Upper Motueka River catchment, such that groundwater abstraction can be authorised while maintaining river flows above a prescribed level.

Description of the study area

The Motueka Catchment drains an area of 2180 km² and is dominated by mountains and hill country, with about 67% of the catchment area having land surface slopes greater than 15°. The Upper Motueka River catchment is composed of three main river valleys: the Motupiko River (344 km²), the Tadmor River (124 km²) and the Upper Motueka River (419 km²). The main morphological features of the catchment area are steep, narrow headwater channels and broad floodplains and terrace systems within hilly Moutere gravel terrain below the Upper Motueka Gorge to the Wangapeka River confluence.

The study area covers 31.9 km² and encompasses almost all of the areas of groundwater abstraction in the Upper Motueka River catchment (Fig. 1). The study area incorporates the Motueka River just above the confluence with the Wangapeka River to approximately 8 km upstream of the confluence with the Motupiko River, 3 km of the Tadmor River upstream of the confluence with the Motueka River, and approximately 15 km of the Motupiko River upstream of the confluence with the Motueka River. The terrain elevation ranges from 110 m above sea level (asl) at the downstream model boundary to 240 m asl at the Gold-pine river gauging site and 305 m asl upstream of the Korere river gauging site (Fig. 1). The terrain elevation in the area below the Tapawera gauging site ranges from approximately 113 m asl in the centre of the valley to 155 m asl on the valley sides. Likewise, the elevation across the valley bottom at the confluence of the Motupiko River and the Motueka River near the Kohatu river gauging site ranges from approximately 185 to 200 m asl. The average ground elevations at the upstream ends of the Motupiko and Motueka rivers, as implemented in the model, are approximately 310 m asl and 245 m asl, respectively.

Groundwater in the Upper Motueka River catchment is abstracted from shallow unconfined alluvial aquifers in the Quaternary river terrace formations and modern river deposits. In hydrogeological terms, these aquifers are considered as a single unit because they are hydraulically highly connected. Five gravel formations have been identified within the study area upstream of the Wangapeka River confluence (Fig. 2). These are (from oldest to youngest) the Moutere Gravel, Manuka, Tophouse, Speargrass, and modern river gravel formations. Characteristics of these gravel formations are provided in great detail by Stewart *et al.* (2003) and summarised by Hong *et al.* (2010). The Quaternary gravels are underlain by the Moutere Gravel Formation throughout the whole study area (Stewart *et al.*, 2003). Soil information is derived from a regional soil survey (Chittenden *et al.*, 1966) and is summarized by Hong *et al.* (2010). The most common soils in the area are Tapawera sandy loams, Motupiko loams, and Atapo stony silt loams. There are also small areas of Dovedale, Sherry and Kikiwa loams and Korere and Spooner soils.

Mean annual rainfall for the Motueka River catchment is 1600 mm, while mean annual rainfall for the Upper Motueka River catchment is slightly lower (Basher, 2003).

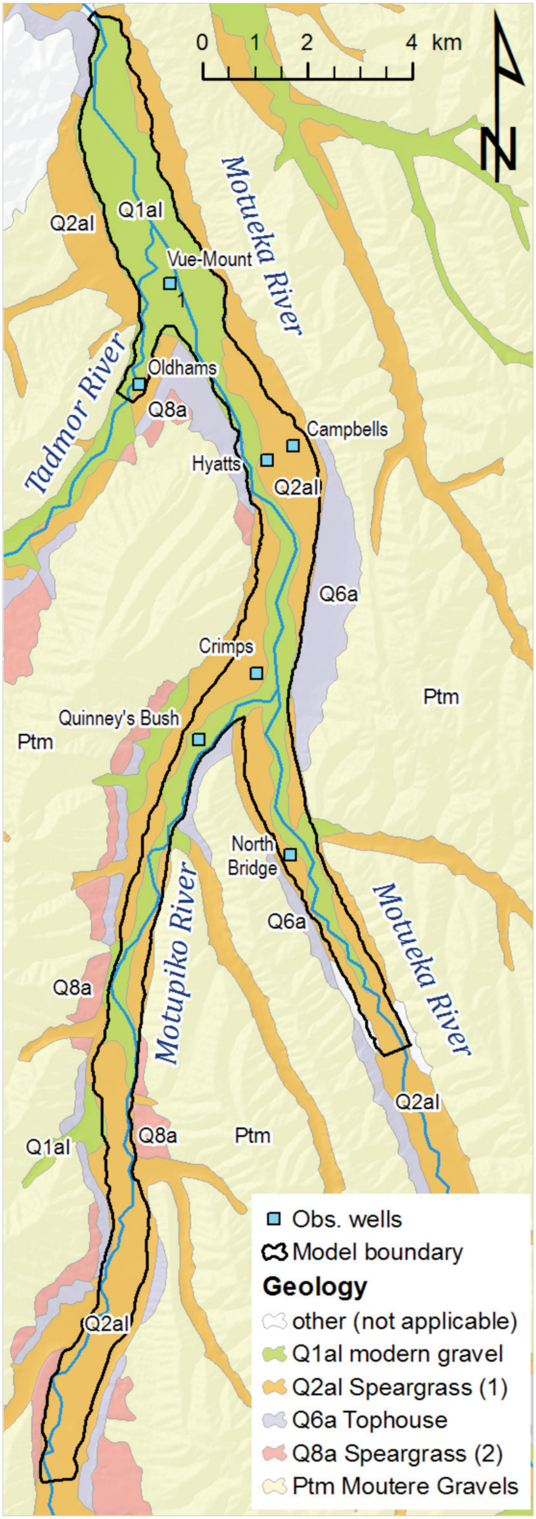


Figure 2 – Simplified geological map of the model domain and surrounding area of the Upper Motueka River catchment. For a full explanation of geologic symbols (Q1al, Ptm, etc.), see Rattenbury *et al.* (1998).

The rainfall distribution varies within the Upper Motueka River catchment study area, with an increasing gradient both northwards and southwards away from the Tapawera gauge, such that at the north and south margins of the study area the annual precipitation higher than at Tapawera (Basher, 2003). The annual precipitation data records at Wangapeka station, which is located west of the study area, are available for 1924-1928 and 1963-1996 and vary from 1200 mm to 2500 mm for the period of record (Basher, 2003). In 2002, the annual precipitation in the Upper Motueka River catchment study area ranged from 1010 mm to 1150 mm and is below the long-term mean annual precipitation at the Wangapeka station. The monthly precipitation in the study area in July was <20 mm in 2001, <40 mm in 2002 and <16 mm in 2003. The monthly precipitation in February was <52 mm in 2002 and <10 mm in 2003. Therefore, the 2001-2003 time period used in this study represents drier climatic conditions in the Upper Motueka River catchment and was specifically selected to evaluate the effects of the groundwater abstraction scenarios for a water-stressed period.

Annual open-pan evaporation downstream at Motueka is 1106 mm and is strongly seasonal, with mean monthly values ranging from 27 mm in July to 179 mm in January. Evaporation is expected to be slightly lower at Tapawera, based on data from Tasman District Council (Basher, 2003). Although annual evaporation is less than annual rainfall, soil moisture deficits are common in summer when evaporation exceeds rainfall, and irrigation is required for many crops in the catchment. The hydrogeology information has been already presented by Stewart *et al.* (2003), Basher (2003) and Hong *et al.* (2010) and is not repeated in this paper.

Methods

Groundwater model

The finite-element model (FEFLOW) was chosen due to its ability to represent narrow and long catchments with high terrain slopes such as those in the Upper Motueka catchment. The groundwater model represented the entire 31.9 km^2 study area (Fig. 2). Terrain elevation was generated using a 20 m resolution Digital Terrain Model data set (Stewart *et al.*, 2003). The aquifer was discretised using one layer of 6-node triangular prisms, with the entire model domain comprising 29299 nodes and 30386 elements of varied vertical thickness (Fig. 3). Aquifer thickness was defined based on previous hydrogeological work (Stewart *et al.*, 2003). The smallest aquifer thickness occurred in the northern part of the model (from Wangapeka to Tapawera) and was estimated to be 9 to 10 m. Greater aquifer thicknesses occurred in the southern part of the model (Kohatu to Goldpine/Korere), where the aquifer was estimated to be 14 to 15 m thick. The bottom slice of the model represented the bottom of the alluvial aquifer. The top of the aquifer was modelled as a freely movable surface that represented the water table.

To simulate a groundwater flow system with FEFLOW, the hydraulic conductivity (K) of the aquifer was specified for each element in the mesh. Hydraulic conductivity measurements were available for the seven wells shown in Figure 2, based on analysis of slug tests and constant rate pump tests conducted by Tasman District Council (Hong *et al.*, 2010). Minimum, median and maximum hydraulic conductivity values in the tested wells were 54, 620 and 940 m/day, respectively. Hydraulic conductivity at other elements was initially estimated by interpolation. The model domain was divided into regions, each representing a different hydraulic conductivity, based on the geological map (Fig. 2). The distribution

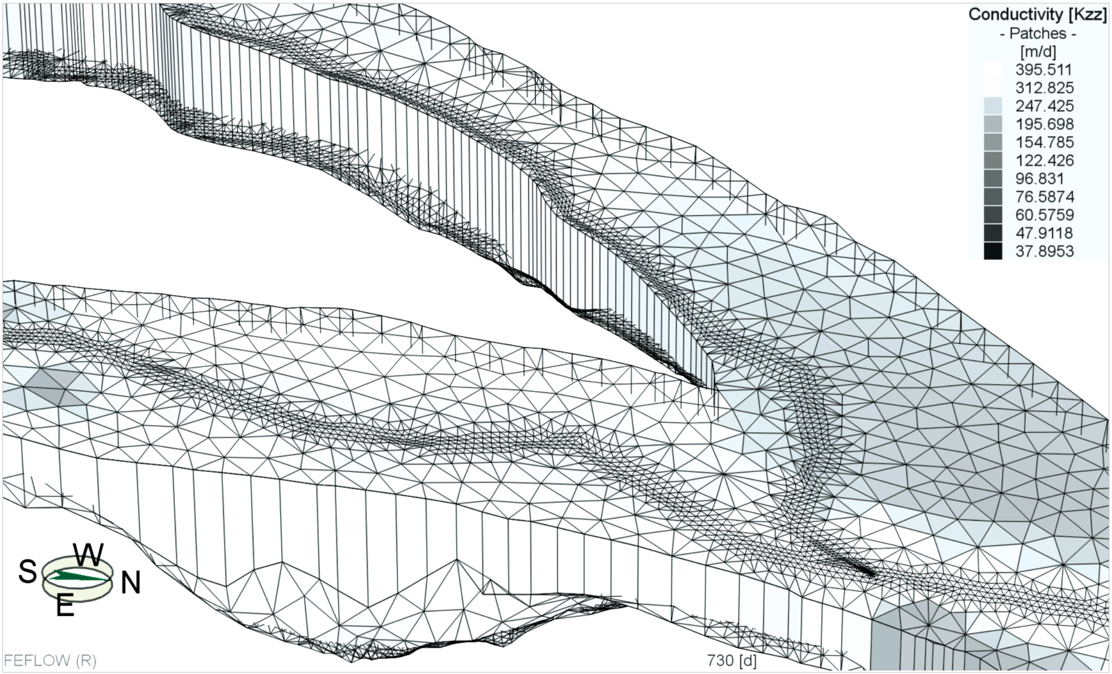


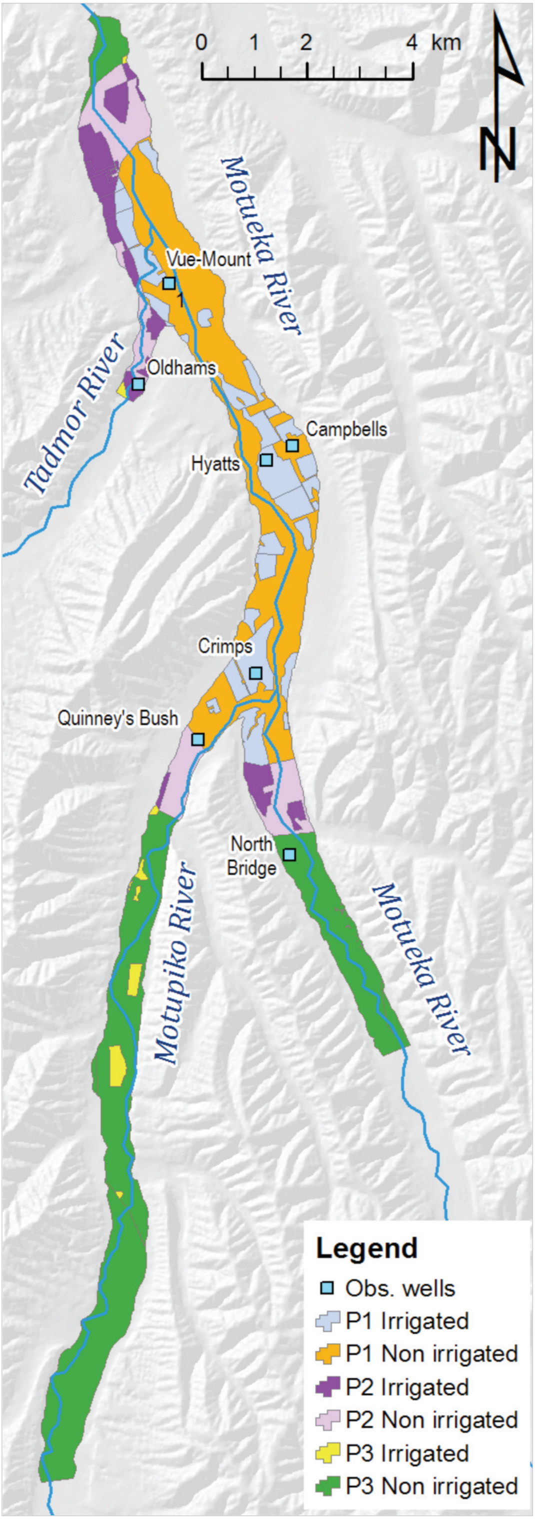
Figure 3 – Three-dimensional view of the aquifer thickness near Kohatu represented by a finite-element mesh in FEFLOW. The shading is vertical hydraulic conductivity, the base of the elements are represented by the bedrock basement and the top of the elements are represented by the water table at the last time step.

of horizontal hydraulic conductivity in each region was based on the Akima inter/extrapolation technique, which employs a cubic transfer function to interpolate between the wells (Hong *et al.*, 2010). The hydraulic conductivity values initially assigned to each zone were subsequently adjusted during the model calibration.

The model was run for a two-year period using a daily time step. The Landcare Research irrigation scheduling model was used to estimate the irrigation demand and drainage for actual irrigated areas in use under 2001-2003 climatic conditions (Ekanayake *et al.*, 2009). Daily groundwater abstraction at each well was estimated by Landcare Research, based on location, irrigated land uses, and abstraction rate consented by Tasman District Council. Groundwater abstraction wells were implemented in the model for the different scenarios. In all cases each abstraction well was positioned at the nearest node in the model mesh.

Modelling rainfall and irrigation recharge

Rainfall and irrigation recharge to the top surface of the finite element mesh was estimated using a daily soil water balance model based on daily evapotranspiration estimates and water-holding capacities for the main soils in the Upper Motueka River catchment (Ekanayake *et al.*, 2009). Three different rainfall recharge zones (P1, P2, and P3) were defined, based on the distribution of the dominant soil types within the study area (Fig. 4). Each recharge zone was further divided into irrigated and non-irrigated areas; the irrigated areas differed between the scenarios as described below. For all recharge zones (P1, P2, P3), the readily available



water capacity of the soil (RAW) was taken as 100 mm and plant available water capacity (PAW) was taken as 220 mm for all soil types. The rainfall at each farm within each zone was scaled according to location using the annual rainfall isohyets for the Upper Motueka River catchment. Rainfall recharge in each zone was estimated using the daily soil water balance model described below.

For all scenarios, the soil water balance model was based on the following equation (see Ekanayake *et al.*, 2009):

$$SD_n = SD_{n-1} + AET - R_e - I_r \tag{1}$$

where R_e [mm] is the effective rain, AET [mm] is the actual evapotranspiration, SD_{n-1} [mm] is the soil water deficit at the start of the day, SD_n [mm] is the soil water deficit at the end of the day, and I_r [mm] is the irrigation. Effective rain (R_e) was estimated by assuming that a fraction of actual daily rainfall (R) would drain through macropores if the daily rain total exceeded a predefined threshold, which was taken as 2 mm. If the daily rain total was larger than the threshold value, 90% of the total daily rain was assumed to be effective rain, and the remaining 10% of the total daily rain was assumed to be drained through macropores.

Actual evapotranspiration (AET) was taken as a function of soil water deficit (SD) (Fig. 5). Modelled AET reached potential evapotranspiration (PET) if SD was less than 1 mm, whereas AET = 0 if SD was greater than the readily available water capacity of the soil (RAW). For RAW < SD > 1, AET varied between 0 and PET according to the function shown in Figure 5. Hence when SD < 0, the soil was modelled as saturated, and when

Figure 4 – Distribution of three different rainfall recharge zones and their irrigated areas. Blue squares indicate seven named groundwater observation wells.

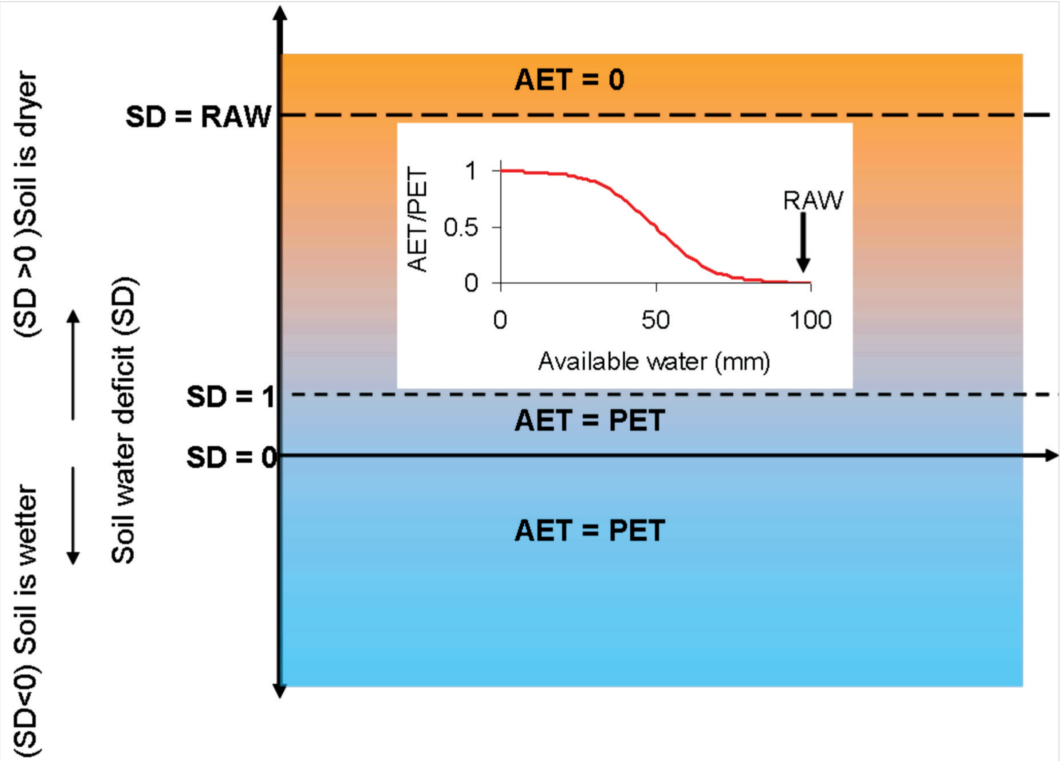


Figure 5 – Estimation of actual evapotranspiration (AET) according to the soil water deficit. The only hydraulic property used in the model is the readily available water capacity (RAW), which is taken as 100 mm for all soil zones in the study area.

SD = 1, the soil was modelled as unsaturated but was assumed to have the potential to meet PET. AET was taken as equal to PET if the soil was irrigated, regardless of the magnitude of the soil water deficit. Soil water deficit at the start and end of the day (SD_{n-1} and SD_n, respectively) were determined from the algebraic sum of irrigation (I_r), AET and effective rain (R_e) based on Equation 1 above.

Irrigation was applied in the model if the soil water deficit exceeded 50% of the readily available water capacity of the soil (Ekanayake *et al.*, 2009). Five millimetres of water was modelled as remaining in the soil if the irrigation exceeded the soil water deficit by 5 mm, and the excess water was assumed to be removed as drainage. Modelled soil drainage took place only if the irrigation plus any rainfall exceeded the soil moisture deficit:

$$\text{Drainage} = -0.1R + (SD - I_r) + 5 \qquad \text{if } (SD - I_r) < -5 \text{ mm} \qquad (2)$$
$$\text{Drainage} = -0.1R \qquad \text{if } (SD - I_r) > -5 \text{ mm}$$

where 0.1R is the macropore drainage if the rainfall exceeded the 2 mm threshold value defined above. Note that the sign of the drainage is negative.

Hill slope recharge model

Eleven zones of potential hill slope recharge to the aquifer were identified (Fig. 6). This hill slope recharge has been found to have a small impact on river flows or groundwater levels, compared to rainfall

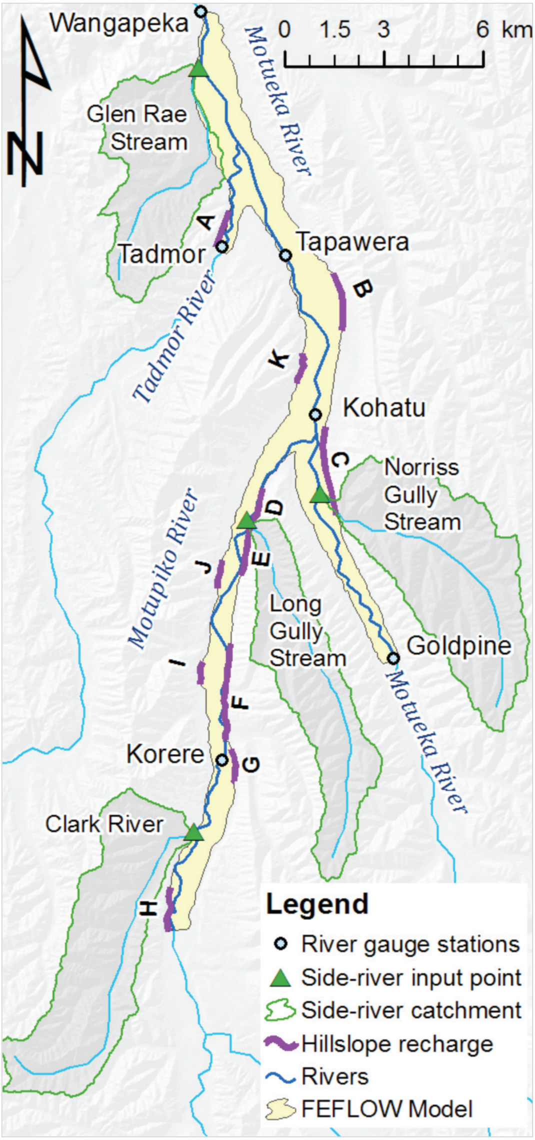


Figure 6 – Locations of river gauging stations, side-river inputs, and hill slope recharge zones used in the FEFLOW groundwater model.

recharge and river recharge to the aquifer (Ekanayake *et al.*, 2009). This point can be derived from the water balance for the study area shown in Table 1. In the model, the hill slope recharge of 0.092 million m³/year is very small compared to the Scenario 1 total areal drainage of 12.74 million m³/year. However, the hill slope recharge does influence local water budgets, and hence the zones of potential hill slope recharge were implemented in the groundwater model using a flux boundary condition.

Flow net analysis was applied to estimate the hill slope recharge in this study because it requires much less spatial and temporal data compared to other approaches such as numerical groundwater models. The assumptions behind flow net analysis were: 1) the flow is two dimensional; 2) the flow is in steady state for a given time step; 3) the soil is homogenous and isotropic, and hence stream lines are perpendicular to the equipotential lines; 4) the bottom boundary is impermeable; and 5) the pattern of flow nets are drawn as approximate squares, with N_d representing the number of equipotential drops and N_f representing the number of flow tubes. Flux through a unit thickness of one square element Q_{el} [m³/m/day] per meter of section perpendicular to the element is given by (Freeze and Cherry, 1979):

$$Q_{el} = K \frac{\Delta h}{\Delta x} \Delta z \qquad (3)$$

where K[m/day] is the hydraulic conductivity, Δh[m] is the hydraulic head drop across the element, and Δz [m] and Δx [m] are the vertical and horizontal dimensions of a flow net element, respectively. Assuming a square shape of the flow elements, with $\Delta z \approx \Delta x$, the total flow Q [m³/m/day] becomes:

$$Q = \frac{KH_t N_f}{N_d} \qquad (4)$$

where H_t [m] is the total head drop across the flow system, equal to $H_t = \Delta h N_d$.

Details on the development and calibration of the hill slope recharge model are provided by Ekanayake *et al.* (2009) and are briefly introduced below. Capacitance probes and time-domain reflectometry soil moisture instruments were installed at the foot of the hill slopes at Korere and Paratiho to measure changes in phreatic levels due to climate and topography. The instruments were configured to measure and record hourly readings of rainfall and phreatic levels. Measured data at the Paratiho hill slope site in the 2003-2005 summer and winter seasons were used to develop and calibrate the model equations and parameters. All other measured data at both the Paratiho and Korere sites were used to validate the model. A reasonable correlation between the observed drainage and daily rainfall was found (data not shown; see Ekanayake *et al.*, 2009). An empirical formula invoking a scaling factor related to the ratio of catchment area to interface boundary length was then used to estimate hill slope recharge at the other locations shown in Figure 6. Finally, the predicted daily hill slope recharge was input to the groundwater model, using flux boundary conditions at hill slope recharge boundary nodes.

River model

The river system in the model was composed of three large rivers and four small streams (Fig. 6). The large rivers were the Motueka River, the Motupiko River and the Tadmor River. The four small streams, which enter the study area from the hills and were implemented in the model as side river recharge, were the Clark River junction with the Motupiko River, the Glen Rae stream junction with the Motueka River, Long Gully junction with the Motupiko River, and Norriss Gully junction with the Motueka River.

The large rivers and small streams were implemented in FEFLOW using a head-dependent, third-kind (Cauchy) boundary condition. This Cauchy boundary condition simulated head-dependent flow into and out of a stream, similar to the MODFLOW River Package (Diersch, 2005). Modelled stream flow was thereby increased in areas where the river gains water from the aquifer and reduced in areas where river water seeps out of the river into the aquifer. In our study, we used the actual river levels as input for each time step, which means that the modelled river levels incorporate any overland flow that occurred within or upstream of the study area.

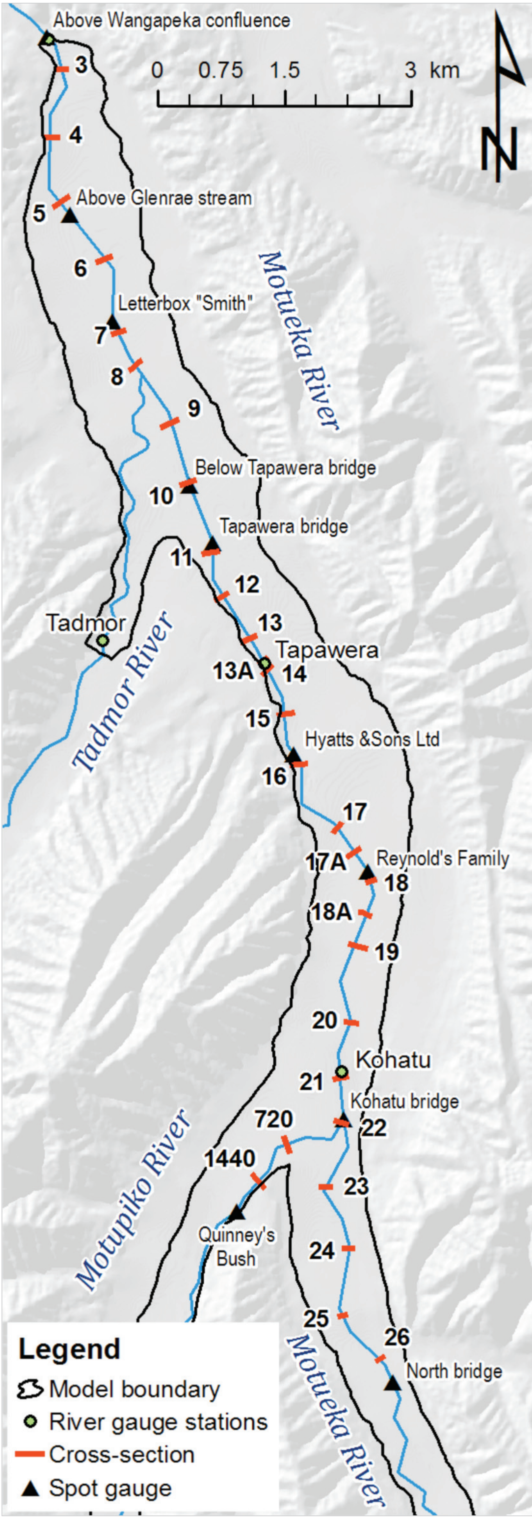
Twenty-eight river cross-sections were surveyed in the three large rivers (Fig. 7). The river cross-sections were used to determine the appropriate finite element size at corresponding locations within the model domain. River widths, depths and cross-sectional profiles vary significantly across the study area, see Hong *et al.* (2010). For example, the average slope of the Motueka River bed between Wangapeka and Goldpine was calculated at 0.007 m/m, whereas the average slope of the Motupiko River bed was estimated to be 0.017 m/m. The river bed was assumed to be sealed by a layer of thickness d [m] and hydraulic conductivity K_0 [m/day]. Normally, K_0 is assumed to be much smaller than the hydraulic conductivity of the adjacent aquifer. The flux q [m/day] between the aquifer and the stream (or vice versa) was controlled by the difference between river stage h^R [m] and groundwater head h [m] at each node and each time step:

$$q = -K_0 \frac{h^R - h}{d} \tag{5}$$

The riverbed resistance coefficient Φ [d^{-1}], sometimes also called the leakance coefficient, represented the sealing of the riverbed in comparison to the adjacent aquifer (Diersch, 2005):

$$\Phi \approx \frac{K_0}{d} \tag{6}$$

It is possible to set differing leakance values for inflowing and outflowing conditions, but this was not been done in the present study due to lack of data confirming any



difference. The leakance values were one of the major variables adjusted during the model calibration process.

The river model was developed in-house by GNS Science and is similar to the recent MODFLOW stream flow routing package (SFR1), which performs river flow routing and allows different methods of correlation of river water levels and flows (USGS, 2004). In our study, we considered coupling of MIKE 11 and FEFLOW, but the temporal resolution of daily river water levels in FEFLOW was too crude for the time steps required for MIKE 11. The river model was implemented in this study using a series of idealised stream reaches, as shown schematically in Figure 8. In our approach, the modelled river flow is routed from the headwater gauging stations to the downstream gauging station and includes the groundwater gains and loses simulated with FEFLOW. River water levels at the inflow and outflow of the stream reach were defined as h^R_{in} and h^R_{out} respectively. The outflow Q^R_{out} [m³/day] from a simplified water budget for the stream reach is:

$$Q^R_{out} = Q^R_{in} - Q^G \tag{7}$$

where Q^R_{in} [m³/day] is the river water inflow into the stream reach and Q^G [m³/day] is the stream flow gain from or loss to the aquifer. Flow data from the Goldpine (Motueka Gorge), Korere and Tadmor gauging stations were selected to provide river inflows Q^R_{in} at the upstream end of the study area. These inflow values were used for river flow routing using Equation 7 for the entire river system. The river discharge was subsequently calculated at the downstream end of each stream reach.

Figure 7 – Location of river cross-section surveys and river sites in the study area. Spot gauging measurements were undertaken by Tasman District Council on 9 February 2002.

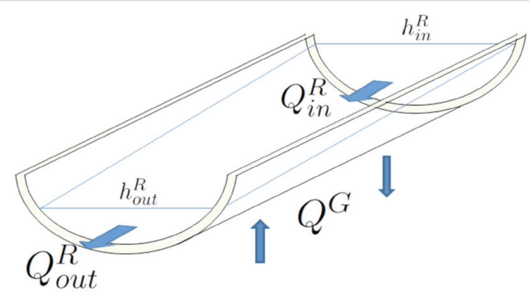


Figure 8 – A hypothetical river channel between two river cross-sections with river inflow Q^R_{in}, river outflow Q^R_{out} and groundwater flow losses or gains to the channel Q^G. The river water levels at the beginning and the end of the river channel are denoted by h^R_{in} and h^R_{out}, respectively. For locations of river cross-sections in the study area refer to Figure 7.

The stream reaches modelled in this study were bounded on their upstream and downstream ends by the cross-section measurements depicted in Figure 7. The river water levels were estimated using rating curves developed from Manning's equation and MIKE 11 river cross-sections. The river discharge Q^R [m^3/day] for uniform river flow in a modelled stream channel was related to river water level using Manning's equation (Chow 1964):

$$Q^R = \frac{1}{n} A R^{2/3} S^{1/2} \tag{8}$$

where A [m^2] is the cross-sectional area of the flowing water in the stream channel, R [m] is the hydraulic radius of the stream reach, S [m] is the energy slope of the river channel and n [-] is the Manning roughness coefficient. The Manning coefficient was determined from the following expression:

$$n = (n_b + n_1 + n_2 + n_3 + n_4)m \tag{9}$$

where n_b [-] is the value for straight, uniform and smooth channels, n_1 [-] is the correction factor for the effect of surface irregularities, n_2 [-] is the value for variations in shape and size of the channel cross section, n_3 [-] is the value for obstructions, n_4 [-] is the value for vegetation and flow conditions and m is the correction factor for meandering of the river channel. A uniform Manning coefficient of 0.05 was used in this study, based on values reported by Chow (1964).

The groundwater flow model was sequentially linked to the river flow model using Equation 7. At a given time step, the groundwater model would have river water levels h^R and would calculate the water exchange Q^G between the aquifer and stream for each river reach. In the river flow model, the new river flows were calculated using river flow routing and the computed value of Q^G, allowing new river water levels to be computed at each river cross-section using Equation 8. Operationally, the groundwater and river models were linked using a FEFLOW plug-in, which was developed to record all time-varying model outputs to a multidimensional array file.

Scenario modelling

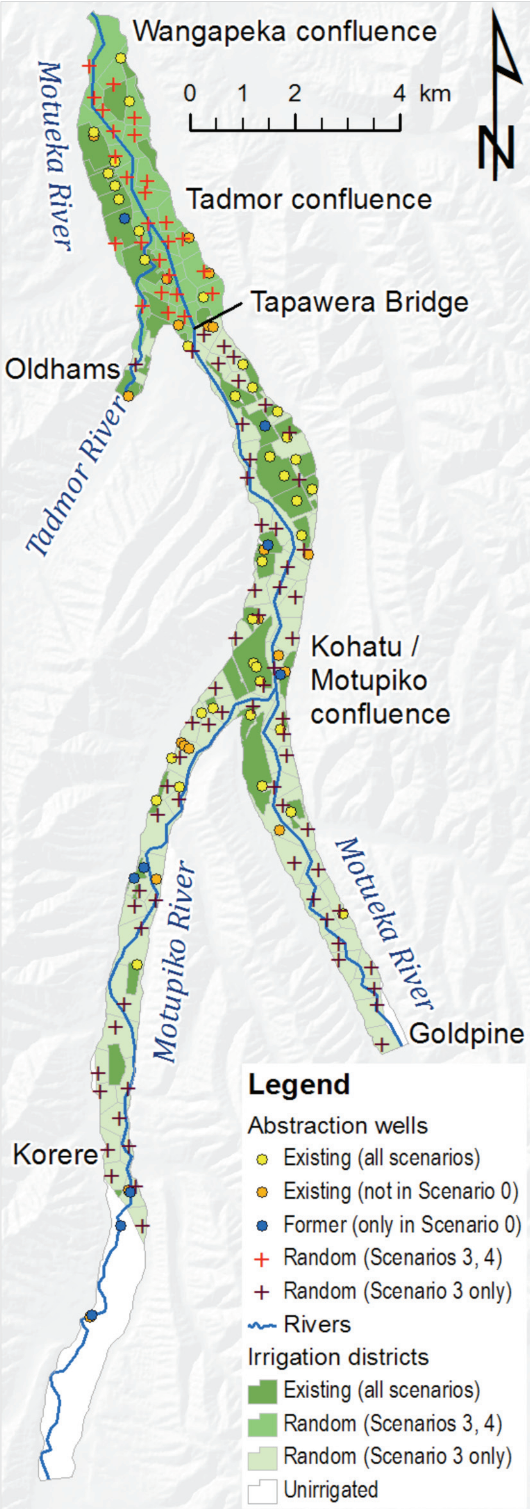
Variations in climatic conditions will affect the hydrology of the catchment, but they are not critical for the purpose of this study. Tasman District Council is interested in setting limits for low-flow conditions, as would occur in the drier years. This is the reason for undertaking the modelling for the 2001-2003 period, which was one of the drier periods on record. Accordingly, the water management scenarios that are compared for this time period allowed us to test the different effects for a period of acute water stress. Therefore, the 2001-2003 climatic conditions were applied for all scenarios to simulate spatial and temporal variations in irrigation demand provided by Tasman District Council.

The effects of increasing groundwater extraction on river flows and water levels were evaluated for six groundwater management scenarios (Scenarios 1-4, 5a and 5b) using the calibrated Upper Motueka River catchment groundwater flow model (Scenario 0). The model domain, mesh structure, aquifer hydraulic properties, initial hydraulic heads and method of linking the groundwater and river models were the same for all scenarios, and all scenarios used the same 2001-2003 climate conditions. The scenarios were distinguished by differing locations and/or pumping schedules of irrigation wells and consequently groundwater recharge rates (Table 1, Fig. 9).

Scenario 0 represented the base case of actual daily groundwater abstraction from 47 wells at rates relevant to the period from 1 July 2001 to 30 June 2003 (Fig. 9). In Figure 9, the locations of these wells are shown by 38 yellow circles, which indicate wells used in all other scenarios, and 9 blue circles, which indicate wells that are unique for Scenario 0. Climate and river flow inputs to the model were based upon data from the 2001-2003 period. Total annual groundwater abstraction was modelled at 1.99 $\times 10^6$ m^3 and total irrigated area was modelled as 737 ha. Total annual drainage input to the groundwater system was modelled as 12.74×10^6 m^3; 77.7% of the annual drainage recharge occurred in non-irrigated areas and therefore represented solely drainage from rainfall, whereas 22.3% of the annual recharge occurred in irrigated areas and therefore represented a combination of drainage from rainfall plus irrigation return flow (the latter accounting for less than 1% of total annual drainage recharge across the whole model). Because Scenario 0 simulated climate and groundwater allocation in 2001-2003, it was used during model

Table 1 – Summary of groundwater abstraction, land use, drainage and river inflows for all scenarios. Locations of groundwater abstraction wells, irrigable areas for all scenarios are shown in Figure 9.

Parameter			Scenario 0	Scenario 1, 5a, 5b	Scenario 2	Scenario 3	Scenario 4
Number of groundwater wells			47	58	58	150	84
Pumping from wells		mean, m^3/day/well	115.7	93.5	290.8	112.7	101.2
		million m^3/year	1.99	1.98	6.16	6.17	3.10
Irrigable area		ha	737	737	737	2759	1270
		% of model area	23.1	23.1	23.1	86.5	39.8
Drainage in irrigated areas	*from irrigation return*	million m^3/year	0.12	0.12	1.72	0.44	0.20
		% of drainage	4.3	4.1	38.7	4.0	4.0
		% of well abstraction	6.1	5.9	27.9	7.1	6.3
	from rainfall	million m^3/year	2.72	2.72	2.72	10.67	4.72
		% of drainage	95.7	95.9	61.3	96.0	96.0
	Sum	million m^3/year	2.84	2.84	4.44	11.11	4.92
Non-irrigated area		hectares	2452	2452	2452	430	1920
		% of model area	76.9	76.9	76.9	13.5	60.2
Drainage in non-irrigated areas		million m^3/year	9.90	9.90	9.90	1.94	7.91
		% of total recharge	77.7	77.7	69.0	14.8	61.6
Total areal drainage		million m^3/year	12.74	12.74	14.34	13.05	12.83
Total river inflows		million m^3/year	486.5				
Hill-side recharge		million m^3/year	0.092				
Side stream recharge		million m^3/year	5.31				
Motueka at Goldpine		million m^3/year	281.9				
Motupiko at Korere		million m^3/year	124.5				
Tadmor at Oldhams		million m^3/year	80.0				



calibration of the daily groundwater head and river flow measurements made during this same time period.

Scenario 1 represented actual and estimated groundwater abstraction at the end of 2008, but applied to the dry climate conditions that existed in 2001-2003. The irrigated area and rainfall drainage were unchanged from Scenario 0. In Figure 9, 38 yellow and 20 orange circles show the locations of 58 irrigation wells used in the model. Although the number of wells had increased, total annual abstraction, at 1.98×10^6 m^3, was roughly the same as in Scenario 0. Note that 9 groundwater abstraction wells (blue circles in Fig. 9) were operational in 2001-2003 and included for Scenario 0 but were not operational in 2007-2008 and therefore were excluded from Scenario 1. In addition, some wells had different groundwater abstraction schedules in Scenario 1 due to different land-use activities in 2007-2008 compared to 2001-2003. In summary, Scenario 1 was based on the calibrated model (Scenario 0) but with adjustments to the number, locations and pumping rates of groundwater abstraction wells to reflect conditions in 2007-2008.

Scenario 2 represented the 2001-2003 climate conditions and the same 58 irrigation wells from Scenario 1, except that simulated groundwater abstraction was increased to the maximum permitted groundwater take specified on each Tasman District Council water permit, corresponding to irrigation of the authorised area or weekly irrigation on each permit. Hence total abstraction in Scenario 2 was 6.16×10^6 m^3, i.e., roughly three times higher than in Scenarios 0 and 1; however, the modelled irrigated area was unchanged (Table 1). Total annual drainage in Scenario 2 was 14.34×10^6 m^3,

Figure 9 – Locations of groundwater abstraction wells and irrigable areas for all scenarios.

38.7% of which was modelled as derived from irrigation return flow.

Scenario 3 represented the 2001-2003 climate conditions under a 'full irrigation scenario' in which complete irrigation was assumed to occur over all potentially irrigable land at the same actual rates per hectare of water use from Scenario 1 (Table 1). The 92 wells shown by red and black crosses in Figure 9 were added to the existing 58 wells included in Scenario 1. The simulated total annual abstraction in Scenario 3 was about the same as for Scenario 2 and equals to 6.17×10^6 m^3/year (Table 1). The total annual abstraction in Scenario 3 is about three times higher than for Scenarios 0 and 1, but it was assumed to occur at 150 abstraction wells. Accordingly, the irrigated land area of Scenario 3 was roughly three times larger than the irrigated area in other scenarios evaluated in this study. A scenario with increased groundwater abstraction as well as increased irrigated land area was not considered because the environmental effects (river flow depletion and aquifer drawdowns) of Scenario 3 would likely be unacceptable to stakeholders.

Scenario 4 simulated the conditions from Scenario 1 (2001-2003 climate and actual irrigation in 2007-2008) at all locations upstream of Tapawera Bridge, in combination with conditions from Scenario 3 (full irrigated area) at all locations downstream of Tapawera Bridge. Scenario 4 included 84 abstraction wells and an irrigated area of 1270 ha, both being intermediate between Scenarios 1 and 3 (Fig. 9). Scenario 4 was designed as a potentially acceptable alternative to the full irrigation in Scenario 3, to provide guidance for Tasman District Council on the possibility of dividing the Upper Motueka River catchment into two subzones, with the subzone downstream of Tapawera Bridge having an increase in its current allocation limit.

Scenarios 5a and 5b were designed to simulate Scenario 1, with river water levels increased by 0.3 m or decreased by 0.3 m, respectively. Sriboonlue and Basher (2003) showed that the average riverbed level of the Motueka River across the Tapawera Plains fell by 0.3 m between 1960 and 2004. Measurements elsewhere in Tasman District confirm that the water table of the unconfined aquifer connected to a river like this will also fall as the river surface level falls. Scenario 5a determined what difference it would have made to Scenario 1 if riverbed levels were 0.3 m higher, as they were in 1960. Scenario 5b evaluated the opposite case, where riverbed levels were 0.3 m lower, as they may be ca. 55 years in the future. These scenarios evaluated the sensitivity of groundwater allocation to river gravel extraction and natural riverbed decline as the catchment continues to stabilise. The results were approximate because the actual changes in riverbed levels down the Tapawera Plains have increased in some locations and decreased in others, with variations of several metres from place to place. The number of modelled abstraction wells, total annual abstraction, irrigated area, and total annual drainage in Scenarios 5a and 5b were the same as for Scenario 1.

Results

Calibrated model (Scenario 0)

The model was calibrated for a daily time step over the period from 1 July 2001 to 30 June 2003. The primary objective in the calibration was to obtain a match between the modelled and observed groundwater levels at seven groundwater monitoring wells (Quinney's Bush, North Bridge, Crimps, Hyatt's, Campbells, Oldhams and Vue Mount) (Fig. 4). The model also aimed to match observed river flow at the Kohatu gauging station and river water levels at the Kohatu and Tadmor gauging sites (Fig. 7).

During the calibration process it was determined that river stage in some reaches did not allow for an accurate simulation of the exchange of water between the aquifer and river, particularly during irrigation periods. To improve the accuracy of the interpolated river stage in the model, six virtual 'intermediate' river stage sites were defined within the model domain (see Hong *et al.*, 2010). After the interpolation of river stage in the model, the spatial distributions of hydraulic conductivity and a single value of the leakance coefficient were adjusted to achieve a match between modelled and observed groundwater levels. In the absence of any other information, the spatial distribution of hydraulic conductivity in the model domain was interpolated between the locations of aquifer tests based on the surficial geology data. The hydraulic conductivity values in the calibrated model varied spatially and covered a range from 38 to 396 m/day (Fig. 10). The hydraulic conductivity values used in the calibrated model were in good agreement with the values determined by slug tests and pump tests (the minimum, median and maximum in the group of six tested pump-tested wells were 54, 620 and 940 m/day respectively). The global value for the river bed leakage coefficient was manually adjusted until the loss and gain of various river sections were as close as possible to the observations. The final value of the leakance coefficient (Φ) used in the model was 60 day^{-1}.

The RMSE fit and the measured and modelled groundwater levels at the seven monitoring wells are compared in Figure 11. The modelled groundwater levels follow observed groundwater level records and decrease during the irrigation season in the

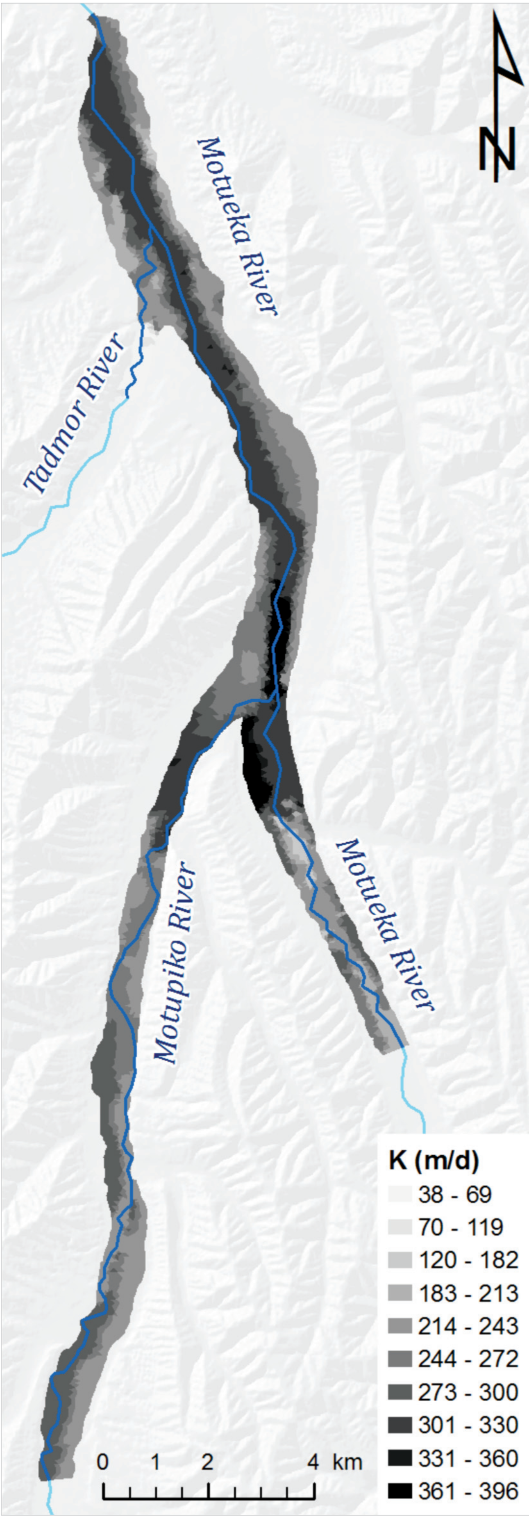


Figure 10 – Calibrated hydraulic conductivity distribution in the upper part of groundwater–river interaction model.

period of November to April, and recover to average levels each winter (by August). The modelled groundwater levels show a good match to the observed levels at all except the Campbells and Oldhams wells. At these two wells the modelled and observed groundwater levels follow the same pattern over time, but the modelled groundwater levels for the Oldhams bore are roughly 2 m too low. This was due to lowered river water levels near the model boundary to account for the absence of regional groundwater flow above the model boundary and is a conservative water balance assumption.

A good match is obtained for the measured and modelled river flow and levels at the Kohatu and Tapawera gauging stations (Fig. 12). The modelled river water levels for the Tapawera gauging station show a good match to observed river water levels at high river stages, but the match is poorer for low river stages. In order to get a better match, a Manning coefficient of 0.075 was selected for the Tapawera cross-section (see Equation 8). It can be seen from Equation 9 that the Manning coefficient is inversely proportional to river flow and a higher value of the Manning coefficient would result in a better match to low river water levels at the Tapawera cross-section.

In addition, one-time flow measurements were made on 9 February 2002 (Stewart *et al.*, 2003) and were available to calibrate the groundwater–river model (Table 2). For this day and over the entire domain (from Quinney's Bush and North Bridge to the Wangapeka confluence), the river flows measured during the gauging survey

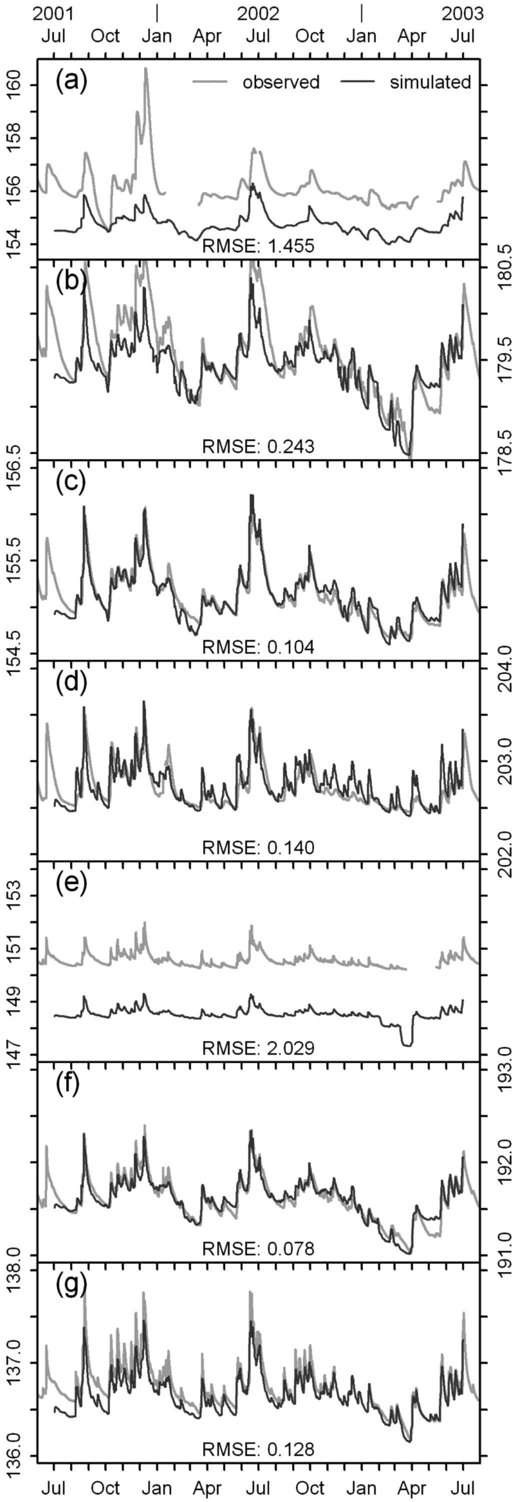
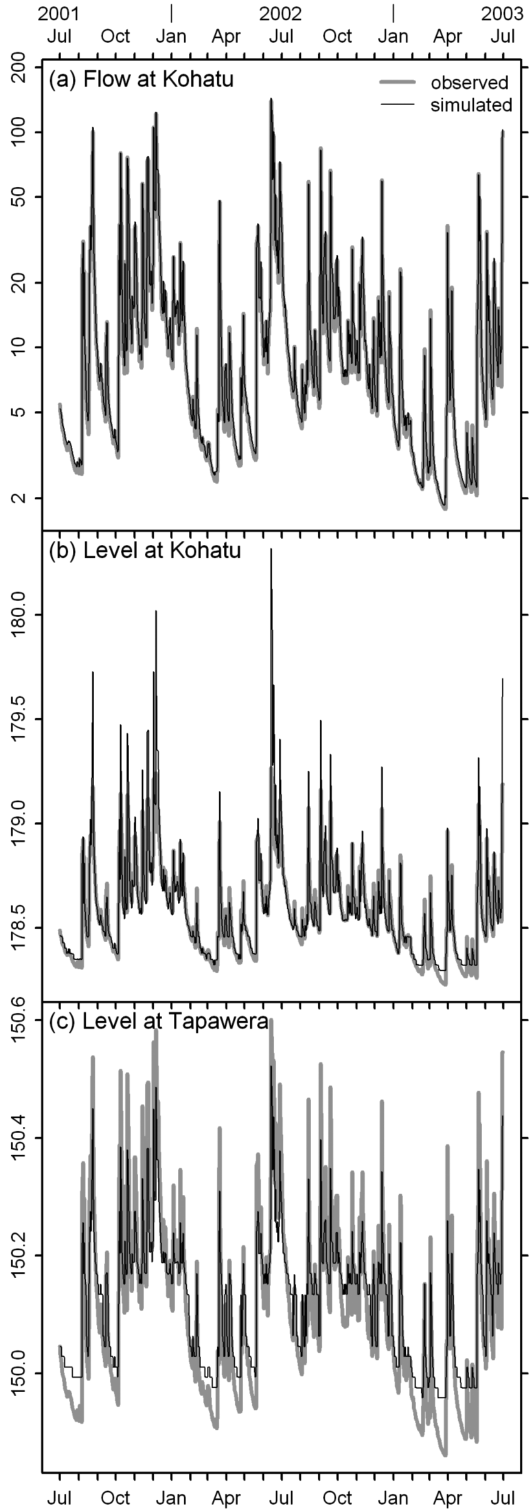


Figure 11 – Model calibration results for the groundwater level observation wells: (a) Campbells, (b) Crimps, (c) Hyatts, (d) North Bridge, (e) Oldhams, (f) Quinneys Bush and (g) Vue-Mount. Vertical scales are 7 m for (a) and (e), and 2 m for all others.



ranged from 1.5 at Kohatu to 2.4 m³/s at the Letterbox Smith site (locations shown in Figure 7). However, for this same day, the automatic flow recorder at the Kohatu gauging station indicated a river flow of 3.848 m³/s, which is significantly different from the flow measured by the gaugings. Therefore, we calculated water gains and losses between reaches and produced an estimate for observed river flow on 9 February 2002 at each site (Table 2). The estimated and modelled flows are comparable and provide confidence in the model predictions. Overall, the model reproduced the general dynamics of groundwater–river interchange acceptably well. The degree of misfit between the model predictions and the field gaugings is considered acceptable for two reasons. Firstly, the model's primary aim is to match groundwater level, which it achieves very well; the ability to match groundwater–river flux exchange is secondary because it is limited by the accuracy of the interpolation of river stage between measurement points. Secondly, the gauging measurements themselves may not be of sufficient accuracy to warrant any additional emphasis on matching them by the model. The measurements of river loss and gain were available for only one day, 9 February 2002, a day on which substantial rainfall of about 40 mm was recorded (greater rainfall was observed on only six other days in the entire two-year period for which the model is developed). The model simulations indicate that the volume of water lost and gained by the river is quite variable from day to day in response to rainfall (Hong *et al.*, 2010). It is therefore quite possible that the river levels may have changed

Figure 12 – Modelled and measured river flows (m³/s) with logarithmic scale and river water levels (m) for Kohatu gauging station (a–b) and river water levels (m) for Tapawera gauging station (c).

Table 2 – Measured, estimated and modelled flows [m³/s] for 9 Feb 2002. The estimated flow is based on differences between the measured sites. The observed and modelled river flows at Kohatu gauging station are shown in Figure 12(a).

Site	Observed Flow	Difference	Estimated flow	Modelled Flow	Difference
Above Wangapeka confluence	1.855	0.428	4.164	5.667	0.344
Glenrae	1.427	-0.992	3.736	5.323	0.130
Smiths	2.419	0.727	4.728	5.193	0.416
Below Tapawera	1.692	-0.188	4.001	4.777	0.045
Tapawera bridge	1.88	0.296	4.189	4.732	0.100
Hyatts	1.584	-0.023	3.893	4.632	0.105
Reynolds	1.607	0.068	3.916	4.527	0.091
Kohatu	1.539	N/A	N/A	4.436	N/A
Kohatu Gauging station	3.848	N/A	N/A		N/A

* N/A stands for 'Not Applicable'

significantly in the time taken to complete the gauging survey, even within individual river reaches, and that increasing river levels would have resulted in reduced recharge from groundwater to the river. This in turn suggests that the one-day record of gauged river gain and loss should be used only to guide to the model development, but not as a hard calibration target. A recommendation for future improvement of the model would be to provide additional data for the model calibration from concurrent river gauging surveys. Until better and concurrent flow measurements are made, no further adjustment of the model is appropriate.

Comparison of modelling results (Scenarios 0, 1-4, 5a and 5b)

The modelling results are presented in terms of modelled river flows and groundwater heads. These modelled river flows are compared to estimated mean and median flows at 'Motupiko at Quinney's Bush' and 'Motueka above Wangapeka confluence' river flow sites, which have available, albeit limited, river flow records (Basher, 2003). In addition, Basher (2003) estimated the mean annual low flow and 7-day low flows from 5-year and 10-year time series data for these two locations. Therefore, these low flow values are available for a comparison with modelled river flows during the irrigation season. Modelled groundwater heads are compared between scenarios at finer time scales at four identified pinch-point locations.

The mean and median modelled river flows for all scenarios are compared in Table 3 for four locations for a) the entire 2-year simulation and b) for only the irrigation seasons. These four locations are selected to represent river flows above river confluences and are therefore referred to as Motueka outflow, Tadmor outflow, Motueka at Tapawera and Motupiko outflow. The Motueka outflow location coincides with 'Motueka above Wangapeka confluence' site and the Motupiko outflow location represents the 'Motupiko at Quinney's Bush' site.

For all scenarios, the modelled river flows for the irrigation seasons are lower than corresponding modelled flows for the

Table 3 – Mean and median modelled river flow rate for all scenarios at four locations for a) the entire 2-year simulation and b) for the irrigation season only (19 December to 3 March). The statistics of change in river flow are calculated from daily differences relative to Scenario 0.

Flow at selected locations				Scenario 0	1	2	3	4	5a	5b
Motueka outflow	Flow rate during 2-year simulation	m^3/s	mean	16.12	16.12	16.04	15.99	16.08	15.85	16.14
			median	9.38	9.37	9.26	9.29	9.36	9.28	9.40
		% change from Sc 0	mean		0.0	-1.1	-3.0	-0.8	-0.9	0.3
			median		0.0	-0.1	-0.1	0.0	-0.3	0.1
	Flow rate during irrigation only	m^3/s	mean	8.69	8.70	8.53	8.32	8.60	8.64	8.71
			median	5.79	5.79	5.53	5.51	5.66	5.69	5.81
		% change from Sc 0	mean		0.2	-3.1	-9.6	-2.4	-0.4	0.4
			median		0.0	-3.7	-4.4	-1.2	-0.1	0.2
Tadmor outflow	Flow rate during 2-year simulation	m^3/s	mean	2.43	2.44	2.43	2.43	2.43	2.42	2.44
			median	1.01	1.02	1.01	1.01	1.01	1.01	1.02
		% change from Sc 0	mean		1.1	-1.0	-1.1	-0.6	0.0	1.9
			median		0.0	0.0	0.0	0.0	-0.5	0.4
	Flow rate during irrigation only	m^3/s	mean	1.05	1.06	1.04	1.04	1.04	1.05	1.06
			median	0.58	0.59	0.56	0.56	0.57	0.57	0.59
		% change from Sc 0	mean		3.4	-3.0	-3.6	-1.9	2.1	4.5
			median		0.1	-2.5	-0.9	-0.5	-0.2	1.5
Motueka at Tapawera	Flow rate during 2-year simulation	m^3/s	mean	13.31	13.32	13.27	13.23	13.32	13.13	13.32
			median	7.73	7.73	7.67	7.69	7.73	7.66	7.73
		% change from Sc 0	mean		0.2	-0.6	-2.4	0.2	-0.5	0.3
			median		0.0	-0.1	0.0	0.0	-0.1	0.0
	Flow rate during irrigation only	m^3/s	mean	7.38	7.39	7.30	7.12	7.39	7.36	7.39
			median	4.82	4.83	4.72	4.61	4.83	4.81	4.83
		% change from Sc 0	mean		0.6	-1.6	-7.5	0.6	0.3	0.6
			median		0.2	-2.0	-3.4	0.2	0.3	0.3
Motupiko outflow	Flow rate during 2-year simulation	m^3/s	mean	4.12	4.13	4.11	4.09	4.13	4.06	4.13
			median	2.31	2.32	2.30	2.30	2.32	2.31	2.32
		% change from Sc 0	mean		0.5	-0.3	-2.8	0.5	-0.3	0.5
			median		0.0	0.0	0.0	0.0	0.0	0.0
	Flow rate during irrigation only	m^3/s	mean	2.22	2.24	2.21	2.13	2.24	2.23	2.24
			median	1.33	1.32	1.31	1.30	1.32	1.31	1.32
		% change from Sc 0	mean		1.7	-0.7	-9.3	1.6	1.4	1.3
			median		0.7	-0.5	-3.3	0.6	0.6	0.4

whole two-year simulation period, and the magnitude of modelled flows are very similar at all four locations (Table 3). Scenarios 0 and 1 produce similar modelled mean and median river flows for the 2-year simulation and for the irrigation seasons. The modelled river flows for Scenario 2 are very similar to or slightly higher than modelled river flows for Scenario 3 at all locations. For instance, for the Tadmor outflow, the modelled river flows are equal for 2-year and irrigation season simulations. The modelled river flows for Scenario 4 are slightly lower than for Scenarios 0 and 1 and slightly higher than for Scenarios 2 and 3 when compared at the Motueka outflow. The modelled river flows for Scenarios 2 and 3 are similar and slightly lower than for Scenarios 0, 1 and 4 at the Motueka outflow, Motueka at Tapawera and Motupiko outflow. Scenario 5a has slightly lower and Scenario 5b has slightly higher modelled river flows compared to Scenario 0 at all four locations.

To evaluate the change in river flow under the various scenarios, the change of modelled river flow is provided relative to Scenario 0 (Table 3). For all four locations and all scenarios except Scenario 5a, the relative change in the modelled river flows is greater during the irrigation season than when the comparison is made for the whole 2-year simulation. For the whole two-year period of simulation, modelled mean river flows at four key locations differ by less than 3% among the various scenarios (Table 3), which is due to high winter flows reducing the difference. For example, the modelled mean flow during 2001-2003 for the Motueka River at Tapawera is 13.15 m^3/s for Scenario 0 and 13.07 m^3/s for Scenario 3, a difference of –0.6%. In comparison, modelled mean flows during the irrigation season at the same location and for the same two scenarios are 7.18 m^3/s and 6.92 m^3/s respectively, a (larger) difference of –3.6%. For Scenario 1, the maximum 1% change for the 2-year simulation and the maximum 1.7% change for the irrigation seasons are modelled to occur at the Motupiko and Tadmor outflows, respectively. The positive change indicates that the modelled river flow for Scenario 1 is larger compared to Scenario 0, which is due to less mean daily pumping from active wells in Scenario 1 (Table 1). The differences in modelled river water levels between Scenario 0 and Scenarios 1-4 show a similar pattern during irrigation seasons (Table 3).

Previously measured mean and median flows for 'Motupiko at Quinney's Bush' are 5.15 m^3/s and 2.50 m^3/s and for 'Motueka above Wangapeka confluence' are 12.03 m^3/s and 6.99 m^3/s, respectively (Basher, 2003). For the 'Motupiko at Quinney's Bush' site, mean annual, 5-year and 10-year 7-day low flows were estimated to be 0.49 m^3/s, 0.21 m^3/s and 0.07 m^3/s, respectively (Basher, 2003). For the 'Motueka above Wangapeka confluence' site, mean annual low flow is 2.13 m^3/s, 5-year 7-day low flow is 1.56 m^3/s, and 10-year 7-day low is 1.42 m^3/s (Basher, 2003). For all scenarios at the Motueka outflow (i.e., the 'Motueka above Wangapeka confluence' location), the modelled mean and median river flows are above the estimated mean and median flows previously reported by Basher (2003). However, the modelled mean and median river flows during the irrigation season are below the estimated mean and median river flows of Basher (2003). For all scenarios at the Motupiko outflow (i.e., the 'Motupiko at Quinney's Bush' location), the modelled mean and median river flows for 2-year simulation are slightly below the estimated mean and median river flows from Basher (2003). For the irrigation season, estimated mean and median annual river flows by Basher (2003) are about 2 times higher than the mean and median modelled river flows. Therefore, we can conclude that mean and median modelled flows are similar to those estimated by Basher (2003).

To compare estimated mean annual, 5-year and 10-year 7-day low flows, the modelled river flows are shown for a representative model day during the irrigation season (8 February 2003) (Fig. 13). The modelled river flows are routed from the headwaters at Korere, Goldpine and Oldhams gauging points via confluences at Kohatu and Tadmor to the outflow from the Upper Motueka River catchment at Wangapeka. In Figure 13, the 'Motupiko at Quinney's Bush' site corresponds to the Motupiko River above the Kohatu confluence and the 'Motueka above Wangapeka confluence' site corresponds to the Wangapeka outflow. For the 'Motupiko at Quinney's Bush' site, the modelled river flows have the smallest values among all scenarios, and for Scenario 3 are below the mean annual flow and above 5-year and 10-year 7-day low flows. Modelled river flows for the rest of the scenarios are very similar to estimated mean annual low flow and are above the 5-year and 10-year 7-day low flows. For the 'Motueka above Wangapeka confluence' site, the modelled river flows for Scenario 3 are slightly below the estimated mean annual low flow and are slightly above the 5-year and 10-year 7-day low flows. The modelled river flows for Scenario 3 are lower than for other scenarios at this location. Scenarios 2 and 4 have similar flows below the Tapawera Bridge. As the result, the low flows reported by Basher (2003) are not breached for any of the modelled scenarios except for Scenario 3 for the estimated mean annual low flow near 'Motupiko at Quinney's Bush' and 'Motueka above Wangapeka confluence' sites.

To evaluate spatial differences among the scenarios, results for one common time step corresponding to a single model day are depicted. Spatial differences in modelled groundwater heads among the scenarios are shown in Figure 14. 'Pinch-points' are defined as locations in which modelled groundwater

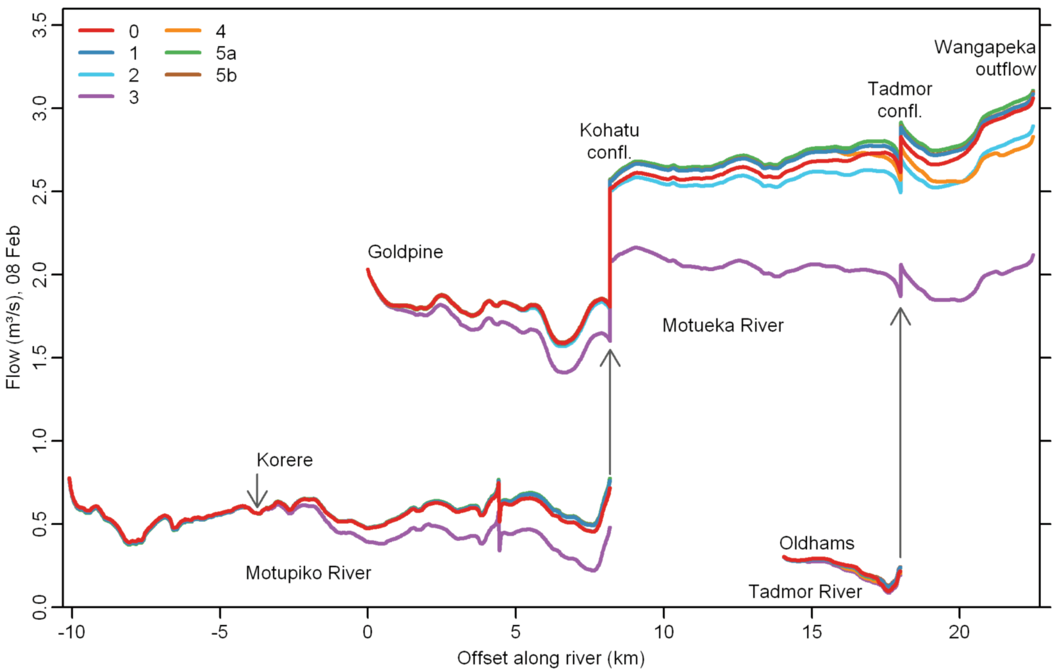


Figure 13 – Modelled river flow for different scenarios from headwaters at Korere, Goldpine and Oldhams gauging points via confluences at Kohatu and Tadmor to outflow from the Upper Motueka catchment at Wangapeka on 8 February 2003.

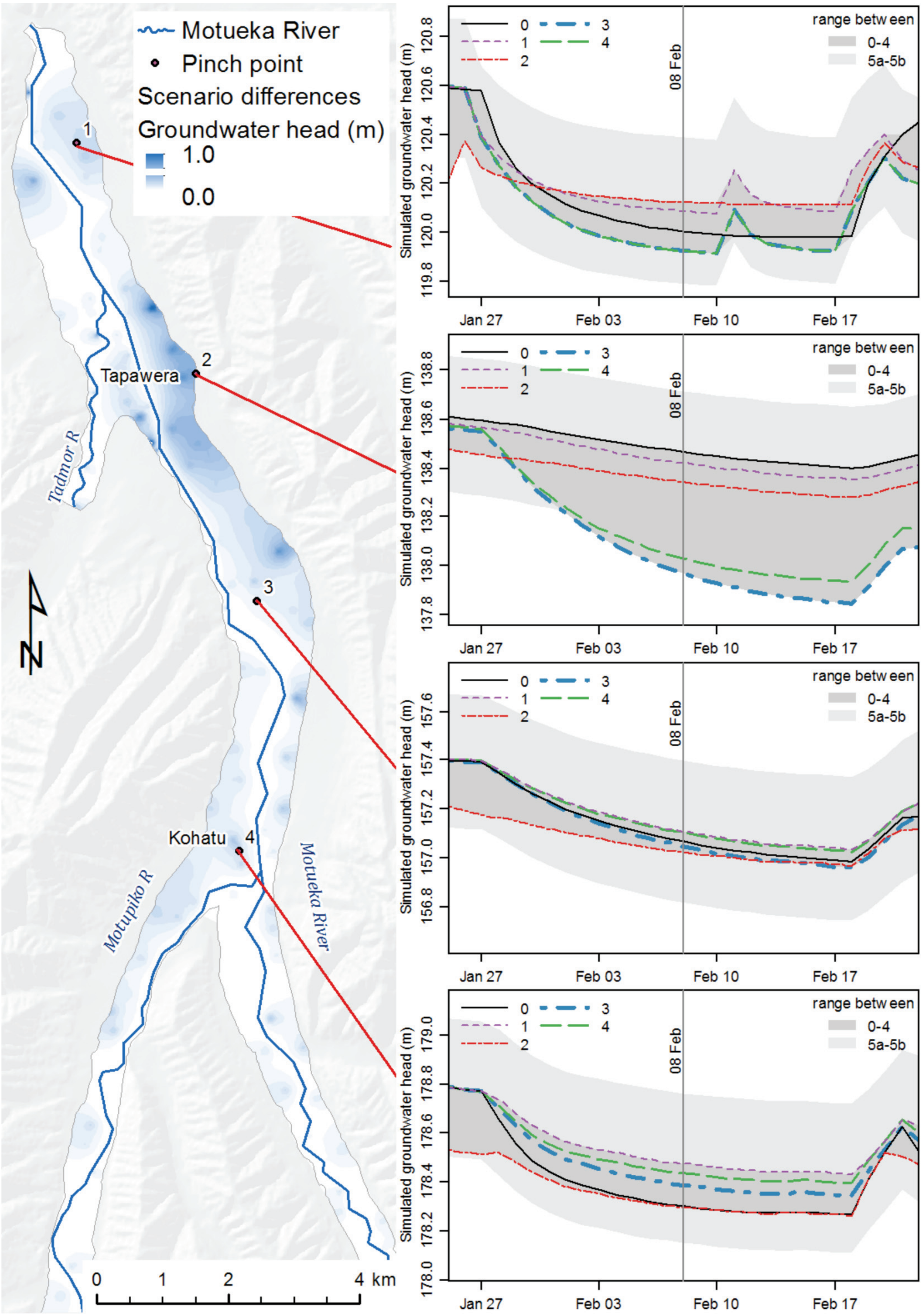


Figure 14 – Part of the model region showing the maximum differences in simulated groundwater head between Scenarios 0-4 on 8 February, 2003. Subsets of time series plots of groundwater head at four pinch-point locations are labelled from 1 to 4. The dark grey range of the time series is equivalent to the shading in the map.

levels show the greatest difference among the various scenarios. Four such pinch-points can be identified within the period from 26 January to 19 February 2003 (Fig. 14). The simulated groundwater heads are the lowest in Scenarios 3 and 4 for pinch-point #1 and in Scenario 3 for pinch-point #2. For pinch-points #3 and #4, Scenario 2 has the lowest modelled groundwater levels. The largest groundwater drawdowns for all scenarios occur along the margins of the catchment in areas of high groundwater abstraction. On 8 February 2003, the difference in modelled groundwater heads between each scenario is up to 1 m in the groundwater abstraction areas located along the margins of the catchment. These drawdowns were localised near the pumping centres due to lower permeability of the aquifer material and a steep groundwater gradient from south to north. Groundwater abstraction from pumping centres located near the river were counterbalanced by river flow due to river-aquifer water exchange and resulted in minor drawdowns.

Conclusion

The purpose of this study was to simulate the effects of dynamic groundwater abstraction on river flow and groundwater levels, so that updated water allocation policies with defensible allocation limits can be set for the water resources in the Upper Motueka River catchment. The groundwater availability and effects of groundwater abstraction on river flows in the catchment are a concern for Tasman District Council water management. Currently, the Upper Motueka River catchment water resources are fully allocated and there is increasing interest in further irrigation from groundwater in the area. To answer groundwater availability questions for the catchment, a groundwater-river model was most appropriate to simulate dynamic interactions between the shallow aquifer and the surface water system. A key aspect for assessing further groundwater availability is the impact of abstraction on the river flow, which has ecological constraints for habitat and community values. Six management scenarios were considered as part of this study to investigate the effects of temporal and spatial variability of groundwater abstraction on river flow and groundwater levels locally and for the entire Upper Motueka River catchment during dry and wet months.

A custom built groundwater–river flow model was developed for this study. The model consisted of a FEFLOW groundwater model that was sequentially linked to a custom-built river flow model that implemented river flow routing on a daily time step using the simulated groundwater losses and gains from the FEFLOW model. The sequential linkage of the two models allowed estimation of changes in river water levels due to groundwater abstraction using rating curves obtained with river cross-section profiles in MIKE 11 and Manning's equation at 28 river section profiles in the catchment, without modifying river water levels in the FEFLOW model. The sequential linkage allowed us to update the river water levels in the FEFLOW model, but it was not useful for a daily time step. The simple approach used in this study avoided the need to couple the groundwater FEFLOW model to a more complicated river model. This in turn avoided the need for substantially more input data for characterising the river system and negated convergence issues that can arise when attempting to link two models with vastly different time steps, and also minimised computation time.

In the transient groundwater–river interaction model for the Upper Motueka River catchment, the daily groundwater levels, rainfall and the river flow data were applied to represent the highly dynamic aquifer-river system. The model was calibrated to match groundwater heads at seven monitoring wells (Quinney's Bush, North Bridge, Oldhams, Campbells, Crimps, Hyatt's and Vue-Mount) and river water levels at the Kohatu and Tapawera gauging sites, based on measurements made in the period from 1 July 2001 to 30 June 2003, which was one of the drier periods on record. The calibration involved adjustment of interpolated values of river stage, spatial distribution of hydraulic conductivity and the leakage coefficient. The calibrated model successfully represented variations and trends in groundwater levels across the model domain. The model also matched observed groundwater–river flux exchange (river gain or loss) to a reasonable degree. Alternative parameterisation schemes could conceivably result in alternative models with equally good fits to the observation data. Model non-uniqueness is a recognised problem in hydrogeology, where typically there is a need to estimate many more parameters than the available observations would allow to be uniquely resolved. Hence the criterion of the model's 'fitness for purpose' is also considered, i.e., whether the model's predictions are useful. In our study, the calibrated model is able to match the observation data suitably well for both wet and dry climate conditions, and on this basis we consider that its predictive capability is adequate for the main objectives of this investigation, which is to simulate various Tasman District Council water management scenarios.

The scenario modelling results illustrate that during the irrigation season 1) river flows are substantially lowered and 2) relatively greater differences occur between the scenarios due to spatial and temporal distribution of allocated water. For all scenarios, at the Motueka outflow (i.e. the 'Motueka above Wangapeka confluence' location), the modelled mean and median river flows are above previous estimates of mean and median flows by about 30%. During low river flows, the groundwater abstraction as implemented in Scenario 3 predicts the lowest river flow that may breach estimated low flow conditions at some locations. For the rest of scenarios, the modelled river flows are above the estimated low flow conditions at all locations. From the simulation results Tasman District Council should be able to allocate further groundwater in the lower reaches of the catchment while still ensuring estimated low flow conditions are not breached during the irrigation season. However, increasing groundwater abstractions near Motupiko and Tadmor rivers may result in adverse reductions in river flows. The simulated scenarios provide useful information for Tasman District Council to establish sustainable water allocation limits for surface and groundwater resource use in this area. The custom built groundwater–river flow model developed for the Upper Motueka River catchment study area has been a key component in evaluating the effects of increasing groundwater abstraction on groundwater levels and river flows.

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