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NEW LIGHT ON STREAMWATER SOURCES IN THE GLENDHU EXPERIMENTAL CATCHMENTS, EAST OTAGO, NEW ZEALAND

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Abstract: The east Otago uplands of New Zealand's South Island have long been studied because of the environmental consequences of converting native tussock grasslands to other land covers, notably forestry and pasture for stock grazing. Early studies showed that afforestation substantially reduced annual water yield, stream peak flows, and 7–day low flows, mainly as a consequence of increased interception. Hydrometric measurements revealed two rates of recession with a sharp break between them, a rapid rate during the early part of the recession and a slow rate during the latter part. Oxygen-18 measurements showed that most storms in the moderate to small size range were dominated by 'old' (stored) water, especially early in the storm, and also in the later phase of base flow recession. It was suggested that the numerous small wetlands in the headwaters of the larger catchments acted as temporary storage areas supplying old water, although later work indicates that the wetlands merely serve to link the surrounding hillslopes with the streams that drain them. Interflow was identified as the source of storm runoff, and drainage from deep loess horizons on the surrounding hillslopes the source of the extended base flow. The present study has used tritium and CFC concentrations to determine the residence times of water contributing to the second part of the recession. Tritium measurements (supported by CFC measurements) indicated that surprisingly old water is present in the (GH5) wetland and contributes strongly to baseflow (and therefore also to quickflow). The age of the water is revealed by the presence of tritium originating from the bomb-peak in NZ rainfall in the late 1960s and early 1970s. The data have been simulated assuming the presence of two types of water in the streams in accordance with the hydrometric and oxygen-18 evidence. A mean residence time of 27 years was estimated for water in the mid-bog area of the GH5 wetland (the old component). Such an age indicates that slow release from a large groundwater reservoir within the bedrock underlying the catchments is a major source of streamflow. Recession analysis of the baseflow supports the presence of a deep groundwater aquifer underlying the catchment.

Keywords: Streamflow sources; land use change; age dating; tritium; CFCs; recession analysis

INTRODUCTION

Understanding streamwater sources is important for managing the quality and quantity of water produced by catchments, especially if land use is changing. This paper describes the application of dating techniques to the identification of water sources in the Glendhu Experimental Catchments.

The east Otago uplands of New Zealand's South Island have long been the focus of attention because of the environmental consequences of converting native tussock grasslands to other land covers, notably forestry and pasture for stock grazing. As a response to some of these concerns, a paired catchment study was established at Glendhu in 1980 in the upper Waipori river basin 60 km west of the city of Dunedin to assess the hydrological effects of the afforestation of tussock grassland. After a 3–year calibration period (1980–1982), one catchment (GH2, 310 ha) was planted in Monterey pine (*Pinus radiata*) and the other (GH1, 218 ha) left in native tussock grassland as a control. Subsequent analyses have shown that afforestation has substantially reduced annual water yield, stream peak flows, and 7–day low flows (Fahey and Jackson 1997) mainly as a consequence of increased interception, but also from increased evapotranspiration.

Previous workers have applied a variety of methods to elucidate the mechanisms responsible for both storm flow and base flow recession in the control catchment (GH1). Bonell et al. (1990) examined the sources of water for selected storms, based on an analysis of the naturally occurring isotope oxygen–18

(^{18}O). They found that most storms in the moderate to small size range were dominated by "old" (stored) water, especially early in the storm. Runoff in the later phase of base flow recession was also dominated by "old" water with a composition identical to that prior to the storm event. They suggested that the numerous small wetlands in the headwaters of the larger catchments acted as temporary storage areas supplying the old water. Miller (1994) however, concluded that these features may not be important sources of base flow, but merely serve to link the surrounding hillslopes with the streams that drain them. Fahey et al. (1998) and Bowden et al. (2001) found that storm runoff occurs primarily as inter flow, and that base flow can be sustained for long periods from soil moisture stored in the deep loess horizons blanketing the surrounding hillslopes, but only for a few days from the water in the bog itself.

The present study sheds new light on the sources of water in the baseflow by using tritium and dissolved CFCs to reveal the residence times of the water in the catchment. This in turn has implications for the complete hydrograph.

BACKGROUND

Glendhu Catchments

The catchments display rolling-to-steep topography, and range in elevation from 460 to 650 m a.s.l. (Fig.1). Bedrock is moderately-to-strongly weathered schist. The weathered material has filled in pre-existing gullies and depression, and much of the bedrock-colluvial surface is overlain by a loess mantle of variable thickness (0.5 to 3 m). Well-to-poorly drained silt loams are found on the broad interfluves and steep side slopes, and poorly drained peaty soils in the valley bottoms. Amphitheatre-like sub-catchments (e.g., GH5) are common features in the headwaters of both GH1 and GH2. They frequently exhibit central wetlands that extend downstream as riparian bogs. Snow tussock (*Chionochloa rigida*) is the dominant vegetation cover in the control catchment (GH1). Headwater wetlands have a mixed cover of sphagnum moss, tussock, and wire grass (*Empodisma minus*). The mean annual temperature at GH5 (elevation 625 m a.s.l.) is 7.6º, and the mean annual rainfall is 1350 mm. Annual runoff is measured at all weirs to an accuracy of ±5% (Pearce, et al. 1984).

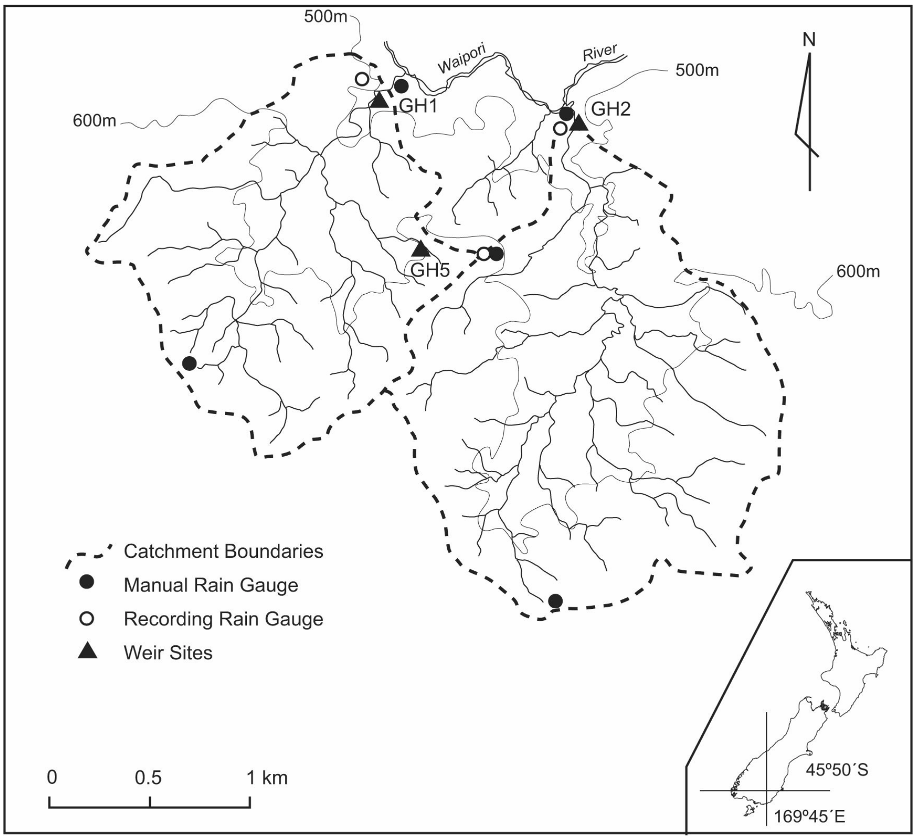


Figure 1. Map of Glendhu experimental catchments (GH1, GH2 and GH5).

Master Recession Curve

Figure 2 shows the master recession curve, not involving snowmelt or additional rainfall, derived by Pearce et al. (1984) from the longest recessions observed during a 3-year study period. This recession curve is typical of high to medium runoff events. The plot shows that there is a marked change of slope between the early and late parts of the recessions (at a flow of about 2.6 mm/day, where 1 mm/day equals 0.12 L/s/ha). Quickflow, as defined by Hewlett and Hibbert (1967), comprises 50% of the annual hydrograph and ceases shortly after the change in recession rate in most storm hydrographs (Pearce et al., 1984).

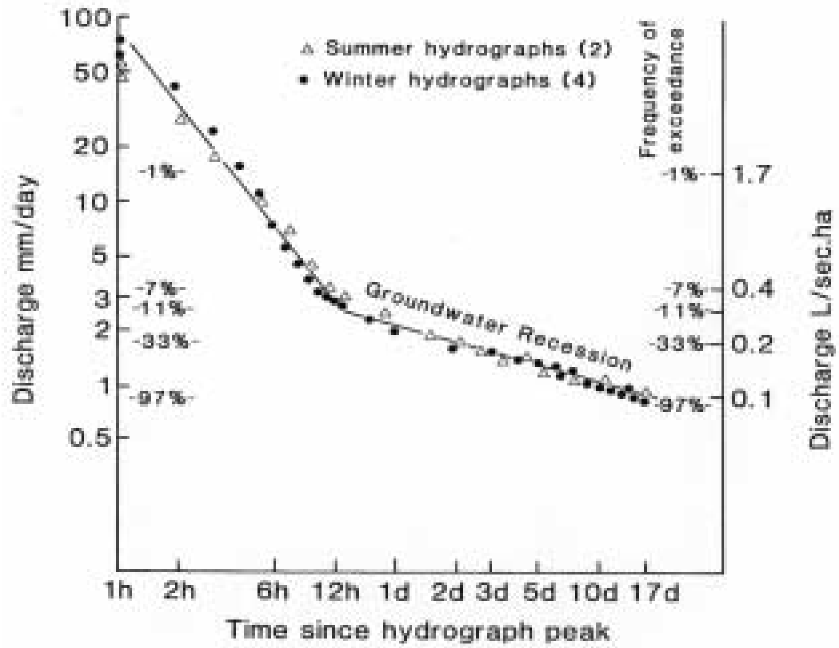


Figure 2. Master recession curve for Glendhu experimental catchments.

Oxygen-18 Results
Hydrograph separation of 'new' and 'old' water was carried out using oxygen-18 to investigate the runoff mechanisms operating and the causes of the master recession curve (Bonell et al., 1990). Results showed that for quickflow volumes greater than 10 mm, the first part of the storm hydrograph could be attributed to two sources, 'new' water from saturation overland flow, and 'old' water from a shallow unconfined groundwater aquifer. For quickflow volumes less than 10 mm, only 'old' water from groundwater contributed. The second part of the hydrograph consisted only of 'old' water, from a very well-mixed shallow unconfined groundwater body.

Hydrological Balance
A hydrological balance can be estimated for catchment GH5 based on rainfall and runoff measured in 1996. This is: Precipitation (1344 mm) – PET (600 mm) = Runoff (489 mm) + Loss (255 mm). (Assuming a 5% measurement error for Precipitation, PET, and Runoff, leaves the estimated Loss term with an accuracy of ±120 mm). PET is potential evapotranspiration. (Actual evapotranspiration of 622 mm was measured for tussock grassland in the period April 1985 to March 1986 at a nearby site in catchment GH1 (570 m a.s.l.) by Campbell and Murray (1990) using a weighing lysimeter. The Priestley-Taylor estimate of PET was 643 mm for the period. The Priestley-Taylor PET for 1996 was 599 mm.) The Loss of 255 mm (34% of total GH5 drainage) is considered to be water which bypasses/underflows the GH5 weir, situated 30 m downstream of the sill at the lower end of the wetland. This water probably appears in the stream at lower levels beyond the weir. Note also that the 1996-1999 average annual runoffs for GH5 and GH1 were 404 and 743 mm respectively, showing that there is loss at GH5 but probably not at GH1.

METHODS
Tritium, CFC and SF_6 Measurements
Samples were collected from the small wetland (0.39 ha) in GH5 (3.64 ha), from different sites along the stream originating in the wetland, and from the outlets of catchments GH1 and GH2, in December 2001 and February 2005. The measurements were made at the Water Dating Laboratory of GNS Science in New Zealand.

Tritium samples were collected in 1.1 L glass bottles, which were allowed to overflow before being tightly capped, in order to minimise contact with the atmosphere. The samples were electolytically enriched in tritium by a factor of 70, and counted in an ultra low-background Quantalus liquid scintillation counter (Taylor 1994, Morgenstern & Taylor 2005). The results are based on the new radioactive half-life of tritium of 12.32 years, and new calibration of standard water SRM4926C (1.100462±0.366% at 3 September 1998, Morgenstern & Taylor 2005). The high precision of the measurements are documented in IAEA (1995) and Morgenstern & Taylor (2005).

Tritium is produced naturally in the atmosphere by cosmic rays, and large amounts were released into the atmosphere by nuclear weapons tests in the early 1960s, giving rain and surface water a relatively high tritium concentration compared to the natural level. The bomb-peak is now much smaller, because of radioactive decay and dispersion, or has completely passed through shorter residence time hydrological systems, but is still the most direct way of determining water ages using tritium. Cosmic ray tritium can also be used for dating groundwater and streamflow, if sufficiently precise tritium measurements are available (Morgenstern and Taylor 2005, McGlynn et al. 2003).

CFC samples were collected air-free in 2.5 L glass bottles according to methods developed by van der Raaij (2003). The bottles were rinsed in the water to be collected, then filled smoothly from the bottom and allowed to overflow. Care was taken to ensure that there were no small bubbles adhering to the inner sides of the bottle. After overflowing for some time, the tube was slowly removed, leaving a convex meniscus on the top of the bottle. The cap was filled with water, then placed over the meniscus and firmly secured. A shaped nylon liner within the cap expelled any surplus water as the cap was being tightened. Then the bottle was tipped upside down and closely observed to see if any bubbles rose up through the water in the bottle. If any did, the sample was discarded and a new sample was collected. Samples were stored at constant temperature.

Measurements of the dissolved CFC concentrations in the water were made by gas chromatography using a purge and trap method, and EC detector (van der Raaij, 2003). Measurement and use of CFC concentrations for dating groundwater is described by Plummer & Busenberg (1999). Dissolved argon and nitrogen concentrations were also analysed by gas chromatography for the February 2005 samples (van der Raaij 2003). These were used to determine the excess air concentrations and recharge temperatures of the samples (Plummer & Busenberg 1999).

Residence Time Determination

Transport of water through the unsaturated and saturated zones of catchments results in mixing and dispersion of water. The water does not have a discrete age, but has a distribution of ages. This distribution is described by a flow or mixing model, which reflects the conditions in the catchment.

Inputs to the catchment (tritium or CFC concentrations in the recharge water) are modified by passing through the hydrological system (as represented by the flow model) before appearing in the output. The convolution integral and an appropriate flow model are used to relate the tracer input and output. The convolution integral is given by

$$C_{out}(t) = \int_0^\infty C_{in}(t - \tau)\, h(\tau) \exp(-\lambda\tau)\, d\tau \qquad (1)$$

where C_{in} and C_{out} are the input and output concentrations in the precipitation and baseflow respectively. t is calendar time and the integration is carried out over the transit times τ. $h(\tau)$ is the flow model or reaction function of the hydrological system. λ (= ln2 / $T_{½}$) is the tritium decay constant. ($T_{½}$ is the half-life of tritium (12.32 years).)

Two flow models are commonly used in stable isotope studies. The exponential-piston flow model (EPM) combines a section with exponential transit times followed by a piston flow section to give a model with parameters of mean residence time (τ_m) and exponential volume fraction (f) (parameters slightly modified from Maloszewski & Zuber 1982). The response function is given by

$$h(\tau) = 0 \qquad \text{for } \tau < \tau_m (1-f) \qquad (2a)$$

$$h(\tau) = (f\,\tau_m)^{-1} \cdot \exp[\, -(\tau / f\,\tau_m) + (1/f) - 1\,] \qquad \text{for } \tau \geq \tau_m (1-f) \qquad (2b)$$

where f is the ratio of the exponential to the total volumes, and $\tau_m(1-f)$ the time required for water to flow through the piston flow section.

The dispersion model (DM) assumes a tracer transport which is controlled by advection and dispersion processes (Maloszewski & Zuber 1982)

$$h(\vartheta) \mid \frac{1}{\vartheta\sqrt{4\phi(D/vx)\vartheta/\vartheta_m}} \exp\left(4\, \frac{(1\,4\,\vartheta/\vartheta_m)^2}{4(D/vx)\vartheta/\vartheta_m} \right) \qquad (3)$$

where D is the longitudinal dispersion coefficient, v is the flow velocity and x is the flow distance. The model parameters are the mean residence time (Ű$_m$) and the dispersion parameter (DP = D/vx).

Recession Analysis

Many different conceptual models have been used for baseflow recession analysis (e.g. see review in Dewandel et al. 2003). The two-part master recession curve (Figure 2) encourages application of aquifer recession formulae to both parts of the recession. We have applied the quadratic equation of Boussinesq (1903) (which is an exact solution for drainage of a homogeneous aquifer limited by an impermeable horizontal layer at the level of the outlet) and the frequently-used exponential recession equation (which describes emptying of a water-filled reservoir through a porous plug, Maillot 1905). The
quadratic equation is

$$Q_t = Q_o/(1 + \text{Ǔ}t)^2, \qquad (4)$$

the exponential equation is

$$Q_t = Q_o \exp(-\text{Ǔ}t), \qquad (5)$$

and Ǔ is given by

$$\text{Ǔ} = KB/SL^2 \qquad (6)$$

where K is the hydraulic conductivity, B is the effective aquifer thickness, S is the effective porosity and L is the length of the flow path (Bidwell 2004).

RESULTS

Tritium, CFC and SF_6 Patterns

Results are given in Table 1. Two samples were collected from the central wetland in GH5 on 4/12/01 for tritium analysis. One was from an old 1 m deep tube near the mid-bog piezometer nest, the other was from an N-tube near the lower piezometer nest drawing from 1.2 m depth. The results are 2.97 and 2.77 TU respectively. The mid-bog sample has a significantly higher concentration than the GH5 stream samples (below), while the lower bog sample has the same concentration. A third bog sample was collected on 22/2/05, but has not been analysed yet. CFC samples could not be collected from these sites as the entire amount of water extractable from the tubes was needed for tritium measurements.

Three samples were collected from the small stream originating in the wetland on 4/12/01 (Table 1). The stream gains in flow as it traverses the gradually steepening lower section of the bog. One sample was collected from 20 m above the weir, where the flow is very small. Another was collected at the GH5 weir. The last was collected 30 m below the weir, where the stream has the largest flow. The tritium results are 2.78, 2.78 and 2.71 TU respectively, and are not distinguishable from each other when the error of measurement (± 0.08 TU) is considered, although the lower value in the last sample could indicate greater input of young water (see below). The mean value of the samples is 2.76 ± 0.04 TU. CFC samples were also collected at these sites. The CFC-11 and CFC-12 concentrations are considerably less than the concentrations expected for water in equilibrium with the atmosphere at the time of sampling, but are substantially above zero. Hence it is likely that the CFC concentrations reflect the age of the water, rather than being in equilibrium with the atmosphere or affected by chemical degradation in the wetland.

Further GH5 stream samples were collected on 22/2/05. Tritium concentrations are still being measured for these, but the CFC concentrations show increases downstream away from the wetland like the earlier samples.

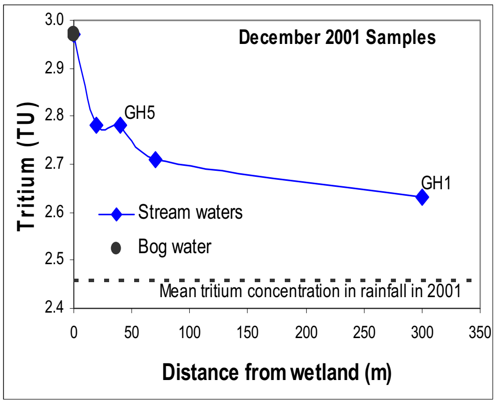
The final samples were collected from the streams at the outlets of GH1 and GH2 catchments in 4/12/01, and from GH1 on 21/2/05. The 4/12/01 samples had tritium concentrations not distinguishable from each other (Table 1) with a mean concentration of 2.66 ± 0.04 TU. The CFC concentrations are close to the atmospheric levels pertaining in 2001 and 2005.

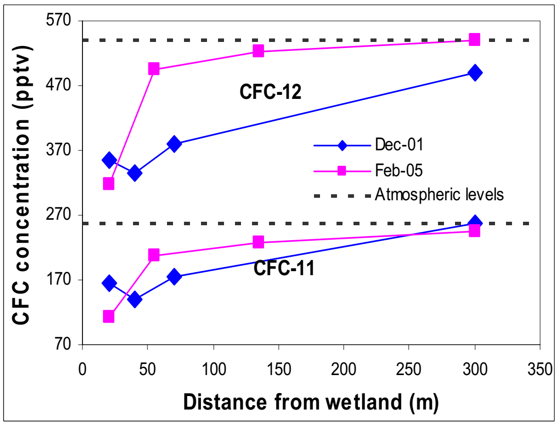
Table 1. Tritium, CFC-11 and CFC-12 concentrations in samples collected from tubes in the GH5 wetland, from GH5 stream, and from GH1 and GH2 streams. (yf is the fraction of young water, see text.)

Sample	Date	Tritium		Excess Air	Temp	CFC-11		CFC-12	
		TU	yf	mL/kg	°C	pptv	yf	pptv	yf
1m tube - mid bog	4/12/2001	2.97 ± 0.11	0			ns		ns	
N tube - lower bog	4/12/2001	2.77 ± 0.08				ns		ns	
A1 tube - lower bog	22/02/05	Being measured				ns		ns	
GH5	4/12/2001	2.78 ± 0.08		(0)	(8)	139.4 ± 8.2		335.0 ± 18.6	
20 m above GH5	4/12/2001	2.78 ± 0.06		(0)	(8)	165.1 ± 4.2		353.8 ± 9.8	
30 m below GH5	4/12/2001	2.71 ± 0.06		(0)	(8)	175.6 ± 2.5		379.4 ± 1.0	
Mean for GH5 stream	4/12/2001	2.76 ± 0.04	0.40 ± 0.08			160.0 ± 18.6	0.41 ± 0.11	356.1 ± 22.3	0.49 ± 0.06
15 m above GH5	22/02/05	Being measured		0.4	7.6	112.3 ± 9.7		318.1 ±18.8	
20 m below GH5	22/02/05	Being measured		-0.2	8.3	208.3 ± 1.8		494.9 ± 3.7	
100 m below GH5	22/02/05	Sample stored		0	8.3	228.4 ± 4.4		522.5 ± 9.9	
GH1 stream	4/12/2001	2.63 ± 0.10		(0)	(8)	258.2 ± 19.9		491.1 ± 1.4	
GH2 stream	5/12/2001	2.69 ± 0.07		(0)	(8)	252.3 ± 1.9		499.5 ± 0.1	
Mean for streams	4/12/2001	2.66 ± 0.04	0.59 ± 0.08			(194)	0.59	(403)	0.59
GH1 - 50m above weir	21/02/05	Sample stored		-0.1	10.0	245.4 ± 2.6		540.9 ±2.0	

ns - no sample collected

The data are plotted in Figures 3 and 4. Water from depth in the wetland ('bog water' point, Figure 3) had a tritium concentration much higher than mean rainfall in 2001, suggesting that the water contains 'bomb' tritium (i.e. tritium originating from atmospheric atom bomb testing in the 1960s and 70s, see





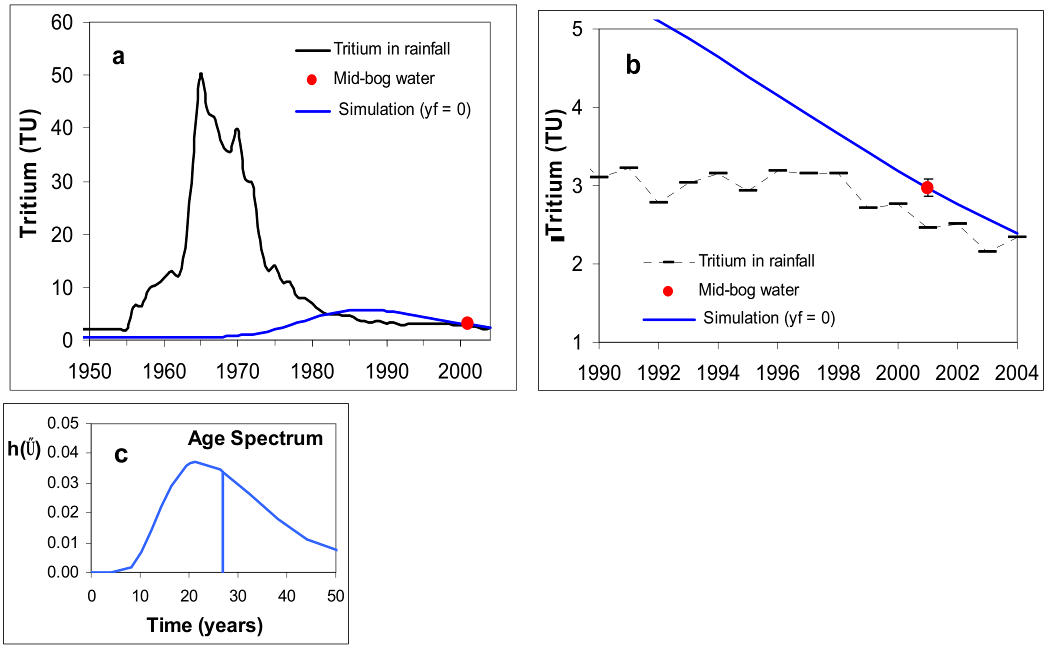
Figures 3 & 4. Tritium and CFC concentrations in Glendhu catchment streams.

below), and consequently has an age of close to 30 years. The streams draining the wetland (GH5), and catchment GH1 also have higher tritium than mean rainfall, and therefore are also likely to contain some 30 year-old water, which is mixed with increasing amounts of young water away from the wetland.

The CFC concentrations increase with distance away from the wetland (Figure 4). Unlike tritium, however, the CFC concentrations quite quickly approach equilibrium with respect to the atmosphere. This shows that the CFC concentrations are affected by interaction with the atmosphere as well as by input of young water.

Estimation of Mean Residence Times

The tritium concentrations in all of the samples are higher than expected for precipitation in the last fifteen years based on the tritium concentrations measured at Kaitoke (near Wellington), as adjusted for latitude and altitude (Figure 5a, Stewart & Taylor 1981). Many years of monthly tritium measurements at Kaitoke and Invercargill Airport have shown that Invercargill Airport has tritium concentrations higher than Kaitoke by a factor of 1.1. Adjusting for the 600 m altitude of the Glendhu Catchments increases this factor to at most 1.3. The adjusted mean precipitation value in 2001 is considerably less



Figures 5a,b Annual mean tritium concentration in rainfall for scale factor 1.3, mid-bog tritium concentration and dispersion model simulation with mean age 27 years. 5c Age distribution.

than the values observed in these samples (Figure 5b). Consequently, the samples must contain tritium from the 'bomb' peak years when nuclear weapons testing was being carried out in the atmosphere in the 1960s and 70s. The waters must therefore have considerable mean residence times in the catchments.

The mean age of the water with the highest tritium concentration (the mid-bog sample) has been estimated using a dispersion mixing model with a dispersion parameter (DP) of 0.095. (This value has been used because it is the highest DP value that will produce a match to the measured tritium value.) The mean age obtained is 27 years. Figures 5a,b show the history of tritium input to the catchment (assuming Glendhu rainfall concentrations can be represented by applying a scale factor 1.3 to the tritium concentration measured in Kaitoke rainfall; Stewart & Taylor 1981), the mid-bog sample and the dispersion model simulation with mean age of 27 years. Figure 5c shows the residence time distribution of the simulation model. Other mean ages around this value can be obtained by assuming lower values of DP, but these become more unlikely the lower the assumed value of DP, because the age distribution implied becomes increasingly narrow. In any event, the age cannot be younger than 20 years on average. This water (i.e. the 27-year-old water) has been assumed to be representative of old water from the bog feeding the stream. The bog stream samples (and N-tube sample) are therefore assumed to be composed of mixtures of 27-year-old water from within the bog, and young water (assumed to have a mean residence time of 1 month) from the surface of the bog and surrounding hillsides. A mixture of 60% old water and 40% young water (i.e. a young fraction (yf) of 0.4) matches the average tritium concentration measured in the stream (Table 1). Note that the young water alone or intermediate age water cannot reproduce the tritium concentration in the stream, because there has to be some old (bomb-tritium bearing) water in it. The CFC-11 and CFC-12 concentrations in the stream are also matched by similar mixtures of old and young waters (yf = 0.41 and 0.49 respectively, Table 1). The same model is therefore supported by the tritium and the CFC measurements.

The stream samples from GH1 and GH2 have lower tritium concentrations (2.66 TU). This value can be reproduced by a mixture with yf = 0.59. Such a mixture produces CFC concentrations which are lower than those observed in these samples, but it is likely that these larger streams will have had more opportunity for their CFC concentrations to have been increased by dissolution of atmospheric CFCs since the water was in the stream. For CFC-11 the simulated concentration is 194 pptv, whereas the observed value was 255 pptv. The latter is close to the equilibrium value expected with respect to the atmosphere in 2001. For CFC-12 the simulated concentration is 403 pptv, while the observed concentration was 495 pptv (still somewhat less than the expected equilibrium value (550 pptv) with respect to the atmosphere). The tritium results show that old water contributes significantly to streamflow produced in these catchments.

Measurements of dissolved Ar and N_2 gas were used to calculate the excess air concentration and recharge temperatures of the 22/2/05 samples (Table 1). (Excess air is air in excess of the equilibrium amount expected by interaction with the atmosphere.) The samples had only very minor amounts of excess air. The recharge temperature obtained for the GH5 stream sample nearest the bog (Table 1) agrees with the mean temperature given by Fahey et al. (1998) of 7.6°C; the other GH5 stream samples are slightly warmer (8.3°C). The recharge temperature for GH1 is warmer still (10°C) suggesting that gas interaction with the atmosphere has occurred near the time of sampling (which was summer).

Assuming that the 60% of 27-year old water in the GH5 stream during sampling conditions is sourced from a large store of water supplying the baseflow (i.e. a deep aquifer underlying the catchment) allows the water storage volume to be estimated. This is annual baseflow (50% of 404 mm/yr) x mean residence time (27 yr) x 60% (= 3.3 m). If the effective porosity (S) is 0.1, then the aquifer depth determined is 33 m.

Recession Analysis

The quadratic and exponential expressions (equations 4 and 5) were fitted to the master recession data as shown in Figure 6, using least squares regression. The quadratic equation produced the better fits. Dewandel et al. (2003) have commented that only the quadratic form is likely to give correct values of the aquifer characteristics because it is an exact analytical solution to the diffusion equation, albeit with simplifying assumptions, whereas the exponential form is an approximate solution. The early (influenced) and late (baseflow recession) parts of the recession had values of Ŭ of 13.0 day^{-1} and 0.036 day^{-1} respectively.

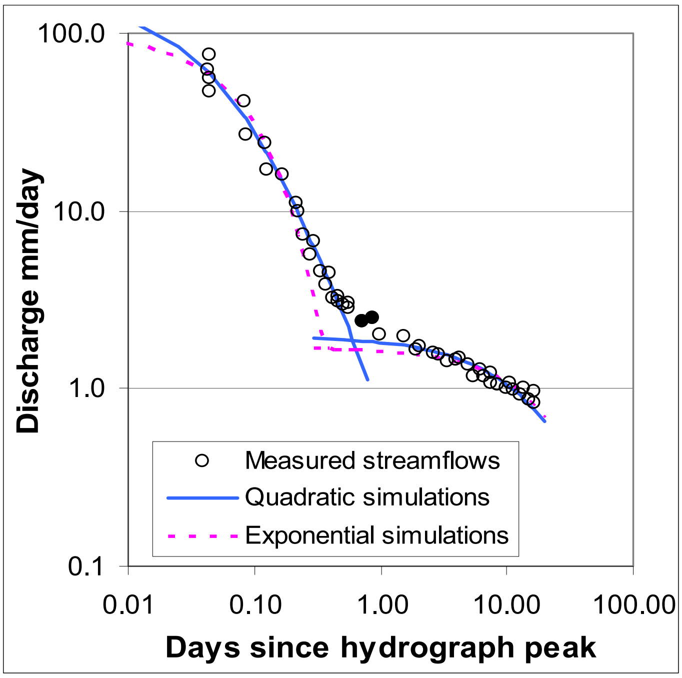


Figure 6. Simulations to the master recession curve data from Figure 2. The filled data points were not included in the simulations.

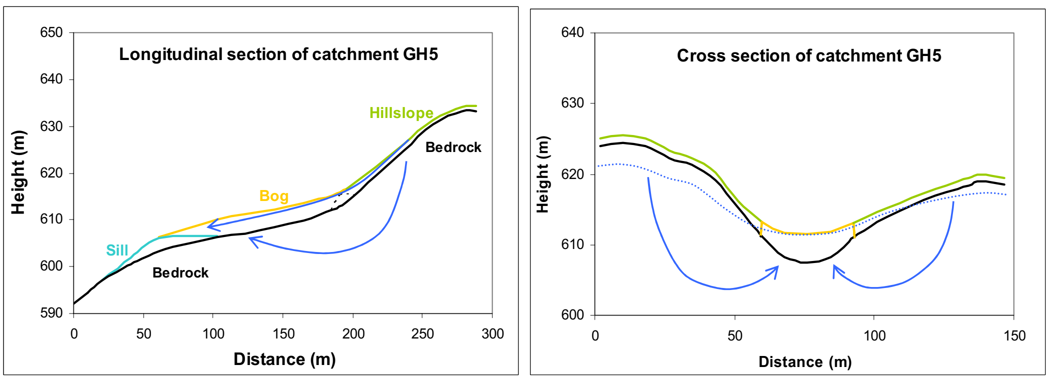
The early part of the recession represents surface and near-surface flows in the wetlands area. The Ŭ value may have limited relevance to a near-surface wetlands aquifer because occasional flows over the surface of the wetlands may be included during high-flow events. Of more interest is the baseflow recession, for which Ŭ can give information on aquifer characteristics that can be compared with those from the baseflow dating results above. Using equation 6, and S=0.1 and L=100 m gives KB=36 m^2/day, or K=0.0013 cm/sec on putting in the aquifer depth (B) estimate from the dating above. A hydraulic conductivity value of 0.0013 cm/sec is equivalent to the hydraulic conductivity of fine sand and an order of magnitude or two higher than that expected for loess.

DISCUSSION

A variety of types of evidence has shown that two sources of water (or runoff mechanisms) produce streamflow in the Glendhu Catchements. Previous hydrometric evidence revealed a marked change of slope in the recession hydrograph (Pearce et al. 1984), suggesting that two major runoff mechanisms were operating. Oxygen-18 measurements in streamflow (Bonell et al. 1990) showed that the first part of the recession contained old water (from a remarkably well-mixed groundwater body), plus new water (from the current event) if quickflow yields exceeded 10 mm. The second part of the recession contained only old water. Clearly, the Glendhu streams are produced mainly from groundwater bodies which connect to unsaturated regolith on the hillsides.

This study has probed the residence times of water contributing to the second part of the recession. Tritium measurements (supported by CFC measurements) have indicated that surprisingly old water is present in the (GH5) wetland and contributes strongly to baseflow (and therefore to quickflow). The age of the water is revealed by the presence of tritium originating from the bomb-peak in NZ rainfall in the late 1960s and early 1970s. The data have been simulated assuming the presence of two types of water in the streams in accordance with the hydrometric and oxygen-18 evidence referred to above. An age of 27 years has been estimated for water in the mid-bog area of the GH5 wetland. This implies considerable storage of water within the catchment (within unsaturated and saturated layers estimated at 33 m thick.) Recession analysis has shown that the age is compatible with a hydraulic conductivity somewhat greater than that expected for loess indicating possible involvement of the bedrock schist.

What do these long residence times mean in regard to water flows in the catchment? The importance of interflow in producing stormflow has been demonstrated by earlier workers (Miller 1994, Bowden et al. 2001). Bowden et al. (2001) showed that lateral flow in the thin Organic and A Horizon layers was substantial and probably often emerged as flow over the wetland surface in high quickflow events, contributing to the new water inputs to the streams. They identified slow drainage from deep loess horizons (B and C) as the source of the extended baseflow at the catchments. Such drainage would be connected by groundwater to the stream. However, it is unlikely that the 1.5 m thick loess horizons mantling the slopes could introduce a mean delay of 27 years in the water reaching the streams. Water flowing over bedrock would be expected to travel quite rapidly, hence any delay would have to derive from drainage from the unsaturated loess. It seems much more probable that the delay observed results from drainage from the loess plus slow flow through the bedrock itself, as schematically illustrated in Figures 7a and b.



Figures 7a,b Sections through catchment GH5 showing inferred flows.

An interesting question that arises is: Why does the age of the streamflow become younger with distance from the source of the (GH5) stream, when one would expect it to become older if more groundwater reaches the stream lower down in the catchment? One possible answer may be that the surface relief controls the stream system, whereas a fossil gully system affects the groundwater flow, and the two only intersect in limited areas. Also, there is normally a riparian area along the stream (below GH5), and this could gain younger water from the hillslopes and “dilute” the older water in the stream.

CONCLUSIONS

The east Otago uplands of New Zealand’s South Island have been studied because of the environmental consequences of converting native tussock grasslands to other land covers, notably forestry and pasture for stock grazing. Tritium and CFC concentrations have been used to estimate the residence times of water contributing to baseflow. The tritium measurements (supported by CFC measurements) showed that surprisingly old water is present in the (GH5) wetland and contributes strongly to baseflow (and therefore also to quickflow). The age of the water is revealed by the presence of tritium originating from the bomb-peak in NZ rainfall in the late 1960s and early 1970s. The data have been simulated assuming the presence of two types of water in the streams in accordance with hydrometric and oxygen-18 evidence. A mean residence time of 27 years was estimated for water in the mid-bog area of the GH5 wetland (the old component). Such an age indicates that slow release from a large groundwater reservoir within the bedrock underlying the catchments is a major source of streamflow. Recession analysis of the baseflow supports the presence of a deep groundwater aquifer underlying the catchment.

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