Groundwater Allocation of the Ettrick Basin

GROUNDWATER

Otago Regional Council

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Foreword – Groundwater Allocation in the Ettrick Basin

Otago's prosperity is largely based on water. The Clutha River/Mata-Au drains much of the Otago region and has the largest annual discharge of any river in New Zealand. However, despite the large total water volumes present in the region's water bodies, many areas of Otago are short of water. In many cases, irrigation, particularly in these drier areas, is critical to the continued well-being of the people and communities who rely on the primary production it supports.

The Regional Policy Statements for Water provide access to water for the present and reasonably foreseeable needs of Otago people and communities.

Groundwater is frequently the sole or major source of water to supply basic water needs to communities and stock watering. Currently, groundwater only supplies a small proportion of irrigation needs, however, there is increasing pressure for people to turn to groundwater because surface water supplies are heavily allocated. Over abstraction can result in loss of supply to other users and therefore careful management is required to keep abstraction rates sustainable.

Groundwater resources have varying rates of recharge and often form a complex dependency with adjacent water courses, wetlands and stream networks. The effects of inappropriate land and water use and development on groundwater quantity and quality are often long-term, and in some cases, permanent. It is therefore important that particular consideration be given to the protection of aquifers for the continuing benefit of present and future generations.

Through the Regional Plan: Water and our Annual Plans we ensure linkage with the community to deliver the efficient use and protection of our groundwater aquifers.

This report describes future allocation of water from the Ettrick Basin. It is based on local knowledge, scientific evidence and monitoring information. The best way forward is to use to advantage this valuable resource but to maintain control so that over abstraction does not occur. This is a complex topic and further monitoring and review of the aquifer will continue to ensure a sustainable allocation.

Executive Summary

The Ettrick Basin unconfined aquifer is a vital source of water for local residents for stockwater, horticultural irrigation and domestic use.

A detailed well survey, conducted by Otago Regional Council in May-June 2005, located 144 bores in the Ettrick Basin area. These bores tap the Ettrick Aquifer, a sequence of gravel and sand up to 30m thick. The aquifer is recharged from the Benger Burn, and by rainfall. Usually groundwater flows towards the Clutha River/Mata-Au. However, at times of high flows in the Clutha River/Mata-Au the river can recharge the aquifer.

This report summarises knowledge about groundwater in the Ettrick Basin, and recommends the introduction of integrated water management to achieve sustainable management of both the aquifer and to provide protection of the Benger Burn.

A simple numerical groundwater model explains most of the variations in groundwater levels. Accordingly, groundwater level is predetermined by the position and height of the surface water level in the Clutha River/Mata-Au. Variations, however, can occur due to recharge from the Benger Burn and rainfall.

The main conclusions and recommendations of the report are:

1. The unconfined aquifer of the Ettrick Basin is a vital source of water for local residents to supply stockwater, irrigation water and for domestic use.

2. The Clutha River/Mata-Au has an annual mean flow which is magnitudes larger than the sum of all other water resources of the basin and there is plenty of water available for allocation from the Clutha River/Mata-Au.

3. The aquifer has an estimated recharge of 5.4 Mm^3/year. Consisting of 2.4 Mm^3/year from the Benger Burn, 1.0 Mm^3/year from rainfall recharge and 2.0 Mm^3/year from mountain-front recharge. Episodic high flow events in the Clutha River/Mata-Au also are likely to provide recharge, but the rate is, as yet, unknown.

4. Shallow groundwater storage is used by more than 100 bores. The aquifer stores 20-40 Mm^3 of water.

5. Significant parts of the water balance are uncertain. Further work and focussed monitoring is needed to improve the understanding of groundwater allocation.

6. Ensure good community involvement in future groundwater allocation.

7. Groundwater management in Ettrick needs to ensure that bores will have adequate access to groundwater in the future. Groundwater level response management needs to continue (currently by the Calder Bore) because recharge occurs infrequently and there are many uncertainties in the water balance.

8. Recognise the value of the Benger Burn and protect it from nearby groundwater use by using a stream-groundwater interference zone.

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9. Bores situated, for example, within 350m could be classified as water takes from the Clutha River/Mata-Au and not subject to Ettrick Basin allocation.

10. Only limited new water allocations in Ettrick are possible. The total amount of any new groundwater allocations should not exceed 1 Mm^3/yr (1,000,000 m^3).

11. Water allocation in Ettrick should be reviewed by the Otago Regional Council at five-yearly intervals.

Table of Contents

List of Figures

1. Introduction

The Ettrick Basin has a favourable combination of geography, soils, and climate making the 20 square kilometre area in the southern margin of the Central Otago District (Figure 1.1 and Figure 1.2), suitable for horticulture. The Ettrick Basin unconfined aquifer is a vital source of water for local residents for stockwater, domestic use and irrigation.

Groundwater is not an isolated resource and interacts with surface water. In natural, pre-development conditions, unconfined aquifers (such as the Ettrick Basin) receive recharge from rainfall and surface water and discharge groundwater to surface water and via evaporation. Recharge and discharge are normally equal; the groundwater system is in equilibrium, over long time periods. The sustainable use of groundwater occurs when pumping captures a proportion of the natural groundwater discharge without causing adverse effects on surface water bodies.

The traditional concept of the 'safe yield' of an aquifer was defined as the attainment and maintenance of a long-term balance between the average annual amount of water withdrawn from an aquifer and the average annual amount of water replenishing it (recharge). Thus the safe yield of an aquifer limits groundwater abstraction to the amount of recharge (Sophocleous, 1997). However, it is important that the quantification of the water which is withdrawn from the groundwater system includes natural discharge from the system into springs, streams, rivers, wetlands, etc (generically called 'groundwater dependent ecosystems'). If no allowance is made for surface water features that rely on groundwater recharge, then eventually groundwater dependent ecosystems would dry up. Therefore, it is important to recognise what groundwater dependent ecosystems are present in the Ettrick Basin and their relationship to the groundwater system.

Groundwater, therefore, is normally allocated ensuring a minimum level of water is maintained in bores, or baseflow in surface water. Initially, allocation is based on a first estimate but as water resources are developed, more information becomes available and water allocation becomes more sophisticated and complex. It is important therefore to understand existing information and to recognise shortcomings and gaps in knowledge.

In the absence of adequate hydraulic data, simple approaches can be used. Combined surface and groundwater allocation based on properly calibrated numerical models represent a more sophisticated allocation methodology. The trade-off is that a sophisticated allocation methodology requires more data and investment.

The objective of this report is to provide a better understanding of the Ettrick Basin groundwater resource and to provide guidance on how best to achieve sustainable management of the aquifer into the future. Section 2 identifies the significant water resources in the Ettrick Basin, describes the local physical conditions of the area and what is known of the hydrogeology. Current water allocation and details of a bore survey are described in Section 3. Recharge to the aquifer and an analysis of groundwater levels are discussed in Sections 4 and 5. To further understand the hydrogeology, two simplified models were also constructed and are described in Section 6. Based on the data analysis, Section 7 suggests future groundwater management, including future water allocation and priorities for ongoing data collection. Conclusions and recommendations are in Section 8.

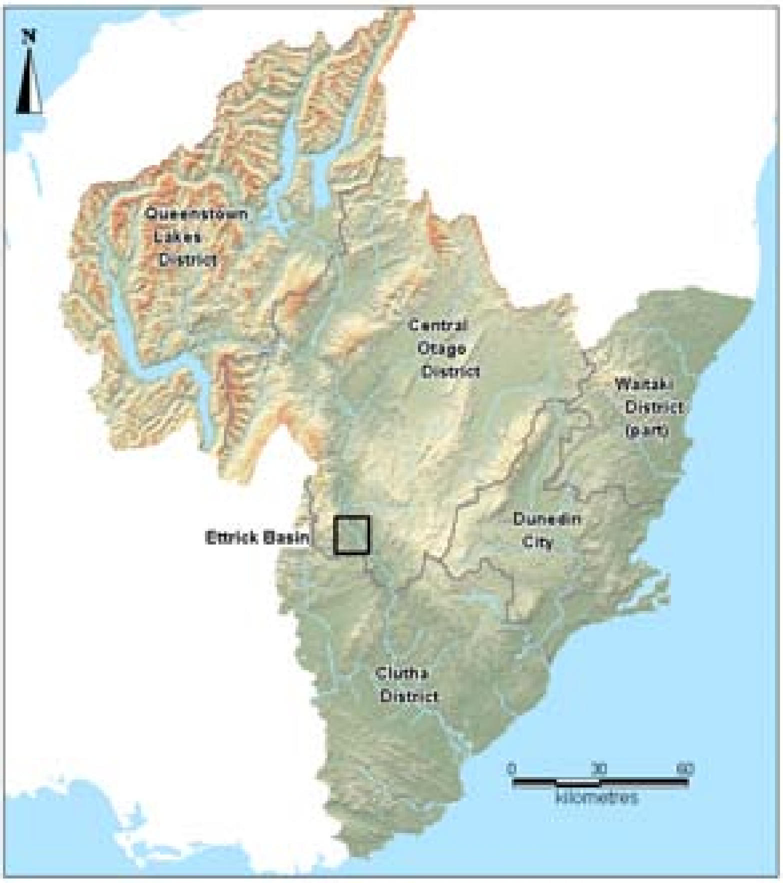

Figure 1.1 Location of the Ettrick Basin in Otago Region

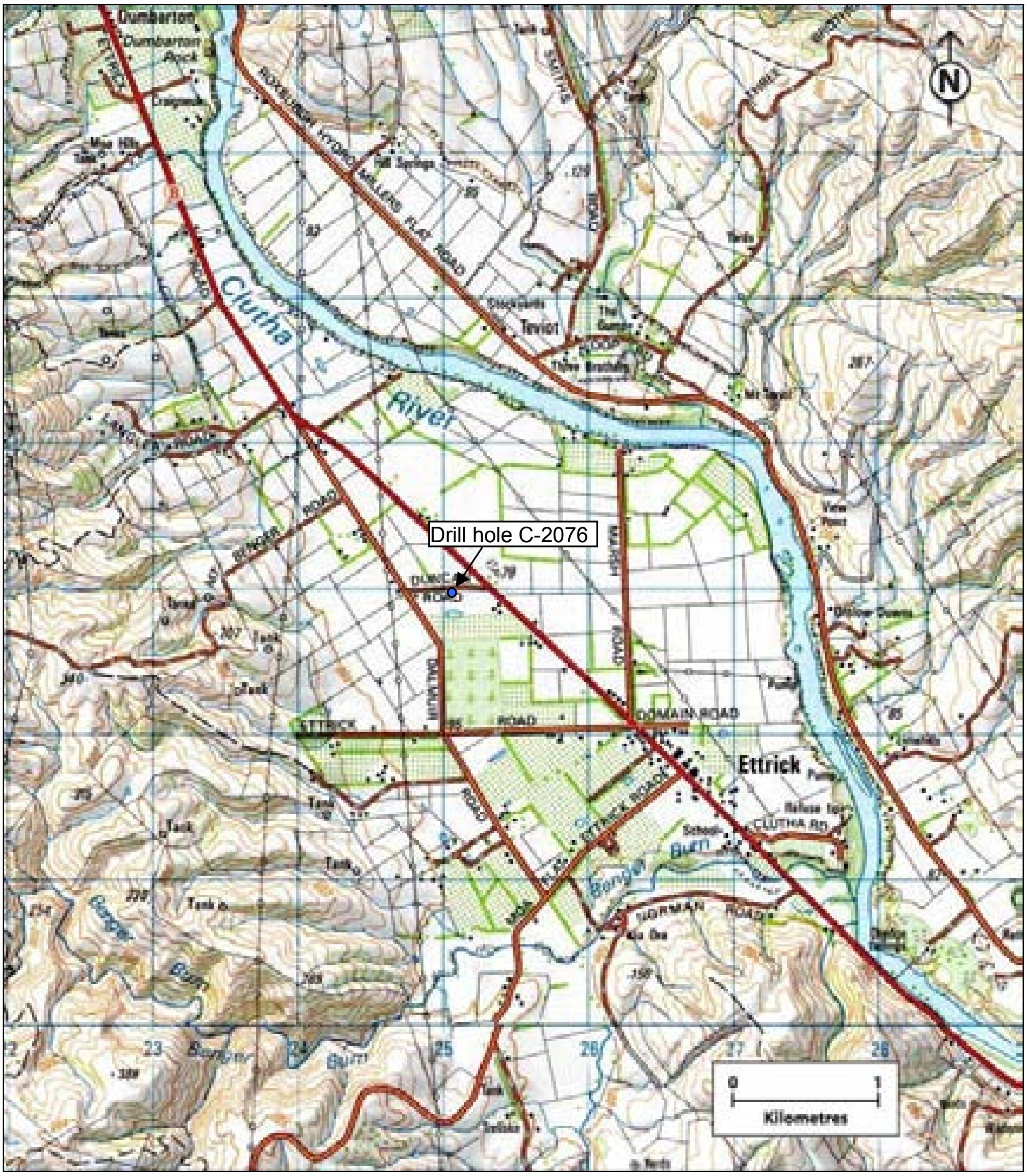

Figure 1.2. The Ettrick Basin. The basin extent is indicated by the change in the density of the topographic contour lines (orange).

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2. Ettrick Basin water resources

2.1 *Significant water resources in the Ettrick Basin*

There are several significant water resources in the Ettrick Basin:

1. The **Clutha River/Mata-Au** dominates the Ettrick Basin. Its annual mean flow, 15,000 mega cubic metres per year (Mm^3/yr), is magnitudes larger than the sum of all other water resources of the basin. There is plenty water is available for allocation from the Clutha River/Mata-Au.

2. The **Benger Burn**, has an estimated mean annual flow of 16 Mm^3/yr or 500 l/sec. The Benger Burn is listed in Schedule 1A by Otago Regional Council's Regional Plan: Water (2004) because of its natural values. The important characteristics of the Benger Burn are:
    - indigenous fish species (non-migratory galaxiid species) threatened with extinction;
    - presence of significant fish spawning areas for trout and salmon; and
    - riparian vegetation of significance to aquatic habitats.

    The Benger Burn loses approximately 2.4 Mm^3/yr to groundwater annually near Moa Flat Road.

3. **Mountain-front recharge** or infiltration by streams and run-off near the contact between the basement schist rock mountains and alluvial sediments is estimated as 2 Mm^3/yr (or 5600 m^3/day) from the groundwater levels (see also Section 4).

4. **Groundwater resources** of the Ettrick area. The Ettrick Aquifer stores approximately 20-40 Mm^3 of water. The only present value attributed to this groundwater resource is the consumptive value (use from bores). No groundwater dependent ecosystems are recognised, other than the Benger Burn, and the role of groundwater is not regarded as important for the Clutha River/Mata-Au.

5. **Net or excess rainfall**, including rainfall recharge to groundwater. Rainfall recharge will is a relatively small component (1 Mm^3/yr) of the water budget.

Therefore, management of the groundwater in the Ettrick Basin needs to ensure the protection of the Benger Burn and that bores will have adequate access to groundwater in the future.

2.2 *Soils, land use and climate*

The Ettrick Basin has a favourable combination of geography, soils, and climate making the 20 square kilometre area suitable for horticulture (Hewitt, 1983). The best soils in Ettrick for horticulture are deep sandy loams and fine sandy loams. Stony loamy sand soils close to the Clutha River/Mata-Au terrace restrict rooting depth and have limited water holding capacity. Fruit production and pastoral farming are the dominant land use.

The climate of the Ettrick Basin is characterised by hot summers and cold winters and semi-arid conditions. The mean annual temperature in neighbouring Roxburgh is 11° C. The mean annual rainfall in Roxburgh is 594 millimetres (mm) (1986-2004) with a standard deviation of 99mm. Rainfall is distributed over the seasons fairly evenly, with spring being slightly wetter and winter drier, on average, than the other seasons. The mean annual pan evaporation is 1120mm and standard deviation is 90mm. There is a small moisture surplus, on average through the months of May to August; and large soil moisture deficits from September to March. These deficits are significantly limiting to horticulture and there is a strong demand for irrigation water from September to March.

2.3 *Hydrogeology of the Ettrick Basin*

The understanding of Ettrick Basin hydrogeology comes from several sources. Deep hydrogeological information is available from coal resource exploration and dam site investigation drill-logs from the 1970s and 1980s (summarised in Appendix A). This information, and Irricon and ESR (1997) data were used to construct a conceptual model for the Ettrick aquifer. The log of drill hole C-2076 (Figure 2.1) is used as an example to describe the following five hydrogeological units (each of which are described in more detail in sections 2.3.1 – 2.3.5):

- Ettrick Aquifer
- Manuherikia Aquitard
- Ettrick Confined Aquifer
- Lower Manuherikia Aquitard
- Haast Schist Basement

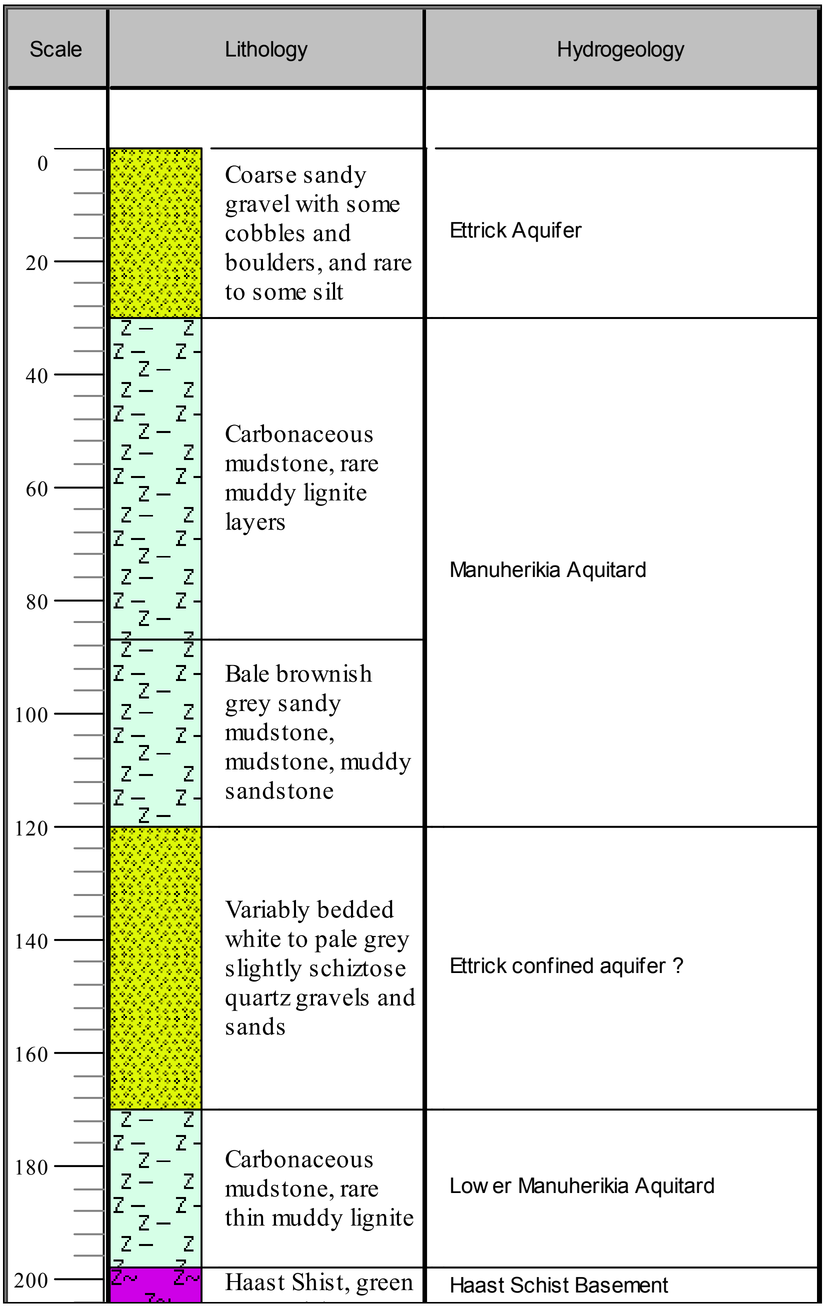

Figure 2.1 Conceptual hydrogeology, Ettrick basin, using the log of C-2076 coal investigation drill hole.

2.3.1 Ettrick Aquifer

The Ettrick Aquifer is a thin veneer of saturated Quaternary sandy gravels overlain by an unsaturated zone of the same materials. All Ettrick water bores appear to tap the Ettrick Aquifer but only a few borelogs are available. Drillers' logs describe this aquifer as loose sandy gravel, coarse sandy gravels, and sandy gravel with cobbles or boulders, indicating an aquifer with medium to large hydraulic conductivity.

The total thickness of the sandy gravels is between 18 and 30 metres. However, the top part of the sandy gravels is dry (Figure 2.2, above the water table). The saturated thickness of the Ettrick Aquifer is a very important property for water allocation. It not only influences how much water is stored in the aquifer but also affects bore performance. If water level fluctuations and/or drawdown are comparable to the saturated thickness, bore yields will be noticeably less when groundwater levels are low. Most of the drillers' logs do not indicate the full thickness of the aquifer because drilling stopped once enough water bearing strata were encountered without being extended to the base of the aquifer (Figure 2.3). Only the deep coal investigation logs penetrated through the Ettrick Aquifer but they do not contain information on the groundwater levels. Therefore, a synthesis of information is needed. Figure 2.2 shows a southwest-northeast cross-section of the Ettrick Basin based on deep drill logs.

West of the Clutha River/Mata-Au, the average saturated thickness of the Ettrick Aquifer is approximately 10 to 15 metres. Available water borelogs west of the Clutha River/Mata-Au indicate a saturated thickness of 5 to 10 metres when drilling stopped. The coal investigation drill hole indicates another 5 metres to the base of the Ettrick Aquifer. East of the Clutha River/Mata-Au, the saturated thickness is considerably thinner. In the future, analysis of systematically collected drillers logs and surveying of wellhead locations can be used to fine tune the estimated thickness.

The values of aquifer properties in the Ettrick Aquifer are largely unknown. Aquifer test information is not available. However, based on the well logs and basic production tests available, estimates of the general range of properties can be obtained. The specific discharges (the ratio between discharge and drawdown) for bores in the area are 60, 200, 200, 210, 230, 250, 350, 385, 400, 970, 1440 and 1900 m^3/day/m. These values indicate a general transmissivity of 100-1000 m^2/day (hydraulic conductivity multiplied by saturated thickness). Drillers generally installed very short (half to one metre long) screens with large 2.5mm slot (opening) screens in the wells, indicating high yielding coarse aquifer material. The hydraulic conductivity is estimated as 30-3000 m/day for gravels and 0.1-500 m/day for coarse sand (Domenico and Schwartz, 1990). For the coarse sandy gravel and cobbles described by the Ettrick borelogs, 10-250 m/day hydraulic conductivity appears a reasonable estimate. Specific yield is estimated as between 0.07 and 0.2.

Irricon and ESR (1997) report that groundwater from the Ettrick Aquifer is generally safe for human consumption with moderate nitrate levels in some bores.

2.3.2 Upper Manuherikia Aquitard

A barrier to vertical movement of groundwater beneath the Ettrick Aquifer is comprised of a carbonaceous mudstone of the upper Tertiary Manuherikia Group (Manuherikia Aquitard). These materials allow very little if any groundwater throughflow. This unit is approximately 150 metres thick in the west (Figure 2.2). The Tertiary Manuherikia Group dips towards the west and is therefore the thickest near the western boundary of the basin. The top of the Manuherikia Group (and the base of the Ettrick Aquifer) is around 60m above mean sea level (amsl) in Ettrick and 71-75m amsl on the west bank of the Clutha River/Mata-Au.

2.3.3 Ettrick Confined Aquifer

The lower section of the Manuherikia Group contains sandy gravels that are up to 40m thick near Moa Flat, Duncan and Marsh Roads. This potential aquifer is not fully understood and needs further investigation. In this report, it is tentatively referred to as the Ettrick Confined Aquifer. It is either very thin or absent on the west bank of the Clutha River/Mata-Au. Thick individual sub-layers of gravel can potentially yield significant amounts of groundwater. This aquifer is yet to be explored by water wells.

2.3.4 Lower Manuherikia Aquitard

Another mudstone layer, where it exists, forms the Lower Manuherikia Aquitard, allowing limited water movement only.

2.3.5 Haast Schist Basement

The schist rock acts as hydrogeological basement, although fractured schist can yield considerable water. Schist is a metamorphic rock and apart from the top, weathered zone and any fractured or faulted zones, it can yield little if any water. Therefore, the schist is considered as impervious and the local hydrologic basement.

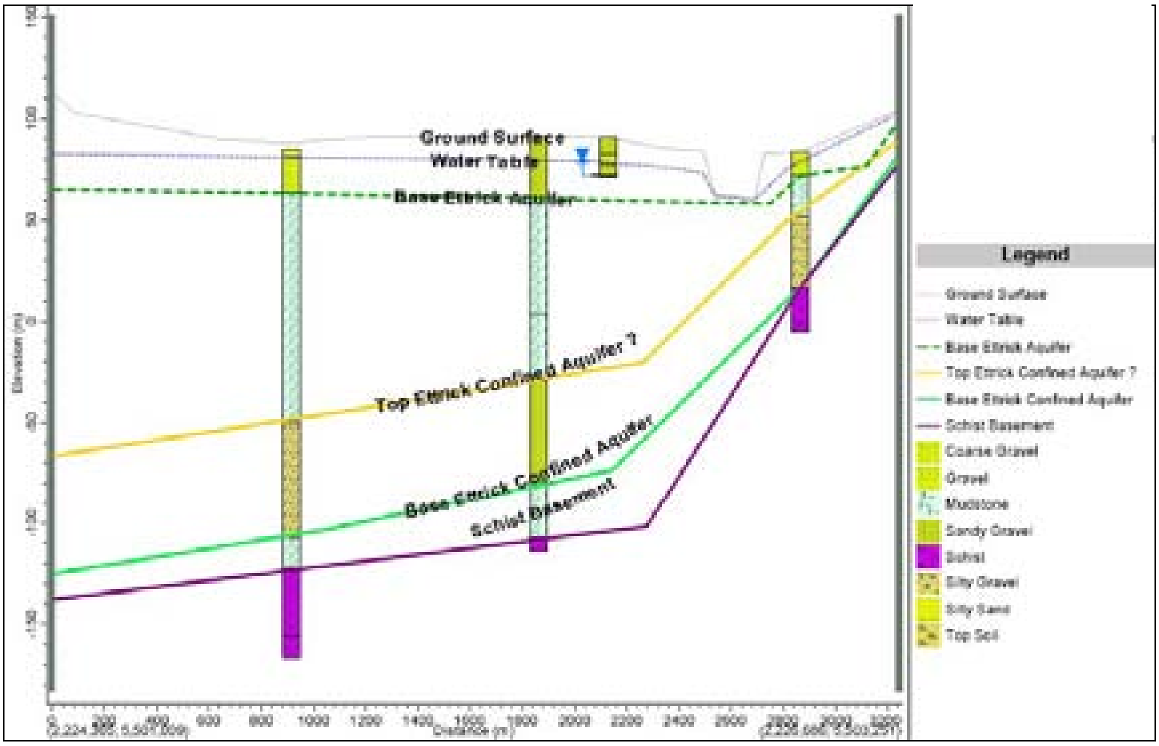

Figure 2.2. Conceptual south-west-north-east cross-section, Ettrick Basin. Dotted blue line represents the position of the water table (phreatic surface). Yellow colour indicates aquifers, pale blue indicates aquitards, and pink the schist basement.

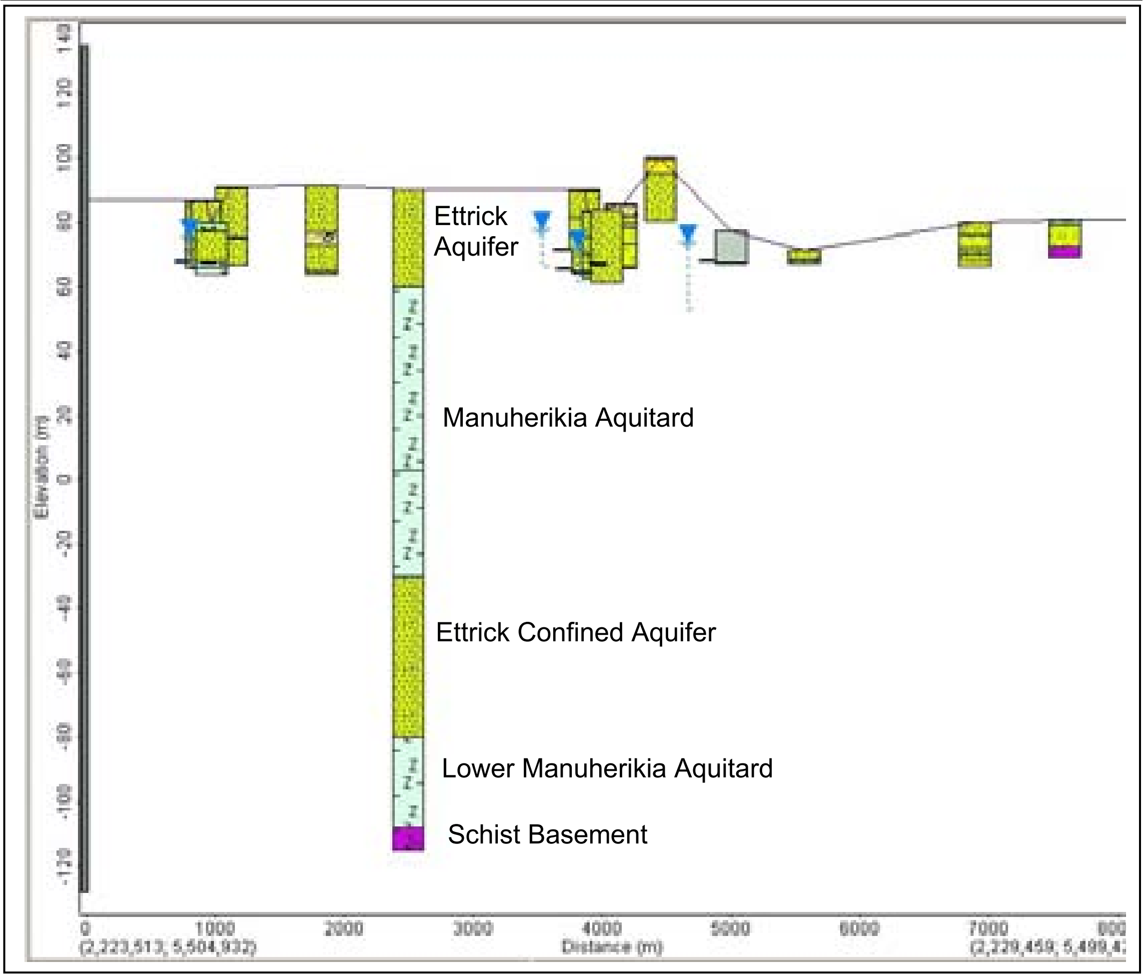

Figure 2.3. North-west to south-east cross-section along State Highway 8, Ettrick. Blue triangles illustrate static water level. Yellow colour indicates aquifers, pale blue aquitards, and pink the schist basement.

3. Water allocation

3.1 *Surface water*

As of July 2005, seven consumptive water permits, totalling 566 litres per second (l/sec) of water, were issued from the Clutha River/Mata-Au. One surface water permit exists, for 167 l/sec, to take water from the Benger Burn. There is an additional permit for a small water take (1.25 l/sec) for an unnamed creek, adjacent to Langlea Road.

3.2 *Groundwater*

Total instantaneous groundwater allocation from the Ettrick Aquifer is just below 200 l/sec. Annual groundwater allocation is estimated as a total of 2,800,000 m^3/yr (2.8 Mm^3/yr) from eleven permits, based on a seven month irrigation season at 400,000 m^3/month. The calculation of total groundwater allocation is not straightforward as several permits do not have an annual allocation limit while others do not have monthly or weekly allocation limits. Also, there are further groundwater applications on hold for an additional allocation of 400,000 m^3/yr.

Of the 2.8 Mm^3/yr of currently allocated groundwater, four permits, totalling approximately 1 Mm^3/yr, have the potential for stressing the Benger Burn directly by causing additional flow loss. None of the consented groundwater permits are likely to induce loss directly from the Clutha River/Mata-Au.

Schedule 4 of the Otago Regional Council Regional Plan: Water (ORC, 2004) prescribes that either restrictions on water use, or allocation committee response are required if 30-day mean water level of the Calder bore (G43/0032) falls below certain levels: 25% restriction or allocation committee action below 170.29m; 50% restriction below 169.79m; and 100% restriction applies below 169.29m (Otago Datum; to convert to sea level, deduct 100m).

The Calder bore, Otago Regional Council Bore No. G43/0032, is 18m deep (Irricon and ESR, 1997). It has no driller's log and it is not known if a screen was installed. The bore is equipped with an automatic recorder that logs groundwater levels every 15 minutes and the data is telemetered back to Otago Regional Council.

3.3 *Bore survey*

A detailed, property scale reconnaissance well survey was conducted by the Otago Regional Council in May-June 2005 in the Ettrick area. This survey located 144 bores (including 13 bores in the Millers Flat area). The location of each bore (using a hand-held GPS) and, where possible, static water level was measured. In addition, basic well attributes (owner, depth, diameter etc.) were recorded. Bore summary data is given in Appendix B. This data was entered into the Otago Regional Council's groundwater database. Static water level was measured in 64 bores. To facilitate future identification and measurements, digital photos were also taken. Approximately 25 wells were selected for a subsequent precise GPS well-head survey and static water level measurements.

4. Recharge to the aquifer

Recharge can be classified as diffuse or local recharge.

- **Diffuse recharge** occurs over large areas. For example, rainfall accumulates in the soil column until the limit of the soil's moisture holding capacity, whereupon it drains below the soil and can become groundwater recharge.
- **Local recharge** is site-specific and does not occur everywhere. Examples of local recharge include mountain-front recharge, losses from lakes, rivers, wetlands and irrigation water losses.

The Ettrick Unconfined Aquifer is thought to be recharged from both diffuse rainfall and local recharge from the Benger Burn and/or Clutha River/Mata-Au. These assumptions are tested in this report.

4.1 *Diffuse recharge*

Irricon and ESR (1997) estimated diffuse recharge as 50mm/yr. In this report, diffuse recharge is estimated using the Monte-Carlo method using a soil bucket model (Bekesi and McConchie, 1999). The soil bucket model is one of the water budget methods, the most common way of estimating recharge using the residual approach. This approach involves measuring or calculating all the variables of the soil water budget except recharge and the remaining volume or residual is predicted to be the recharge. The method and results are described in full in Appendix C.

Diffuse annualised recharge is estimated for Ettrick as up to 55mm/yr, depending on soil depth and crop type. Assuming a mean 50mm/yr recharge for the Ettrick area, recharge is 1 Mm^3/yr for the entire Ettrick Basin. To put this quantity in context, if the entire Ettrick area was irrigated with this volume, there would only be enough for approximately one week of irrigation.

4.2 *Local recharge*

Sources of potential local recharge in Ettrick include the Benger Burn, Clutha River/Mata-Au, mountain-front recharge, and return irrigation water.

Mean annual flow of the Benger Burn is estimated as 16 Mm^3/yr, while the seven–day Mean Annual Low Flow (7-day MALF) is estimated as 76 l/sec. It is assumed that flow loss from the Benger Burn, at a rate of at least the 7-day MALF (2.4 Mm^3/yr), is recharging the Ettrick Aquifer. This is two to three times the annualised diffuse recharge for the Ettrick Basin. The Benger Burn, therefore, is a major source of Ettrick groundwater.

The Clutha River/Mata-Au is considered as the sink of groundwater, i.e. groundwater levels are higher than the river most of the time and groundwater flows into the river. It is possible, however, that the Clutha River/Mata-Au episodically recharges the aquifer. Normally, Ettrick unconfined groundwater flows into the Clutha River/Mata-Au. However, if the river stage is abnormally high, the river water can infiltrate the aquifer. Once the river flow declines, the surface water - groundwater equilibrium will revert to normal conditions. AquaFirma (1998) noted that river floods and fluctuations were exhibited in Alexandra groundwater hydrographs and showed such bank storage occurring near Alexandra, which is an area similar in hydrogeology to Ettrick.

To assess such bank storage and groundwater flow pattern, the potentiometric (groundwater level) map was created using results of the 2005 bore survey and selected water levels in the Clutha River/Mata-Au and Benger Burn. These water levels were obtained either from Otago Regional Council records (Clutha River/Mata-Au) or from topographical maps (Benger Burn).

The water levels for the Clutha River/Mata-Au were derived from Otago Regional Council records for Clutha River/Mata-Au bed levels and pegged flood levels, and also routine monitoring that included measuring water levels in the Clutha River/Mata-Au at the end of Marsh Road. Figure 4.1 indicates a long-section of the Clutha River/Mata-Au bed. Near Ettrick, the slope of the river bed is approximately 1.1×10^{-3} or 10 metres change in height over 9 kilometres. Average water level at Marsh Road (70.5m) and the slope were used to calculate average river levels at five locations.

Flood levels pegged during the 1999 flood show a water level of 76 metres (amsl) at the upstream end of Ettrick and 70 metres at Millers Flat. This data indicates that at high flows or floods, the Clutha River/Mata-Au level would be several metres above adjacent groundwater levels at the upstream end of Ettrick, opposite and north of Langlea Road. Therefore, the Clutha River/Mata-Au can inundate at least the northern part of the Ettrick Aquifer at high flows.

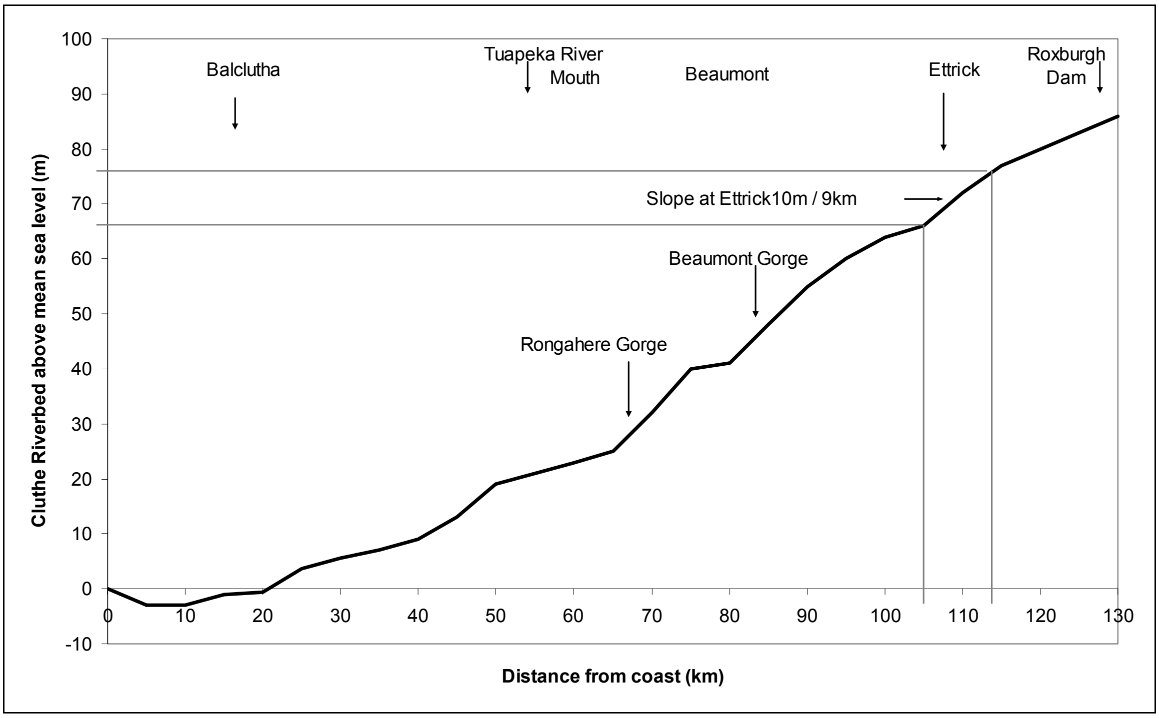

Figure 4.1. Clutha River/Mata-Au longitudinal cross-section.

Figure 4.2 depicts groundwater levels in terms of sea level. Horizontal groundwater movements would be approximately perpendicular to the contours. As expected, groundwater movement in general follows topography, from Mount Benger towards the Clutha River/Mata-Au. Notable deviations from this pattern are:

- Apparent inflow from the Clutha River/Mata-Au approximately 2km upstream of Marsh Road (opposite and north of Langlea Road). The riverbank in that location is composed of unconsolidated sediments and borelogs indicate gravels and sand below. These sediments would allow water flow to the aquifer.
- Apparent inflow from Benger Burn upstream of Moa Flat Road.
- Possible outflow to the Benger Burn close to the confluence with the Clutha River/Mata-Au.

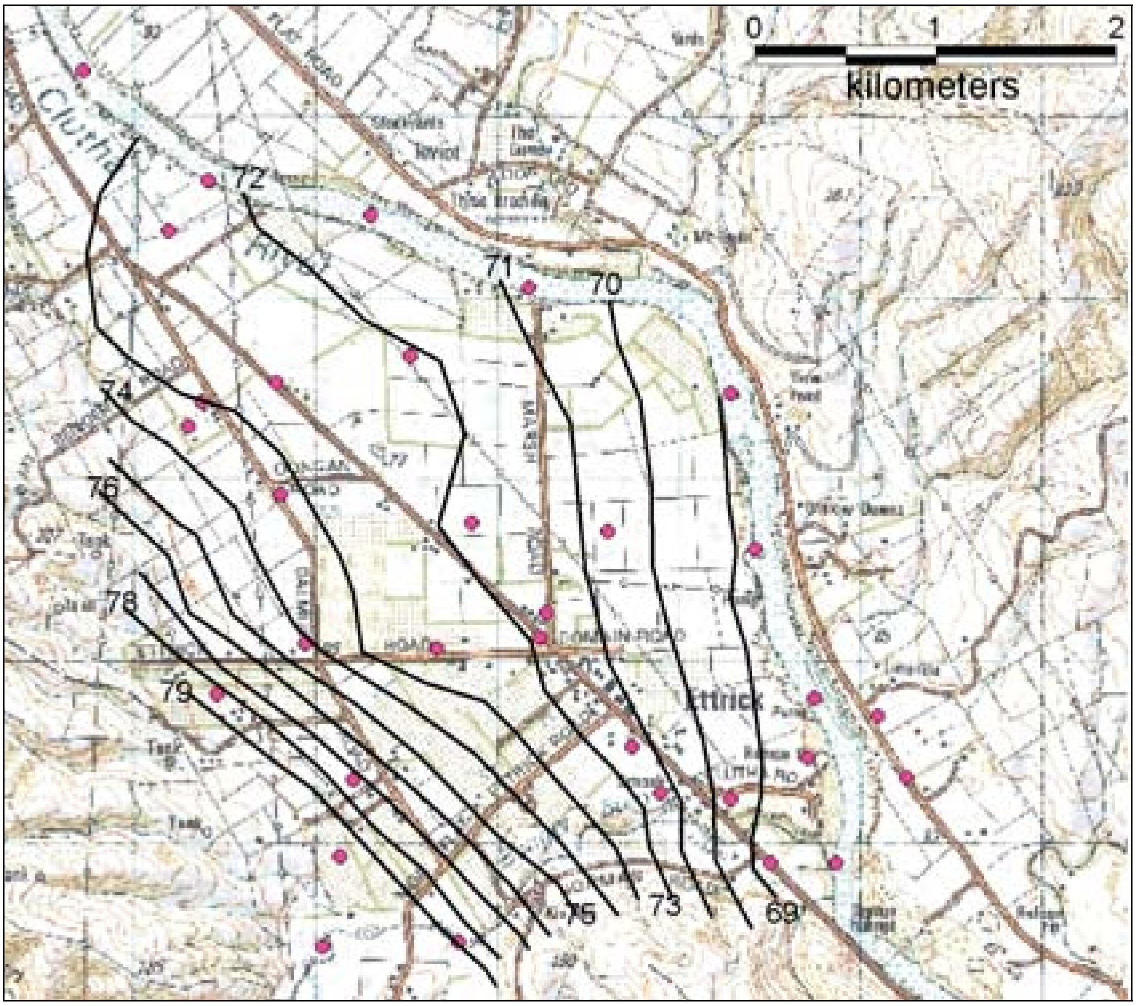

Figure 4.2. Groundwater level (potentiometric map) based on water bore data and river water levels. Red circles represent observation sites.

Creeks, streams, and runoff can infiltrate the soils typically at the contact between mountains and the flatter basin areas where a break in topographic slope occurs (mountain-front recharge). This type of recharge can be calculated from surface water flow records or groundwater flow net analysis and pumping test data for bores close to the mountain-front. These data are currently not available therefore mountain-front recharge can only be estimated.

Mountain-front recharge was estimated as approximately 5600 m^3/day (or 2 Mm^3/yr) using a hydraulic gradient of 0.006, a hydraulic conductivity of 10 m/day, a saturated thickness of 15m, and a mountain-front length of 6200 m.

4.3 *Discharge*

Discharge to the Clutha River/Mata-Au, based on Figure 4.2, assuming 100 m/day for hydraulic conductivity and a 3500m wide flow zone north of the Benger Burn, is estimated as 5.4 Mm^3/yr. While it is acknowledged that recharge and discharge are in equilibrium over long time periods in most systems, recharge and discharge over a few years does not have to be equal.

Direct diffuse discharge by evaporation from the water table is negligible as the water table in Ettrick is generally deep.

5. Groundwater level trends (Hydrograph analysis)

5.1 *Hydrograph analysis of Calder Bore*

For the purposes of this report, it is assumed that the Otago Regional Council automatic groundwater monitoring site (Calder bore) represents the trend in the entire Ettrick basin. This assumption appears to be valid, in a qualitative sense, as Otago Regional Council manual monitoring in six wells in Ettrick show similar trends to those obtained from the Calder bore.

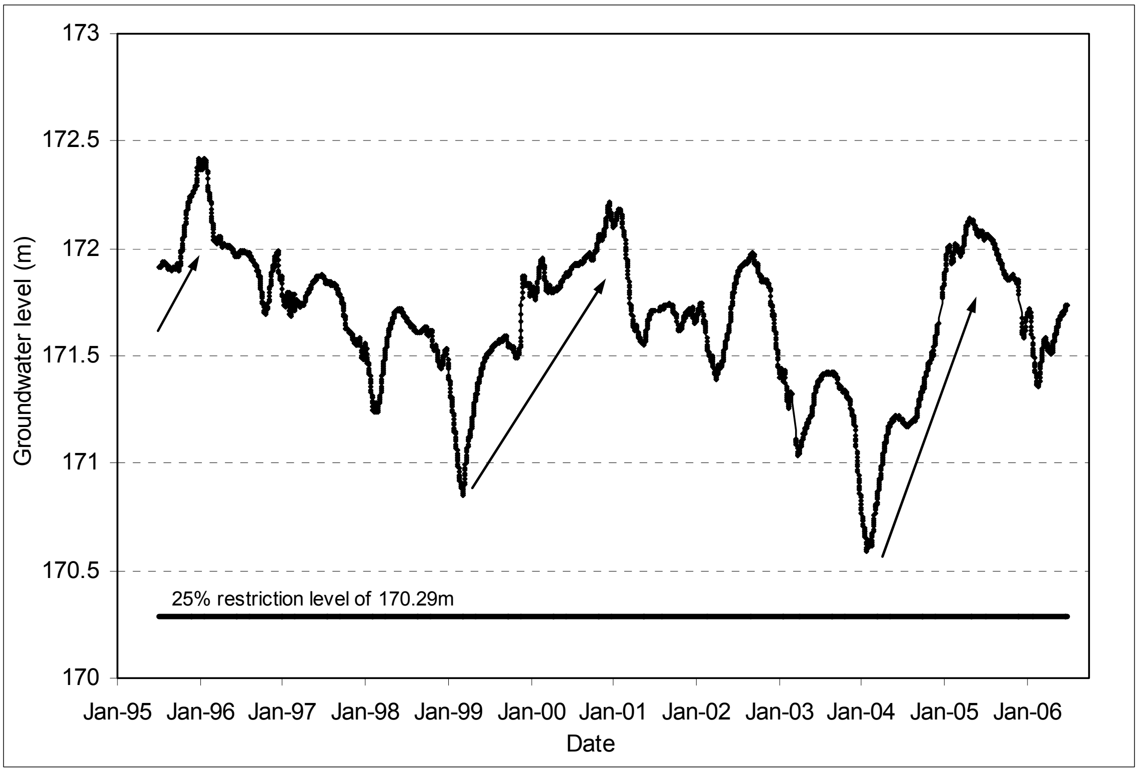

Figure 5.1. Hydrograph for Otago Regional Council monitoring site (Calder bore) showing episodic fluctuations in 1995, 1999, 2004 and annual variations. Arrows indicate major episodic recharge events. The 25% restriction level of 170.29m is shown for comparison. Heights are in terms of Otago datum (to convert to mean sea level, deduct 100m).

The most conspicuous features of the Calder bore hydrograph are the major apparent recharge events in 1999-2000 and 2004-2005. These two episodic events, marked by arrows in Figure 5.1, caused groundwater to rise significantly above the less distinguishable annual maxima or pattern. There could be another main recharge even in 1995, indicated by the earliest (and incomplete) part of the hydrograph.

The Calder bore hydrograph is an excellent example of why semi-arid groundwater allocation is unreliable on an annual basis. An examination of the hydrograph at the end of 2003 could have easily concluded that groundwater use from the Ettrick Aquifer was unsustainable because of the declining trend between 2000 and 2003. However, by 2004 this decline had been reversed and, in fact, it was only one of the three long recession periods observed between major episodic groundwater recharge events. The recharge event(s) starting from early February 2004 brought the groundwater level back to near the highest recorded levels. Managing groundwater year-to-year in such an environment is not wise and almost certainly could put excessive restrictions on users. The recognition of these episodic recharge cycles places a greater emphasis on understanding the mechanism of the episodic recharge pulse to better manage Ettrick groundwater.

Through analysis of the Calder bore hydrograph, information about the episodic and annual defuse recharge can be gained. This is explained in detail in Appendix D. It was found that water from the Benger Burn (and at high flows the Clutha River/Mata-Au) can infiltrate the Ettrick Aquifer in large quantities. Once the river flow declines, surface water - groundwater equilibrium will revert to normal conditions. Diffuse rainfall recharge is also significant albeit unreliable on a year to year basis.

The annualised recharge from flow losses is estimated as 2.4 Mm^3 from the Benger Burn and is unknown from the Clutha River/Mata-Au. Annualised diffuse recharge is estimated as 1 Mm^3/yr based on an average 50mm/yr rainfall recharge over 20 km^2. Mountain-front recharge was estimated as approximately 2 Mm^3/yr. Combined annualised recharge therefore is 5.4 Mm^3/yr plus the unknown contribution from the Clutha River/Mata-Au. This compares poorly with the estimated annualised recharge from the Calder bore hydrograph of 2.4 Mm^3/yr, assuming 0.1 specific yield.

Reasons for the poor comparison can be numerous and include:

- The Calder bore hydrograph does not represent the entire basin because it is far from the surface water courses
- The specific yield varies significantly from the assumed 0.1 in the Ettrick Basin
- Flow loss estimates from the Benger Burn are not precise. Some groundwater potentially discharges into the Benger Burn just above the confluence with Clutha River/Mata-Au
- The concepts and assumptions used for diffuse recharge are wrong.

Only systematic data collection and interpretation can reveal the source of discrepancy. In particular, a systematic collection of bore and pumping test information is required to estimate hydraulic parameters. The most certain and practical way of estimating river flow losses from the Benger Burn is monitoring the flow and conducting simultaneous gaugings at selected flows.

5.2 *Hydrograph analysis of manual monitoring sites*

Figure 5.1 indicates that the current groundwater level in the Calder bore is close to the 1995 level. Non-automated Otago Regional Council groundwater level monitoring sites indicate similar trends. Figure 5.2 shows the manual groundwater levels of six Ettrick wells. These hydrographs indicate either a small decline or relatively stable conditions since 1995.

The colours in Figure 5.2 refer to the distance from the Benger Burn, red for the closer bores, green for intermediate positions, and black for monitoring sites situated furthest from the Benger Burn. If episodic recharge in 1999-2000 and 2004-2005 were caused by the Benger Burn, it would be reasonable to assume that the most abrupt changes would occur in bores closest to the Benger Burn (red coloured curves). This might be valid for 1999-2000, however, the changes for 2004-2005 appear to be similar for most sites in Figure 5.2. This indicates that sources other than the Benger Burn can also recharge groundwater in Ettrick, such as the Clutha River/Mata-Au and surface water courses draining Mount Berger.

Figure 5.2 also indicates the shortcomings of existing monitoring in the Ettrick Basin. The large episodic recharges in 1999-2000 and in 2004 are not captured properly with the current two measurements per year and annual fluctuations do not show up properly. Improved monitoring is crucial for sustainable groundwater management.

To gain the necessary data to monitor trends in the groundwater level, the Otago Regional Council manual sites would have to be monitored at least four times a year. In addition, event-based monitoring runs could capture significant changes. As the Calder bore is telemetered, analysing the hydrograph regularly can drive such event-based monitoring. For example, large changes in the Calder bore could trigger manual groundwater level measurements or even a larger scale survey to create a groundwater level map at high surface water flows.

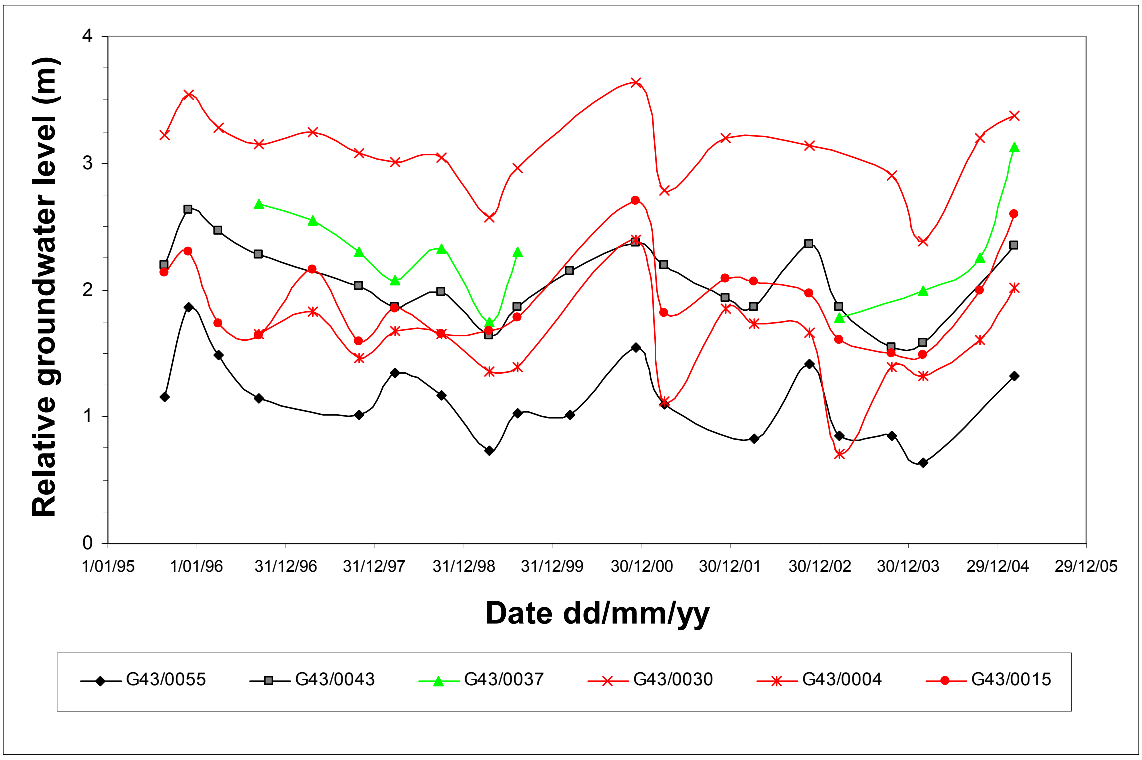

Figure 5.2. Hydrographs for six manually monitored bores in Ettrick. Note that water levels were transformed so that all the sites can be displayed on one plot. Red colour represents bores close to the Benger Burn, and black colour depicts hydrographs for bores further away. The green line represents a bore in intermediate position; no data is available for Site G43/0037 for 2000-2002

The Irricon report (1995) includes some handwritten notes about several water level measurements made in 1994. These records were not referenced to Otago Regional Council well numbers. However, they provide an opportunity to compare groundwater levels from 1994 and the present 2005 surveys. Seven bores were identified, based on matching location and owners, as having water level measurements in both 1994 and 2005.

Since 1994, groundwater levels declined significantly in one bore (-0.49m) while the other six bores indicate either no change or insignificant change (0.016, -0.02, -0.02, -0.04, -0.175, and -0.18 m).

In summary, available groundwater level monitoring data indicates that 2005 groundwater levels are very similar to those in 1994-1995. Otago Regional Council manual monitoring data indicates the large rises in groundwater level in 1999-2000 and 2004, in agreement with the hydrograph from the Calder bore.

6. Numerical groundwater modelling

Two simplified models were constructed to understand the hydrogeology of the Ettrick Aquifer. One is a steady state model to look at the hydrogeology of the basin and interactions with surface water bodies and the other is a transient model looking at groundwater level trends through time and the impacts of climate and changing aquifer management. A numerical model is usually constructed to predict what would happen at various water allocation scenarios. The present models are based on little data therefore they are merely a starting point for future data acquisition. The models are described in more detail in Appendix E.

These simplified numerical groundwater models explain most of the variations in groundwater levels. Accordingly, groundwater level is predetermined by the position and height of the surface water level in the Clutha River/Mata-Au. However, variations can occur due to recharge from the Benger Burn and rainfall.

6.1 *Improvements for future modelling*

The steady-state model could be improved by new data acquisition. In particular, pumping tests and data on hydraulic conductivity would vastly improve the reliability of the model. Actual flow gaugings on the Benger Burn would also re-fine the south-western portion of the model.

The transient model requires reliable time-series of groundwater use (i.e. how much water is pumped out from each consented bore) and more frequent monitoring of Otago Regional Council manual groundwater level monitoring sites.

6.2 *Hypothetical scenarios*

The following scenarios are based on the models created and a reasonable but far from perfect calibration. They represent best estimates for groundwater level at the Calder bore, rather than correct estimates and should be tested in the future by systematic data collection.

Scenario 1: Five year 'groundwater drought' (no rainfall recharge), constant mountain-front recharge, constant recharge from Benger Burn, no pumping.

Analysis of a five year long recession curve (no diffuse rainfall recharge) indicates that the Calder bore water would decline to 71.3m. 71.3m above mean sea level is still 1m higher than the 25% cutback threshold level.

Scenario 2: Five year 'groundwater drought', constant mountain-front recharge, 50% reduction from Benger Burn, no pumping.

No rainfall recharge combined with a 50% reduction of the contribution of the Benger Burn would lower groundwater level to approximately 70.7m (no abstraction wells).

Scenario 3: Five year 'groundwater drought', constant mountain-front recharge, 50% reduction from Benger Burn, all year-round pumping at consented levels.

Groundwater level at the Calder bore would decline to approximately 68.5m, which is below the 100% restriction level.

Scenario 4: Diffuse rainfall recharge at 50 mm/yr, Benger Burn recharge at 2.4 Mm^3/yr, mountain-front recharge at 2 Mm^3/yr combined with groundwater use at consented rates.

The groundwater level (steady state) would lower to 69.9m, which is just above the 50% restriction level.

7. Groundwater management

7.1 *Water balance summary*

Surface water courses, the Benger Burn and the Clutha River/Mata-Au dominate the water balance of the Ettrick area. The mean annual flow (15,000 Mm3) of the Clutha River/Mata-Au is several orders of magnitudes larger than the sum of all other water resources of the basin. There is plenty of water available for allocation from the Clutha River/Mata-Au.

The other important surface water resource, the Benger Burn, is important because of its indigenous fish species (threatened non-migratory galaxiid species) and the presence of significant fish spawning areas for trout and salmon. Mean annual flow of the Benger Burn is estimated as 16 Mm^3/yr, while the seven–day Mean Annual Low Flow (7-day MALF) is estimated as 76 l/sec. It is assumed that flow loss from the Benger Burn, at the rate of at least the 7-day MALF (2.4 Mm^3/yr) is recharging the Ettrick Aquifer.

The Ettrick Aquifer also appears to be recharged by episodic large recharge events from the Benger Burn and the Clutha River/Mata-Au. Rainfall recharge is much smaller than this recharge from surface water. Annualised groundwater recharge is estimated as 5.4 Mm^3/yr in addition to recharge from the Clutha River/Mata-Au. This sum comprises an estimated annualised recharge of 2.4 Mm^3/yr from the Benger Burn, 2 Mm^3/yr from mountain-front recharge, plus 1 Mm^3/yr from rainfall recharge. Recharge from the Clutha River/Mata-Au is, as yet, unknown.

Shallow groundwater stored in the Ettrick Aquifer is used by more than 100 bores for irrigation, stock and domestic purposes. The aquifer stores 20-40 Mm^3 of water (Figure 7.1).

Outflows from the aquifer include groundwater discharge to the Clutha River/Mata-Au, at an estimated rate of 2.5 Mm^3/yr. Groundwater allocation to users is approximately 3.25 Mm^3/yr, of which 2.8 Mm^3/yr is for consented and around 450,000 m^3/yr for permitted uses. Direct diffuse discharge by evaporation from the water table is negligible as the water table in Ettrick is generally deep.

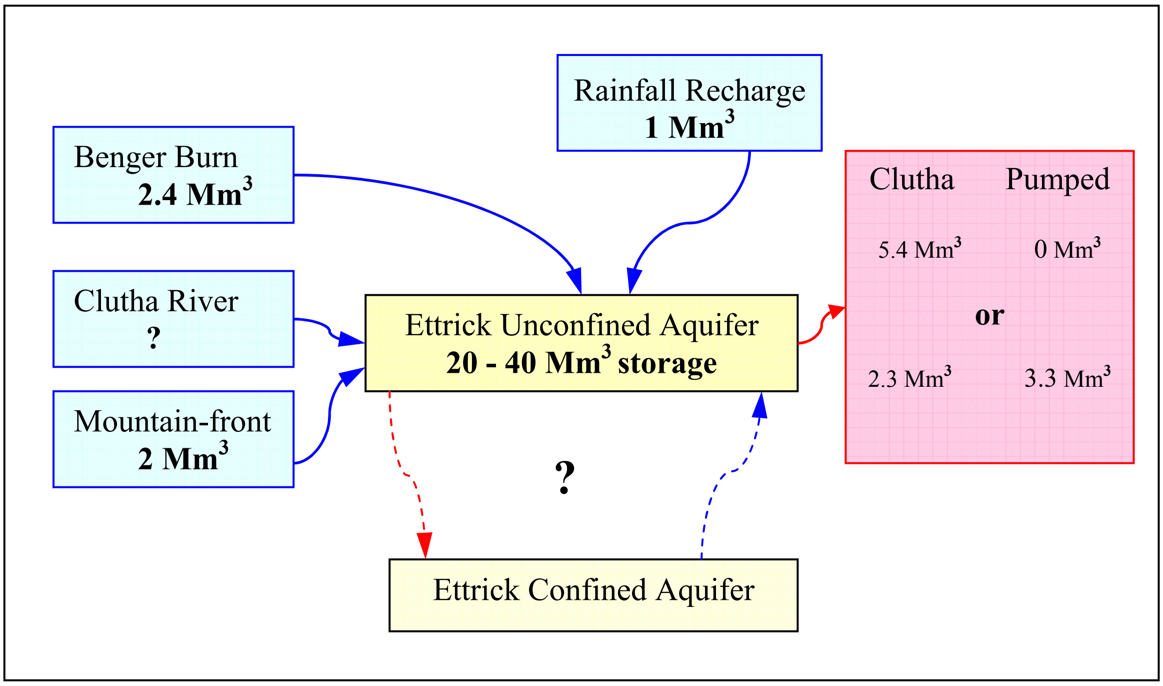

Figure 7.1. Steady state annualised groundwater storage, input and output for the Ettrick Aquifer. Recharge is from the Clutha River/Mata-Au , Benger Burn, and rainfall; discharge is to the Clutha River/Mata-Au. Leakage between the unconfined and, if exists, the confined aquifer, is not known.

Note: Explanation of groundwater discharge; first number assumes no water use, second number allowing all year round groundwater use. If no water is pumped from bores, discharge to the Clutha is estimated as 5.4 Mm^3/yr. If a total of 3.3 Mm^3/yr is pumped from bores, discharge to the Clutha is reduced to 2.3 Mm^3/yr; and the remaining small balance, 200,000 m^3/yr (0.2 Mm^3), is from pumping induced Clutha River/Mata-Au contribution.

7.2 *Water allocation*

The only present value attributed to the Ettrick Unconfined Aquifer is the consumptive value (use from bores). No groundwater dependent ecosystems, other than the Benger Burn, are recognised and the role of groundwater is not regarded as important for the Clutha River/Mata-Au.

Therefore, the sole present objective of managing groundwater in Ettrick is to ensure that bores will have adequate access to groundwater in the future. Available information suggests groundwater recharge occurs infrequently. There are also large uncertainties about the water balance for the Ettrick Basin. Consideration of these factors lends itself to groundwater level response management. At present, groundwater use is controlled by the water level in the Calder bore and users are required to reduce their pumping once certain levels are reached in the Calder bore.

Community involvement in water allocation could review groundwater management in the area regularly with the Otago Regional Council. In particular, the setting of threshold levels in the Calder bore can be reviewed and changed if appropriate.

Water allocation in the Benger Burn and the connected groundwater system should be considered together, recognising the value of Benger Burn and protecting it from nearby groundwater use by using a stream-groundwater Interference Zone. The recommended distance from the Benger Burn for an Interference Zone is defined as:

$$r = 65 \times Q \qquad \text{if } Q \leq 25 \text{ l/sec}$$
$$r = 1138 \times \log Q \qquad \text{if } Q > 25 \text{ l/sec}$$

Where **Q** is the pumping rate in l/sec and **r** is the distance from the Benger Burn in metres (Bekesi and Hodges, 2005). People who wish to obtain consent for a water take within this Interference Zone would be required to show that their proposal does not significantly affect the Benger Burn or tributaries.

If further groundwater takes from the basin are agreed in the future there will be a higher risk of lowered groundwater levels and therefore more time on restrictions. There is a large uncertainty involved in the groundwater budget, therefore, it is recommended that future groundwater allocation in Ettrick should be up to 1 Mm^3/yr (1,000,000 m^3 per year).

It is important for future groundwater management in the Ettrick Basin that applicants provide sufficiently detailed information for the assessment of the environmental effects. This includes bore construction details, lithology information and aquifer testing (pumping tests).

7.3 *Data collection*

The following data collection programme would provide a better basis for groundwater management:

1. Collate borelogs and pumping tests from ORC files, reports, drilling companies and enter this data into a database.
2. Change the frequency of manual groundwater level monitoring to four times a year. Allow or budget for unscheduled monitoring runs to capture large groundwater level changes.
3. Monitor or regularly measure flow loss from the Benger Burn.
4. Plan for establishing a temporary monitoring site opposite Langlea Road where Clutha River/Mata-Au bank storage can be monitored.

8. Conclusions and recommendations

1. The unconfined aquifer of the Ettrick Basin is a vital source of water for local residents to supply stockwater, irrigation water and for domestic use.

2. The Clutha River/Mata-Au has an annual mean flow which is magnitudes larger than the sum of all other water resources of the basin and there is plenty of water available for allocation from the Clutha River/Mata-Au.

3. The aquifer has an estimated recharge of 5.4 Mm^3/year. Consisting of 2.4 Mm^3/year from the Benger Burn, 1.0 Mm^3/year from rainfall recharge and 2.0 Mm^3/year from mountain-front recharge. Episodic high flow events in the Clutha River/Mata-Au are also likely to provide recharge, but the rate is, as yet, unknown.

4. Shallow groundwater storage is used by more than 100 bores. The aquifer stores 20-40 Mm^3 of water.

5. Significant parts of the water balance are uncertain and further work and focussed monitoring is needed to improve the understanding of groundwater allocation.

6. Ensure good community involvement in future water allocation.

7. Groundwater management in Ettrick needs to ensure that bores will have adequate access to groundwater in the future. Groundwater level response management needs to continue (currently by the Calder Bore) because recharge occurs infrequently and there are many uncertainties in the water balance.

8. Recognise the value of the Benger Burn and protect it from nearby groundwater use by using a stream-groundwater interference zone.

9. Bores situated, for example, within 350m, could be classified as water takes from the Clutha River/Mata-Au and not subject to Ettrick Basin allocation.

10. Only limited new water allocations in Ettrick are possible. The total amount of any new allocations should not exceed 1 Mm^3/yr (1,000,000 m^3).

11. Water allocation in Ettrick should be reviewed by the Otago Regional Council at five-yearly intervals.

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10. Glossary

10.1 *Technical terms*

Aquifer - Water bearing layer/strata/geological unit.

Aquitard - Layer which is less permeable and restricts water movement – such as clay.

Hydraulic Conductivity - Aquifer property relating to the ability for water to move through the aquifer.

Storativity - Aquifer property defined as the volume of water that an aquifer releases from storage per unit surface area of aquifer per unit decline in hydraulic head.

Transmissivity - Aquifer property, hydraulic conductivity multiplied by aquifer thickness.

10.2 *Units*

1 Mm^3 - one mega cubic metre = 1,000,000 cubic metres

1 m^3 - one cubic metre = 1,000 litres (l)

l/sec - litres per second

m - metre

Appendix A - Deep drill hole summary

C-2003 Moa Flat and Dalmuir Road. 20m Ettrick Aquifer underlain by 190m thick deposits of the Manuherikia Group, mainly carbonaceous mudstone. From about 150m depth, the Manuherikia Group contains bedded sandstone and fine quartz gravel, the potential Ettrick Confined Aquifer. From 207m (-124 m in terms of sea level), weathered schist was encountered and from 240m the schist basement rock.

C-2004, halfway on Marsh Road. 13m of Ettrick Aquifer underlain by 55m of Manuherikia Group that contains towards the base thin gravels. From 68m depth, weathered schist and from 85m depth (approximately sea level), schist basement followed.

C-2076, Duncan Road. 30m thick Ettrick Aquifer, 165m thick Manuherikia Group (from 60 msl) and schist basement from 110m below sea level.

C-114/2, Dumbarton. 6m of Ettrick Aquifer, 13m thick Manuherikia Group and schist from 19m (66m msl).

C114/13, Hill Springs. 14 m Ettrick Aquifer, from 74m msl Manuherikia Group down to 65m depth (23m msl). Fine gravels from 54m to 65m depth can potentially form the Ettrick Confined Aquifer aquifer.

C114/14, Teviot. 13m Ettrick Aquifer followed by Manuherikia Group from 73m msl to 36m msl. Schist from 50m depth. The fine gravels are very thin (less than 3m) towards the base of the Manuherikia Group.

C114/15, end of Loop Road, Teviot. 8m Ettrick Aquifer followed by Manuherikia Group from 75m msl to 52m msl. Schist from 31m depth. 5m of gravelly sand between 19 and 24m depth.

C114/16, end of Marsh Road. 12m thick Ettrick Aquifer and Manuherikia Group down to 30m depth.

C118, Teviot, Millers Flat Road. 6m of Ettrick Aquifer, 10m of Manuherikia Group and weathered schist from 16m depth. Schist basement from 33m depth.

Appendix B - Bore data summary

Bore No.	Easting (m)	Northing (m)	Elevation (m, amsl)	Depth (m)	Stat.water level (m)	Gw_altit (m)	Code_altit	Diameter (m)	Driller
G43/0001	2227593	5500814	70.56	9.1	-2.14	68.4	GPS	0.25	
G43/0002	2227401	5500859	86.20		-1.55	84.6		1.2	
G43/0003	2226987	5501205	75.98	5	-4.29	71.7	GPS	1	
G43/0004	2226668	5501001	75.31	6.8	-4.00	71.3		1.2	
G43/0005	2227374	5501174	70.40	1.9	-0.60	69.8	GPS	1.2	
G43/0006	2227332	5501125	84.00	0.8	-0.55	83.5		1.5	
G43/0007	2227900	5501100		18				0.1	
G43/0008	2227810	5501283	78.00	6	-5.40	72.6		1.2	
G43/0009	2227194	5501251	92.00	15.2	-12.25	79.8		0.1	
G43/0010	2226265	5501602	94.30	17.8	-13.68	80.7		1.2	
G43/0011	2225980	5501286	87.80	13.5				0.25	
G43/0012	2225874	5501424	87.80	21.3				0.3	
G43/0013	2226182	5501138	85.00	9.1					
G43/0014	2225600	5500900						0.15	
G43/0015	2225259	5500848	87.91	15.8	-10.00	78	Surveyed	0.2	
G43/0016	2225122	5500353	88.19	4.6	-3.91	84.3	GPS	0.9	
G43/0017	2225500	5500400		6				0.075	
G43/0018	2225500	5501400		16.8				0.15	
G43/0019	2225548	5501355	95.30	16.8				0.075	
G43/0020	2225541	5500519	89.00						
G43/0021	2226116	5500693	88.30	8				0.03	
G43/0022	2226800	5501000						0.1	
G43/0023	2226923	5501548	92.70	16	-11.70			0.1	McNeill
G43/0024	2226644	5501771	89.00	14.3	-11.54	77.5		1.2	
G43/0025	2226700	5501800		14	-12.00			0.2	McNeill
G43/0026	2226725	5501701	90.20	15.2	-11.65	78.6		0.2	
G43/0027	2226372	5501825	93.60	15.8	-13.88	79.7		1.5	
G43/0028	2226700	5501800		17.6				0.15	
G43/0029	2226645	5501598	98.20	14.8	-13.70	84.5		1	
G43/0030	2226850	5501461	84.00	13.1	-12.72	71.3	GPS	1.05	
G43/0031	2226285	5502541	102.30	10.8	-9.90	92.4		2	
G43/0032	2226423	5502202	83.58	18.1	-12.00	71.5	Surveyed	0.15	
G43/0033	2225818	5502088	100.30	58	-14.92	85.4		0.3	
G43/0034	2225944	5502698	82.12	48	-10.05	72.1	GPS	1.2	
G43/0035	2225598	5502609	106.80	58	-15.98	90.9		0.3	
G43/0036	2225775	5502015	87.40	60	-14.73	72.7		0.15	
G43/0037	2225800	5502000	87.40	60	-15.00	72	Surveyed	0.075	
G43/0038	2226279	5501889	84.20	16.8	-13.53	70.7		1	
G43/0039	2225779	5501865	95.10	19	-14.44	80.6		1.2	
G43/0040	2225440	5501520	93.40	19.8				1.2	
G43/0041	2225400	5501500						0.25	
G43/0042	2225280	5501508	93.40					0.18	
G43/0043	2225640	5503620	85.20	40	-13.00	72.6	Surveyed	0.475	
G43/0044	2224400	5503600		40				0.018	
G43/0045	2226423	5502018	85.90	69				0.075	
G43/0046	2225185	5501662	93.90	60	-14.96	78.9		0.075	
G43/0047	2225190	5501657	94.00	60					
G43/0048	2225113	5501777	98.00	25.5	-14.96	83		0.3	
G43/0049	2225043	5501904	103.90	70				0.25	
G43/0050	2224540	5501760	97.45	75	-19.65	77.8	GPS	0.15	

Bore No.	Easting (m)	Northing (m)	Elevation (m, amsl)	Depth (m)	Stat.water level (m)	Gw_altit (m)	Code_altit	Diameter (m)	Driller
G43/0051	2225200	5502300						0.15	
G43/0052	2224400	5502900						0.075	
G43/0054	2224892	5502858	89.88	76	-16.50	73.4	GPS	1	
G43/0055	2224453	5503373	91.16		-19.00	72	Surveyed	0.15	
G43/0056	2224161	5503952	107.60	23.9				0.075	
G43/0057	2224600	5504500							
G43/0058	2224300	5504300							
G43/0077	2224500	5504400	80.00	16			Estimated	0.1	McNeill
G43/0078	2227200	5501100		22				0.1	McNeill
G43/0079	2229800	5500000		18				0.1	McNeill
G43/0080	2225888	5500378	80.22	11	-1.53	78.7	GPS	0.25	McNeill
G43/0083	2227200	5501100		22				0.1	McNeill
G43/0100	2226588	5501738	100.10	19.7				0.1	McNeill
G43/0101	2226856	5501621	86.90	17	-10.75	76.1		0.1	McNeill
G43/0102	2224271	5504308	94.30	12				0.1	McNeill
G43/0103	2224200	5504300	87.00	21.4	-14.80		Estimated	0.1	McNeill
G43/0104	2226300	5502100	83.50	20.7	-11.76	71	Estimated	0.1	McNeill
G43/0106	2226600	5501700		20				0.1	
G43/0108	2226700	5501000	77.00	10	-3.53		Estimated	0.1	McNeill
G43/0112	2228700	5500600	80.00	15			Estimated	0.05	McNeill
G43/0113	2227805	5501397	71.18	4	-2.05	69.1	GPS	0.1	McNeill
G43/0122	2228400	5500400		35				0.075	Owner
G43/0123	2228100	5500900		35				0.075	Owner
G43/0132	2229539	5500011	85.68		-9.78	75.9		0.155	
G43/0135	2225842	5504613	84.96					0.075	
G43/0138	2225611	5501007	90.70	17	-5.64	85.1		0.15	McNeill
G43/0141	2224918	5502032	93.40	17.5	-17.73	75.6			
G43/0142	2228532	5500997	86.20	14				0.1	
G43/0143	2226722	5502652	82.10	30	-10.58	71.5	GPS	0.15	McNeill
G43/0145	2226259	5502180	90.00	19	-12.50	77.5		0.125	McNeill
G43/0148	2226370	5501936	85.70	19	-11.93	73.8		0.125	McNeill
G43/0149	2224383	5503236	91.67	36	-19.40	72.9	GPS	0.075	McNeill
G43/0150	2226247	5502175	83.50	19	-13.10	70	Estimated	0.125	McNeill
G43/0151	2225283	5501278	88.28	21	-10.98	77.3	GPS	0.075	
G43/0152	2226505	5502051	85.40	20	-12.85			0.125	McNeill
G43/0153	2224283	5504311	87.15	20	-15.45	71.7	GPS	0.15	McNeill
G43/0154	2226600	5502000		20				0.125	
G43/0155	2227700	5500600		15				0.125	
G43/0158	2224325	5504174	91.20	24	-16.31	74.9		0.125	McNeill
G43/0159	2224700	5504400		25				0.125	
G43/0160	2225046	5502030	89.88	24	-17.24	72.6	GPS	0.125	McNeill
G43/0162	2225761	5501914	98.90		-14.93	84		0.15	
G43/0163	2224864	5503480	85.98		-13.59	72.4	GPS	1.2	
G43/0164	2226956	5501349	95.10		-12.50	82.6		0.1	
G43/0165	2225621	5501003	92.20					0.2	
G43/0166	2226228	5502195	91.20					0.075	
G43/0167	2226528	5502026	94.80		-11.12	83.7		0.075	
G43/0168	2226237	5502208	83.00					0.1	
G43/0169	2226237	5502165	84.00						
G43/0170	2226249	5502177	85.40					0.1	
G43/0171	2226244	5502238	84.50						
G43/0172	2226225	5502262	90.70					0.075	
G43/0173	2226239	5502300	90.70						

Bore No.	Easting (m)	Northing (m)	Elevation (m, amsl)	Depth (m)	Stat.water level (m)	Gw_altit (m)	Code_altit	Diameter (m)	Driller
G43/0174	2226183	5502224	90.00					0.1	
G43/0175	2226512	5501919	93.90					0.075	
G43/0176	2226545	5501934	90.50					0.15	
G43/0177	2226494	5501739	98.70					0.075	
G43/0178	2226538	5501695	93.90					0.075	
G43/0179	2226535	5501759	89.80					0.075	
G43/0180	2226426	5501811	103.00					0.075	
G43/0181	2226558	5501903	89.00					0.075	
G43/0182	2226509	5501740	86.20		-13.55	72.6		0.075	
G43/0183	2228356	5501296	77.00		-9.07	67.9	GPS	0.15	
G43/0184	2228195	5501629	79.74		-9.91	69.8	GPS	0.1	
G43/0185	2228299	5501552	94.00					0.1	
G43/0187	2229290	5500315	80.40					0.3	
G43/0188	2228040	5501825	90.01					0.125	
G43/0189	2227825	5502456	103.95						
G43/0190	2226559	5504469	116.93					0.075	
G43/0191	2225856	5505164	95.78		-3.26	92.5		0.075	
G43/0192	2225924	5504713	97.94					0.05	
G43/0193	2229318	5500091	81.36		-2.50	78.9		0.15	
G43/0194	2225851	5501120	81.60					0.075	
G43/0195	2226215	5502186	93.40					0.1	
G43/0196	2226351	5502065	83.53	20	-11.75	71.8	GPS	0.125	McNeill
G44/0011	2229967	5499302	81.10					0.15	
G44/0012	2229955	5499305	75.80						
G44/0013	2229949	5499316	84.00					0.1	
G44/0014	2229983	5499340	82.10		-8.25	73.8		0.15	
G44/0015	2229887	5499377	71.55		-6.91	64.6	GPS	0.15	
G44/0016	2229906	5499334	63.10					2	
G44/0017	2229900	5499507	85.90					0.075	
G44/0018	2229712	5499643	82.10					0.1	
G44/0019	2229737	5499554	84.70		-9.09	75.6		0.1	
G44/0040	2229753	5499824	91.45		-8.95	82.5		0.1	
G44/0041	2229737	5499882	74.63		-7.54	67.1		0.1	
G44/0106	2229700	5499500		15.2	-10.00			0.1	McNeill
G44/0111	2229700	5499800		13				0.1	McNeill
G44/0115	2228891	5499567	80.90	11.9	-7.40	73.5		0.15	McNeill
G44/0128	2229500	5499600		12				0.1	McNeill
G44/0132	2229700	5499900		12				0.125	McNeill
G44/0202	2229667	5499572	75.60	15				0.15	
G44/0205	2229919	5499589	85.92	12	-6.31	79.6		0.125	McNeill

Note:
Stat.water level (m) = Static water level in metres
Gw_altit (m) = Groundwater level above mean sea level
Code_altit = Method used to determine elevation.

The specific discharges (the ratio between discharge and drawdown) for bores with available information in the area are 60, 200, 200, 210, 230, 250, 350, 385, 400, 970, 1440 and 1900 m^3/day/m.

Appendix C - Diffuse recharge modelling

The soil water budget at any given time interval, t, is:

Recharge(t) = Rainfall(t) + Irrigation(t) - Actual evapotranspiration(t) - Runoff(t) + Change in Soil Moisture Storage(t).

For simplicity of modelling, it is assumed that the soil and unsaturated zone act in a manner similar to a leaking bucket, with recharge to groundwater occurring only when soil moisture content is above field capacity. Inputs to the model therefore include the characteristics of the soil, and daily rainfall and pan evaporation data.

Runoff (over the flat part of the Ettrick basin) was considered insignificant and therefore not included. This is because no surface water courses originate in the flat part of the Ettrick basin and the Benger Burn and other creeks are actually losing flow to groundwater. The impact of irrigation on the entire basin scale is ignored because irrigation water is sourced either from the unconfined aquifer or the Benger Burn where any excess irrigation water could drain back. Although irrigation causes some return water to the aquifer, this water should be minimal because of increased efficiency and therefore should not be relied upon in groundwater allocation.

The soil moisture budget thus becomes:

Recharge(t) = Rainfall(t) - Actual evapotranspiration(t) + Change in Soil Moisture Storage(t)

The major limitation of this method is its limited applicability in arid-zones where the magnitude of recharge is small with respect to other components, particularly evapotranspiration. However, if the water budget is calculated in daily time step (t), rainfall can greatly exceed evapotranspiration on a single day, even in arid-zones (Scanlon et al. 2002). Therefore, the method is implemented in this report using daily rainfall and evaporation data. Averaging over a longer time period would have dampened extreme precipitation events – those that could be responsible for most rainfall recharge events.

The methodology is illustrated in Figure C1. Recharge to groundwater only occurs when the soil is above field capacity. Actual evapotranspiration is equal to potential evapotranspiration at high moisture levels. Actual evapotranspiration is limited by available moisture below a *critical moisture* (defined as the difference between field capacity and readily available water, FC-RAW) and is considered proportional to soil moisture. Evaporation ceases below wilting point.

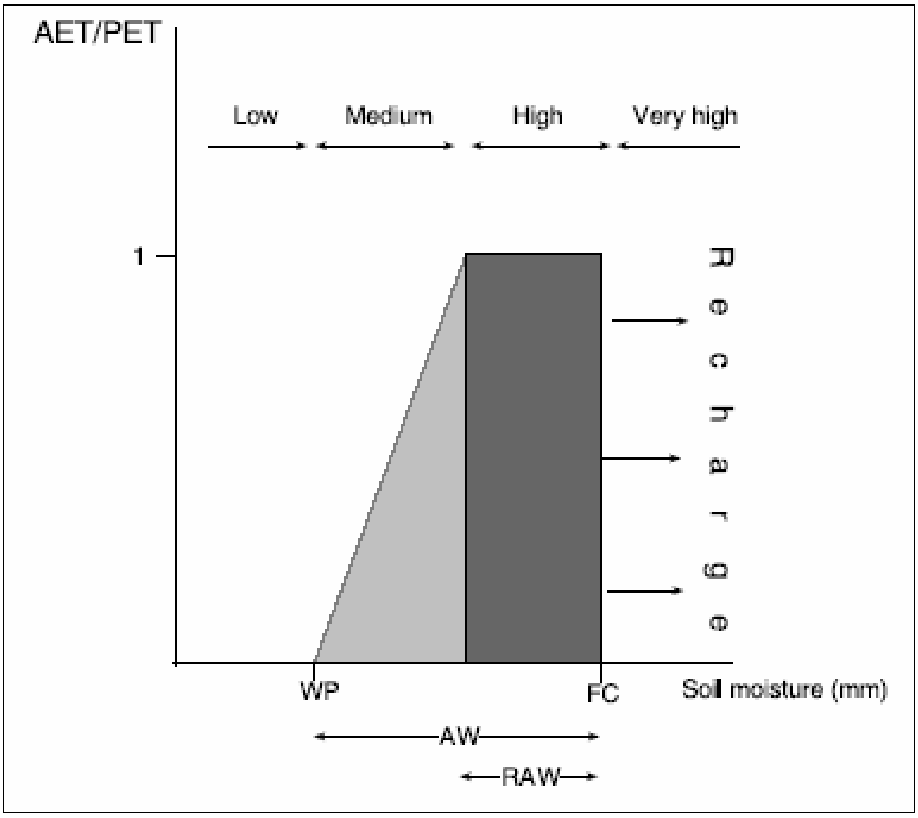

Figure C1. The bucket model used for soil water balance modelling. PET is the potential evapotranspiration, AET is actual evapotranspiration, AW is available water, RAW is readily available water, WP is the wilting point and FC is field capacity (after Bekesi and McConchie, 1999).

The following ranges were used for the soil moisture holding capacity and pan factor:

Available water	150-270mm/1000mm of soil
Readily available water	80-150mm/1000mm of soil
Wilting point	60-150mm/1000mm of soil
Pan factor	0.75-0.9

The inherent variability of soils is reflected in the choice of randomised soil moisture parameters. For each scenario, a randomly chosen value for available water, readily available water, wilting point and pan factor are used as model input. The model calculates recharge each day for a 20-year period.

Results, shown in Figure C2, indicate modelled annualised recharge as the function of soil depth. Estimated diffuse (rainfall) recharge is up to 55mm/yr for shallow soils and less than 20mm/yr for deep soils (and deep roots, for example trees). This is because deep soils require more moisture to fill to field capacity and can hold more moisture for longer times than shallow soils.

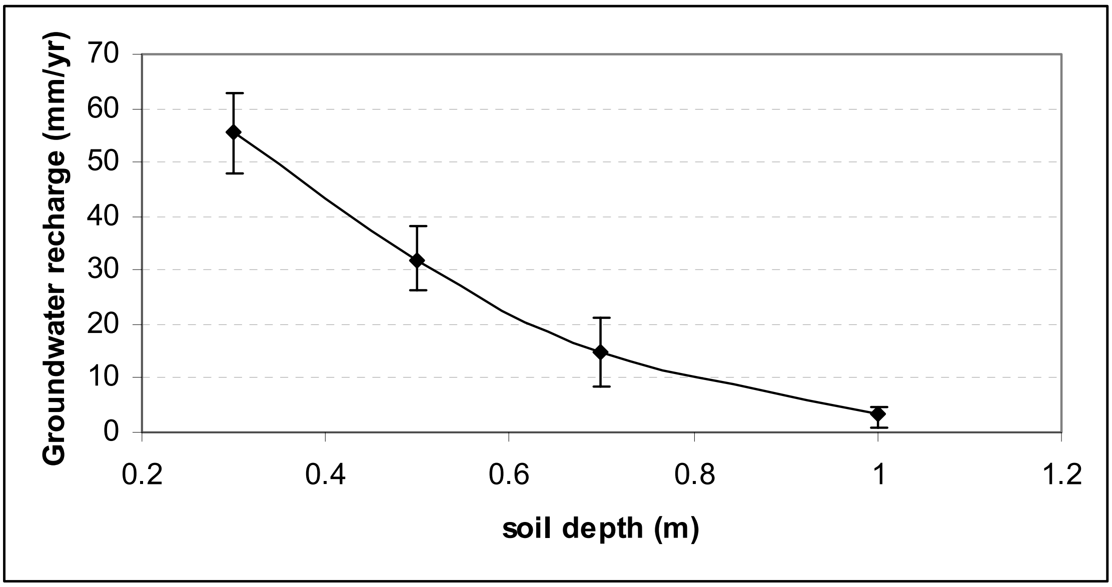

Figure C2. Modelled median recharge vs. soil depth for Ettrick. Error bars are drawn from the 25th percentile to the 75th percentile of modelled annual groundwater recharge. For example, for 0.3m soil depth the 25th percentile of modelled annual recharge is 48mm/yr, the 75th percentile is 63mm.

The recharge estimates of up to 55mm/yr are in general agreement with an earlier estimation of 50mm by Irricon (1997). While the 25th and 75th percentiles of the modelled recharge for shallow soils indicate an average, year to year recharge, it is also important to examine temporal variations in the modelled recharge. This is because diffuse recharge may not happen every year. The typical pattern of diffuse recharge in arid climates consists of large single events causing most of the recharge, often years apart.

Figure C3 indicates small recharge at irregular intervals. For example, no diffuse recharge was calculated between August 1997 and May 2002; while 67mm recharge occurred from May 2002 through to September 2002. Although both the median recharge (32mm/yr) and mean (29mm/yr) are significantly above zero, calculated recharge for seven of the modelled 19 complete years are zero for 500mm soil depth. In other words, diffuse recharge in Ettrick to groundwater is unreliable on an annual basis.

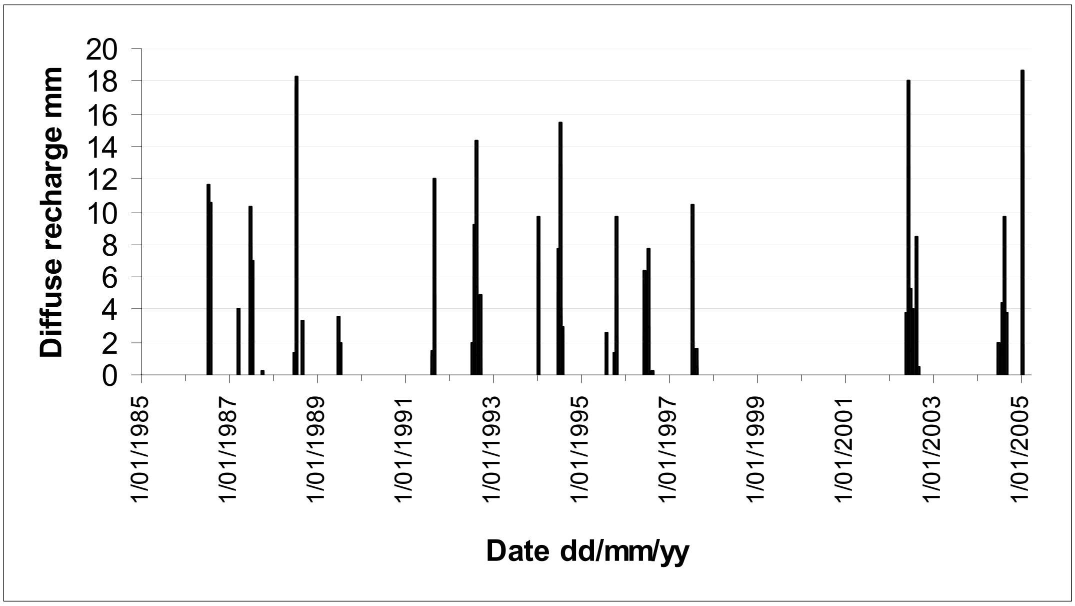

Figure C3. Modelled diffuse (rain) recharge using a bucket model with 500mm soil depth.

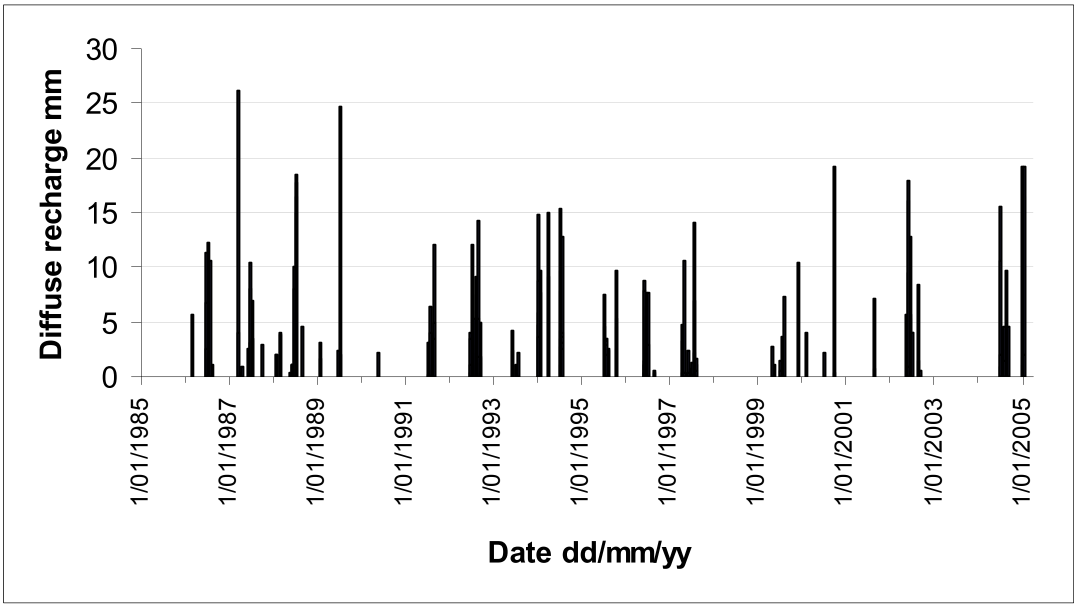

Figure C4. Modelled diffuse (rain) recharge using a bucket model with 300mm soil depth.

Modelling recharge with shallower soils indicates more regular but still small recharge. Assuming 300mm soil depth (a very shallow soil and root depth), the mean annual recharge is close to 55mm and there is still no recharge calculated for three of the 19 years modelled (Figure C4).

Appendix D - Estimating recharge from hydrograph analysis

The 1999-2000 and 2004-2005 recharge events could represent recharge events far greater than those predicted from the diffuse recharge modelling. Disregarding time lags between recharge events and groundwater table rises, the relationship between recharge and groundwater rise is:

$R = S_y \Delta h / \Delta t$

R is the recharge, S_y is the specific yield, $\Delta h / \Delta t$ is the slope of the hydrograph (Δh is the difference between the groundwater base recession and peak caused by the recharge event within Δh time). In a declining groundwater hydrograph, the steepness of the declining water-level trace usually diminishes with time, forming a gently concave curve. The observed falling limb of the water-level hydrograph must be extrapolated to a point lying beneath the peak of the water level rise. The water level rise is then measured as the distance between the peak and the extrapolated falling trend line (Armstrong and Narayan, 1998). The method is called Water Table Fluctuation method (WTF).

The specific yield has to be known or estimated to apply this method. Specific yield can be calculated from pumping tests with observation bores and/or geophysical methods. None of these are available for the Ettrick area. Therefore specific yield can be estimated only using inverse modelling (trial and error) of the hydrograph itself.

In terms of the predicted diffuse rainfall recharge, the most likely period showing such rainfall recharge is the wet winter of 2002. Assuming 500mm soil depth, the predicted recharge, 50mm in 2002, has caused about a 1m net rise which would suggest Sy ~ 0.05. This is somewhat lower than the expected value, or text-book value of 0.07 to 0.2 for sandy gravel aquifers. It is also transparent from Figure D1 that the groundwater rise occurs **before** the predicted recharge, assuming 500mm soil depth. Reducing the soil depth increases the modelled recharge and also creates a better timing for the recharge, as shown in Figure D2.

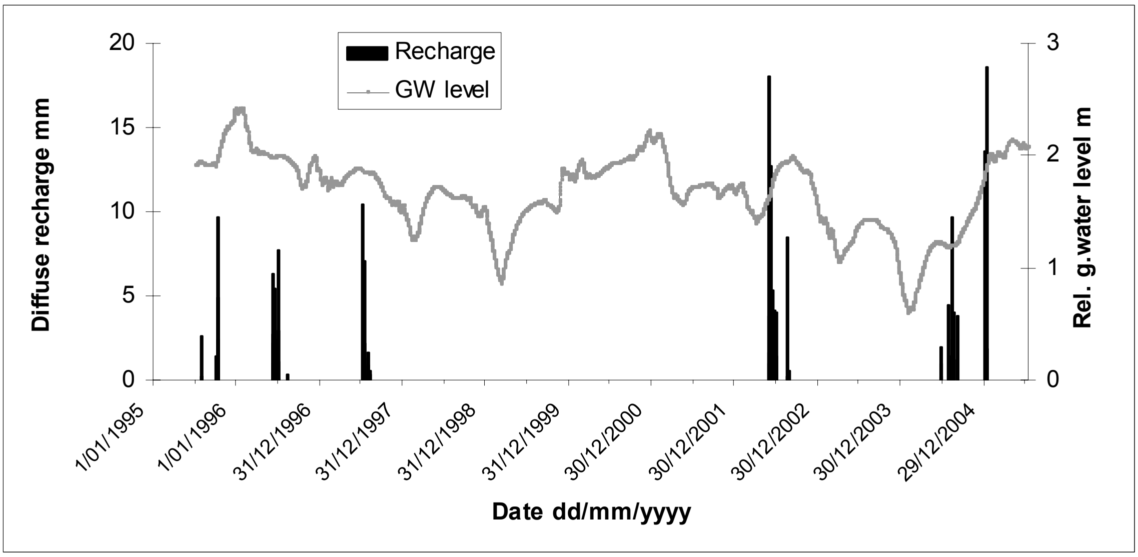

Figure D1. Modelled diffuse recharge and relative groundwater level at the Calder monitoring bore. Soil depth = 500mm

Figure D2 illustrates modelled recharge for 300mm (shallow soil). Using the winter of 2002, the specific yield is around 0.1 or 10% - a value more consistent with textbook values for sand and gravel. Both the match between recharge events and groundwater level rises, and the realistic value of specific yield, point to the use 300mm soil depth. While 300mm represents a very shallow soil, it could be justified by the presence of stoney soils that hold less moisture than loamy soils because large stones cannot hold significant amounts of water on their surface.

Modelling groundwater recharge for 300mm soil indicates diffuse (rainfall) recharge of approximately 100mm in 2002, with a corresponding 1m rise. Substituting these values to the WTF method:

$S_y = R /(\Delta h/ \Delta t) = 0.1m /1 m = 0.1$ or 10%

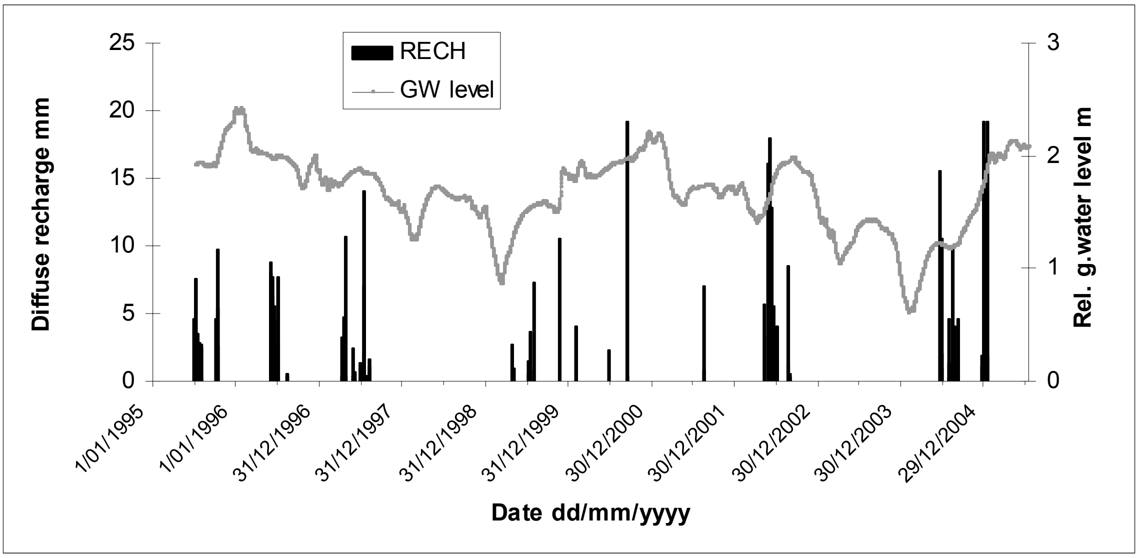

Figure D2. Modelled diffuse recharge and relative groundwater level at the Calder monitoring bore. Soil depth = 300mm

Although Figure D2 represents a better match between recharge and groundwater level than Figure D1, it is transparent that diffuse recharge cannot explain the timing nor the magnitude of the measured changes in the Calder bore. Therefore, factors other than diffuse recharge must contribute to the groundwater level rise.

Possible sources of recharge, in addition to diffuse rainfall recharge, are examined further as follows. The most obvious sources for extra water are the Clutha River/Mata-Au and the Benger Burn. The Calder monitoring bore is situated about 2km from the Moa Flat Road section of the Benger Burn and approximately 3km from the Langlea Road section of the Clutha River/Mata-Au. Therefore, the influence of surface water courses may be dampened by these distances. The suggestions made here, that variability of flow in the Clutha River/Mata-Au or Benger Burn would lead to variations in the groundwater level at the Calder bore, may be tenuous. Nevertheless, a correlation was attempted.

Overlaying the Clutha River/Mata-Au stage or flow plots at Roxburgh with the Calder bore hydrograph has shown only a weak correlation. As the Benger Burn is not monitored continuously, a rainfall monitoring site at higher altitude, Pomahaka at Moa Flat, was used as a proxy for the Benger Burn in an effort to correlate groundwater levels and Benger Burn flows.

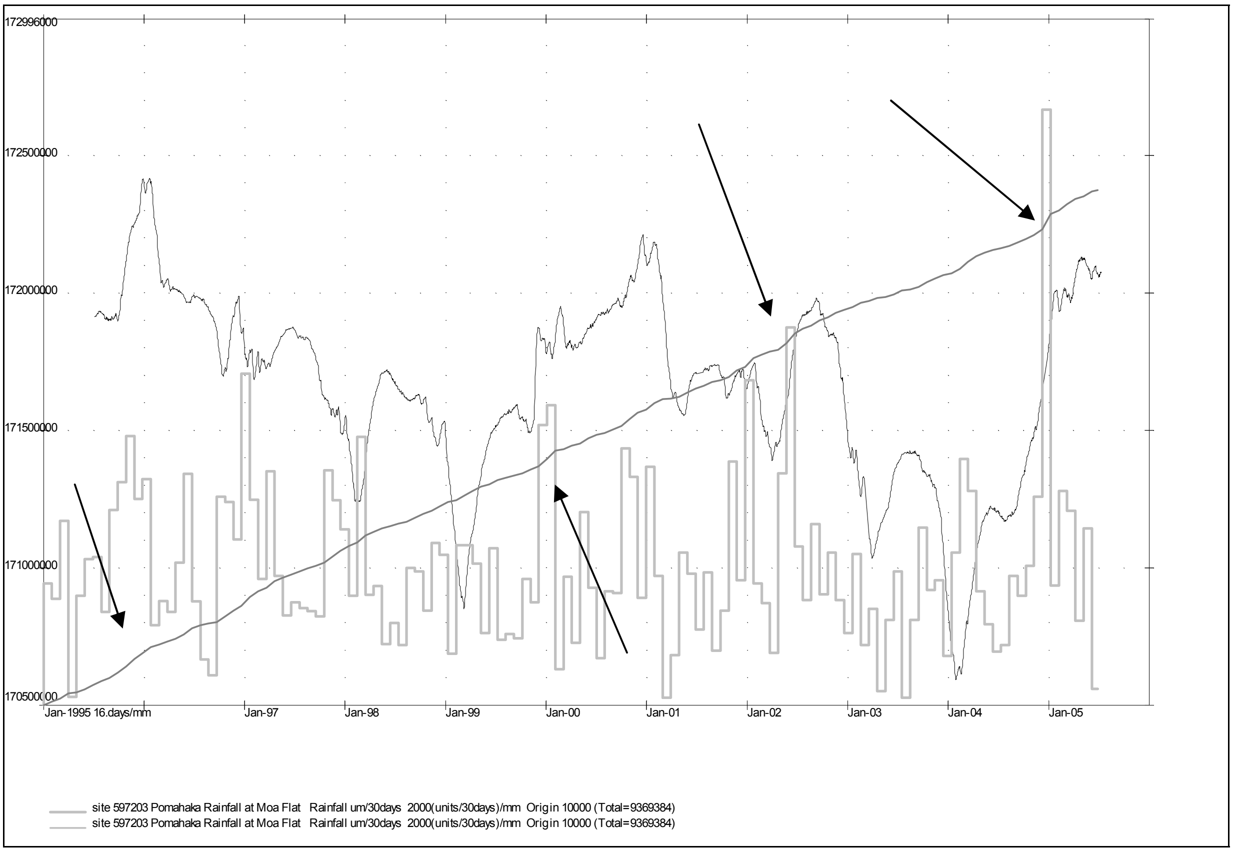

Figure D3. Groundwater level (black) at the Calder bore and 30 days aggregate Pomahaka rainfall (light grey) at Moa Flat (used here as a proxy for Benger Burn). Cumulative rainfall at Moa Flat is shown by dark grey line. One tick on the vertical axes represents 0.5m. Arrows indicate significant rainfall periods that cause steep rises in the cumulative rainfall curve.

Figure D3 indicates a reasonable correlation between the groundwater hydrograph and 30 days total rainfall at Moa Flat. The 2004-2005 and 1999-2000 groundwater recharge events correspond to high and persistent rainfall events. The match, however, is far from perfect and not all the groundwater recharge events are explained, for example, large rainfall events in early 1997 or 2002 do not seem to affect the groundwater level. Cumulative rainfall at Moa Flat is also shown by a dark grey line to indicate how seemingly small deviations (represented by steep increases in the cumulative curve) from the long-term trend in 1999-2000 and 2004-2005 triggered recharge events. It is important to note the groundwater use around the Calder bore can also influence the measured groundwater level.

Applying the WTF method to the Calder bore and assuming $S_y = 0.1$ results in an annualised recharge of 0.12m/yr over the period of 1996-2006:

$$R = S_y \Delta h / \Delta t = 0.1 \times 12 \text{ m} / 10 \text{ years} = 0.12 \text{ m/yr}$$

If a further assumption is made, that the Calder bore represents the entire Ettrick Basin, then the 0.12 m/yr recharge equates to:

$0.12 \text{ m/yr} \times 20 \times 10^6 \text{ m}^2 = 2.4 \times 10^6 \text{ m}^3 = 2.4 \text{ Mm}^3\text{/yr}$.

A proper statistical analysis of confidence intervals for this estimate are impracticable; at present a best-guess for the range of annualised recharge is 1.7 – 3 Mm^3/yr.

Appendix E - Groundwater numerical models

Two simplified models were constructed to understand the hydrogeology of the Ettrick Aquifer. One is a steady state model to look at the hydrogeology of the basin and interactions with surface water bodies and the other is a transient model looking at groundwater level trends through time and the impacts of climate and changing aquifer management

Steady state model

A single layer model was constructed using 70 by 70 cells. Cell size is a uniform 100m by 100m. Surface elevation was obtained from a digital terrain model and the base of the Ettrick Aquifer was set at 64m above sea level. The base of the aquifer in reality is gently sloping, (Figure 2.2 main report) but there are not enough drill logs available to create a reliable contour map.

Inactive cells (no groundwater flow) were defined as those considered to be bedrock (Turnbull, 2000). The area east of the Clutha River/Mata-Au was not modelled because groundwater flow is assumed to be intercepted by the river.

Recharge was considered as a uniform 50mm/year. The Clutha River/Mata-Au was simulated using a line river boundary with high/very high river bed conductances. These allow strong hydraulic link or water flow between groundwater and the river.

The estimated 2.4 Mm^3/yr loss from the Benger Burn was simulated by 20 recharging wells along reaches of the stream where it is known or assumed to lose water. The flow loss was distributed unevenly to match measured groundwater levels. Mountain-front recharge was simulated by 56 recharging wells each pumping in 100 m^3/day of water to the aquifer.

Consented groundwater takes were imported to the model, however, these pumping bores were switched off because the groundwater level map in Figure 4.2 was measured at a time where no irrigation was necessary. No time-series records exist for actual groundwater pumping. Future modelling efforts would be significantly improved by obtaining reliable groundwater use data.

The objective of the modelling was educational and emphasis was placed on keeping the model realistic in the absence of quality information, in particular about the flow in the Benger Burn and the altitudes and bed material of the Clutha River/Mata-Au. Reducing the RMS error once it was below 10% was not attempted.

Two hydraulic conductivity zones were created. A low conductivity zone, with 10 m/day near the mountain-front, was created to simulate the dense groundwater contours in that area (Figure 4.2 main report). The remaining model area was assigned uniform hydraulic conductivity between 50 and 150 m/day and optimised through steady state modelling at 100 m/day.

Calibration was attempted to 21 groundwater levels measured in May/June 2005 (Figure E1). It is accepted that in a steady-state model, long-term averages for groundwater levels should have been used; however, such data was not available. The calibration of observation bores along the Benger Burn and the Clutha River/Mata-Au were not attempted as these water levels can only be matched by setting the river water levels equivalent to the observed static water level. The reasons for these are the close proximity of the model boundary and the large sensitivity of such groundwater levels to surface water levels.

Results are shown in Figure E1 and indicate an acceptable fit between observed and calculated heads or groundwater levels. The calibration of two observation bores along the Benger Burn and the Clutha River/Mata-Au was not attempted as these water levels can only be matched by setting the river water levels equivalent to the observed static water level. The reasons for these are the close proximity of the model boundary and the large sensitivity of such groundwater levels to surface water levels.

Transient model

A transient model, using the same concepts as the steady state model, was constructed to match the observations available at the Calder bore with those calculated by the model.

Recharge from the Benger Burn and mountain-front recharge were considered constant. Diffuse recharge was calculated using the soil bucket model (Bekesi and McConchie, 1999). The daily recharges calculated by the soil bucket model were summed to 90 day-long periods and entered into the numerical model. The model started in July 1995 therefore the time scale in Figure E2 refers to the number of days since July 1995.
No consented pumping wells were used in the model therefore the observed minima of the Calder bore hydrograph could not be matched in the calibration process. These minima, at 1300 and 3100 days in Figure E2 occur after long recession periods (three and two years respectively). It is reasonable to assume that most groundwater abstraction occurs through these recession periods, when the soils get dryer and dryer.

Calibration was at hydraulic conductivity of 130 m/day (in the steady state model it was close to 100 m/day) and a uniform specific yield of 0.1.

The match between observed and calculated heads is surprisingly good considering the lack of data on how well the Calder bore represents the Ettrick Aquifer. The most promising fit between observed and calculated values are the steep rises at 2700 and 3300 days. The worst match is between 1600 and 2100 days and the reasons for such a discrepancy are unknown. If the Calder bore is situated, for example, in a zone where hydraulic conductivity and specific yields are different to representative values of the basin, the calculated red curve could be different to that displayed in Figure E2. Another reason could be additional recharge from the Benger Burn or the Clutha River.

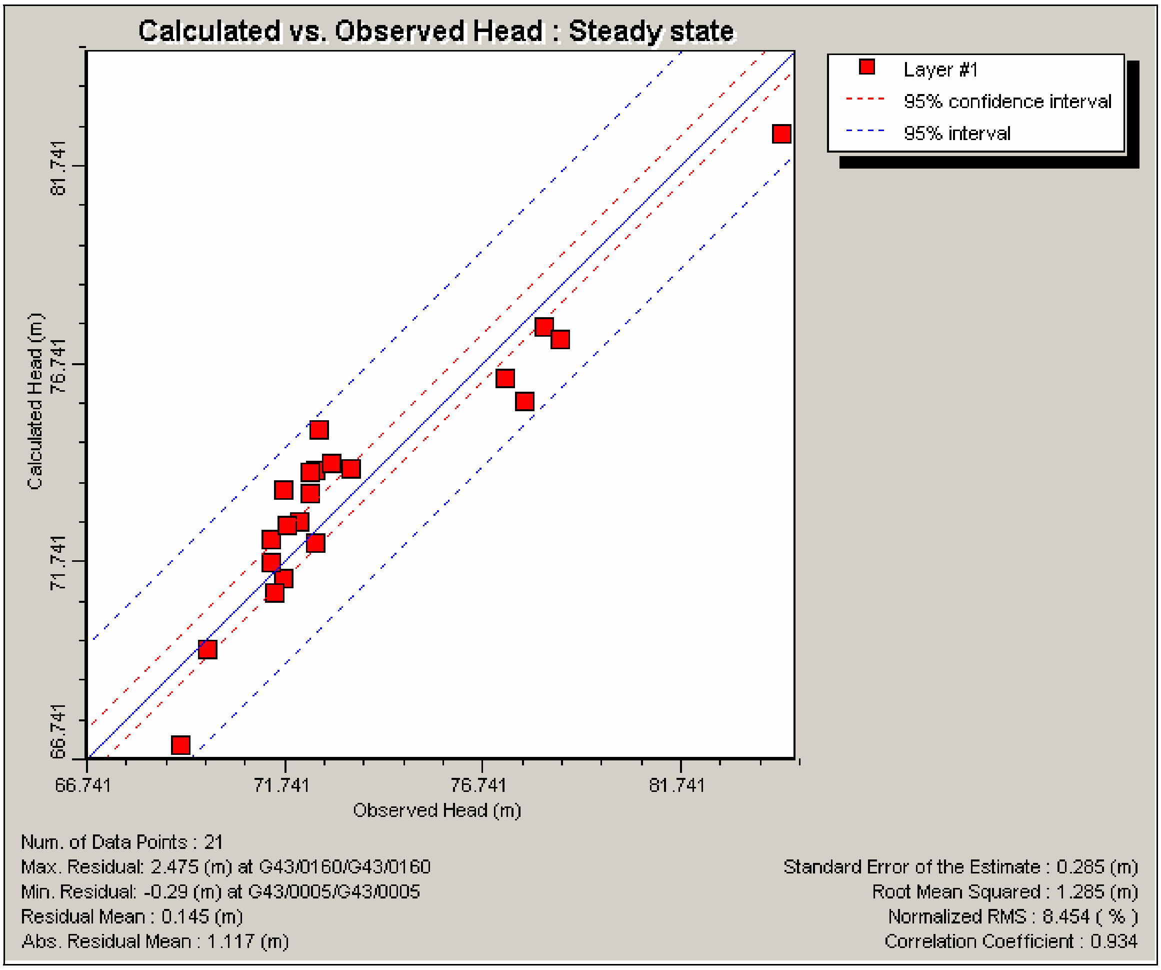

Figure E1. Steady state model output and calibration errors shown here by the observed head (or groundwater level) versus the calculated head. A common measure of fit, between observed and calculated data, is the ratio of standard error of estimate (0.285m) to the useful range of observation (~10m) is ~ 0.03

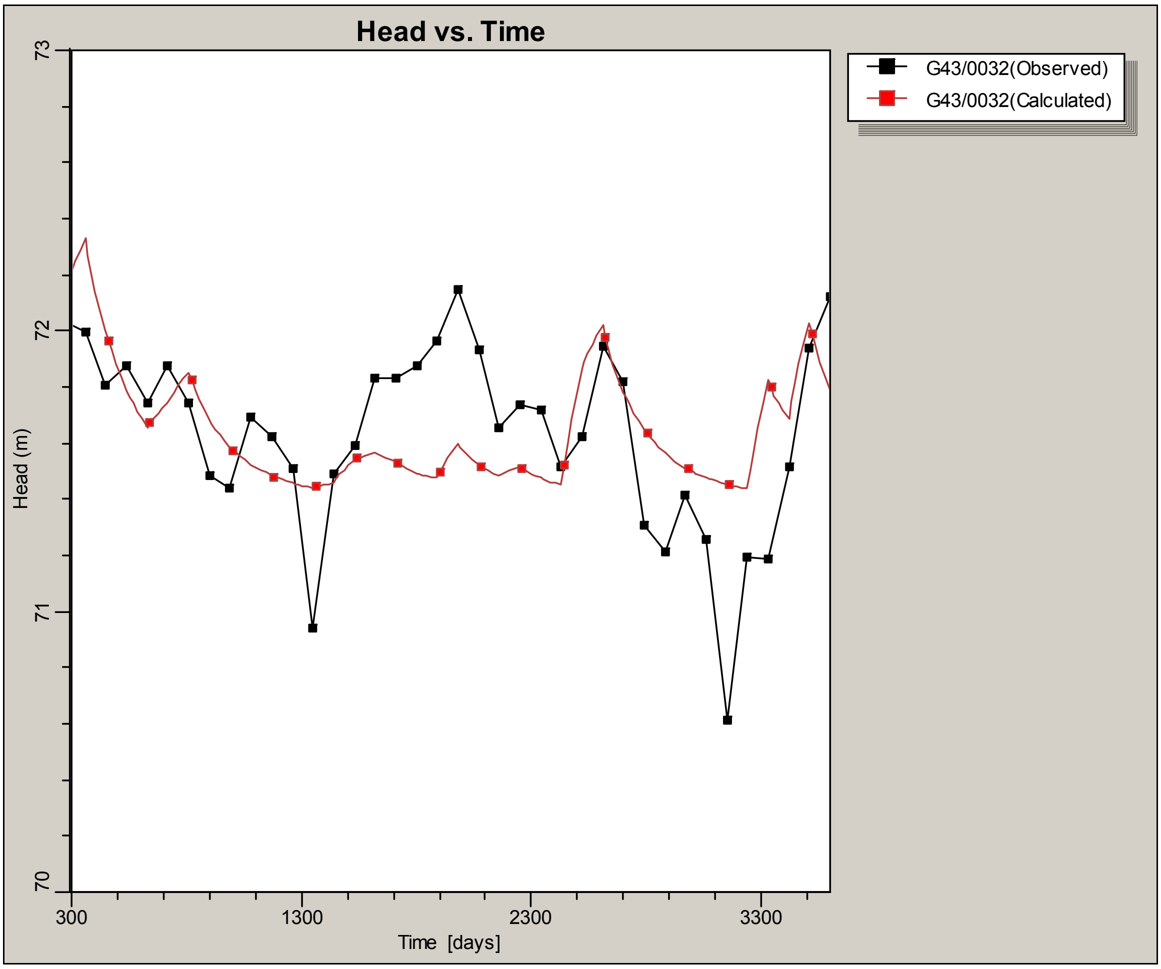

Figure E2. Transient model calibration. The time scale refers to the number of days since July 1995, i.e. represents May 1996 to August 2005. Minima in the observed black curve are not, and cannot be matched as no abstraction bores are active in the model. The departure of the curves between 1600 and 2100 days is unexplained by available data.