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Hydrology of the Kopouatai Peat Dome

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Abstract

This paper investigates the water balance of the Kopouatai Peat Dome, North Island, New Zealand during a three year study period. Annual runoff (including throughflow) from the Kopouatai Peat Dome, calculated using a simplified water balance, varied from 280 to 570 mm, with up to 670 mm from a small part of the Dome. Annual runoff from the raised peatland was similar to that from adjacent low-lying areas with mineral soils. Throughflow forms a small to moderate proportion of annual runoff (< 5% of long-term, mean annual rainfall). The hydraulic conductivity of peat at Kopouatai varied considerably with depth, with hydraulic conductivities of up to about 10^{-3} m s^{-1} in weakly decomposed fibric horizons, but negligible conductivities in deeper, strongly decomposed sapric horizons. Ground water levels in the shallow peat showed a generally small (< 0.3 m) seasonal variation. A moderate relationship ($R^2 = 0.55$) between ground water levels and net rainfall was determined. Reduced ground water levels during summer and autumn corresponded with low rates of surface runoff from the Dome; some streams ceased flowing after prolonged dry weather.

Introduction

There have been numerous investigations of peatlands in New Zealand, but most have focused on peat drainage, mining, or horticulture. Several reviews of peatland hydrology were published in New Zealand in the late 1970s and 1980s. The hydrological characteristics of developed peat have been investigated at Torehape (Fig. 1) (McLay, 1986; McLay *et al.* 1992), and a water balance for summer 1993/94 has been calculated for the Kopouatai Peat Dome (Williamson, 1995). A catchment-based study has been completed for the Bayswater Peat Bog in Southland, New Zealand

(Robertson, 1983). Little emphasis has been given to the water retention and water storage properties, hydraulic conductivity, or the water balance of peatland ecosystems.

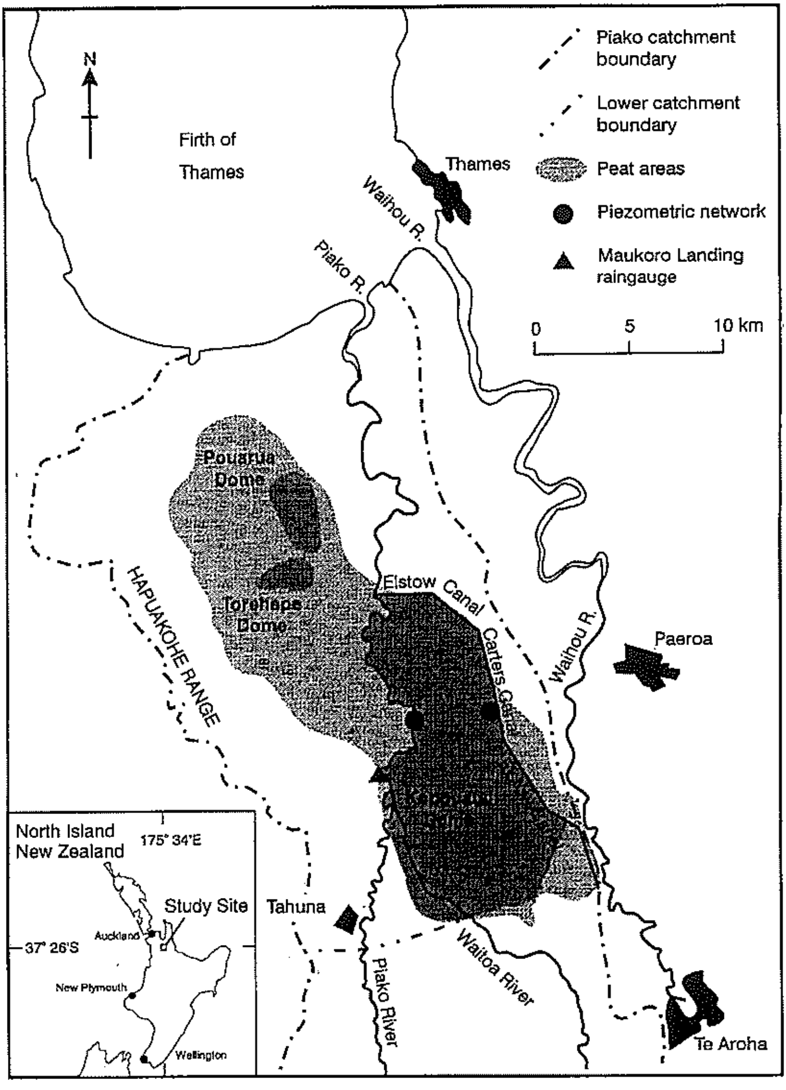


Figure 1 - Location of the Kopouatai Peat Dome and extent of peat areas in the lower Piako catchment (after Harris, 1979).

The Kopouatai Peat Dome is thought to have a major role in mitigating flooding in the lower Piako River, but little was known about runoff generation and ground water flow from the Dome before investigations began there in 1991. This paper evaluates hydrological inputs and outputs at Kopouatai to gain an understanding of the water balance and the flood attenuation role of the Dome. Runoff is estimated for the entire Dome area and a small sub-catchment. Ground water throughflow is estimated using monitoring networks located at the margins of the Dome.

Physiography

The Kopouatai Peat Dome is adjacent to the lower Piako River in the low-lying Hauraki Plains, central North Island, New Zealand (37°26'S, 175°34'E) (Fig. 1). Kopouatai is internationally renowned as a protected wetland. The Dome is the largest (96 km^2) raised peat bog in New Zealand still in a natural state. It has three distinct domes—a main southern dome and two smaller domes towards the north of the bog. Kopouatai Peat Dome is approximately oval, oriented north - south, with a maximum length of 18 km and width of 10 km, and an average length and width of about 16 and 6 km respectively. Ground surface elevation varies from about 2 to 6.5 m asl (Tararu Datum), but most of the Dome is above 3.5 m asl (Fig. 2).

Peat deposits at Kopouatai overlay and are interbedded with fluviatile and estuarine deposits of the Tauranga Group (Schofield, 1967; Kear and Schofield, 1978). The typically domed structure of Kopouatai is the result of relatively high rates of peat accumulation at the centre of the bog and high rates of throughflow and decomposition at the margins (Alexandrov, 1988). However, the rate of vegetation growth is greatest at the margin of a dome (Thompson, 1987).

Restiad rushes are the dominant peat-forming vegetation at Kopouatai (Irving *et al.*, 1984). Restiad peat bogs are dominantly nutrient-poor, highly acidic peat, and are largely dependent on rainfall for nutrients and water. Restiad communities occur in association with moss, sedge and fern communities.

Earlier work (Maggs, 1995) describing the peat at Kopouatai shows that the shallow peat (to 3 m depth) is weakly decomposed, with a high proportion of roots and live vegetation. The deeper peat is typically strongly decomposed, although weakly and moderately decomposed peat can occur at depths up to 6.5 m.

There are few natural drainage channels on the Kopouatai Dome, and these channels are generally short and shallow and are often

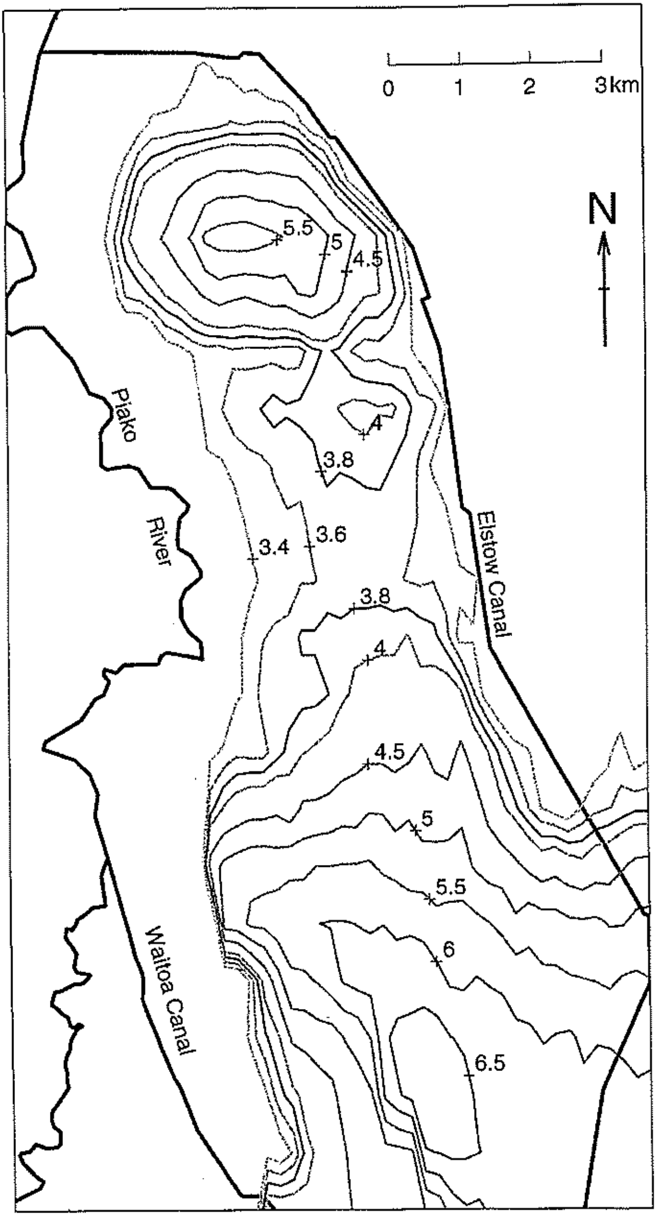


Figure 2 - Peat surface contours (m asl; Tararu Datum) of the Kopouatai Dome.

indistinguishable near the boundaries of the Dome. Aerial photographs show the paths of old manually dug drains in the northern part of the Dome, but these drains are now overgrown and ineffective. Several small streams located at topographic lows at the margins of the Dome may continue flowing during summer and autumn, but such streams on the western margin of the Dome are affected by tidal backwater in the Piako River and little outflow is apparent for much of the tidal cycle.

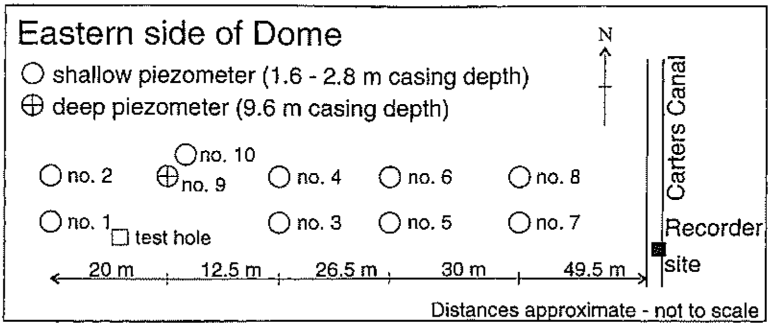
The Dome is bounded on its western side by the main channels of the Piako and Waitoa Rivers. A tidal variation of about 1.5 m is recorded at the Maukoro Landing flow-monitoring site (Fig. 1). The north-eastern boundary of the Dome is approximated by the Elstow Canal, but the south-eastern boundary is poorly defined, extending beyond the Elstow Canal to within 1 km of the Waihou River (Fig. 1). Wooden flumes have been used successfully to control water levels at Carters Canal (a 3 km section of Elstow Canal; Fig. 1) and minimise ground subsidence at the eastern margin (Harris, 1979).

Methods

The difficulty of access across Kopouatai (and budgetary constraints) restricted any detailed investigation of ground water and surface water resources of the entire Dome area. However, as maximum throughflow is likely to occur at the margins of the Dome, representative ground water monitoring networks were established on the eastern and western margins of the Dome (Fig. 3), and rainfall and evaporation data that are representative of the entire bog area were collected.

Surface water was monitored at several sites on the Piako and Waitoa Rivers and at Carters Canal (eastern margin). Rainfall was measured at a telemetered site on the western side of the Dome at Maukoro Landing (Fig. 1). An automatic raingauge site and an evaporimeter (potential evaporation calculated using Priestley and Taylor's (1972) method) were established at the Carters Canal monitoring site. Missing monthly evaporation totals (Priestley-Taylor) were estimated using average daily values for at least 12 days of record preceding or following the missing period. Priestley-Taylor evaporation for August 1994 was assumed to be the same as that for August 1993.

Daily rainfall data were also available for a site (Blake's Farm; Tideda no. 754612) located less than 1 km from the north-eastern margin of the Dome and operated by a local farmer. Evaporation measurements (November 1993 to March 1994) using the Bowen ratio energy balance



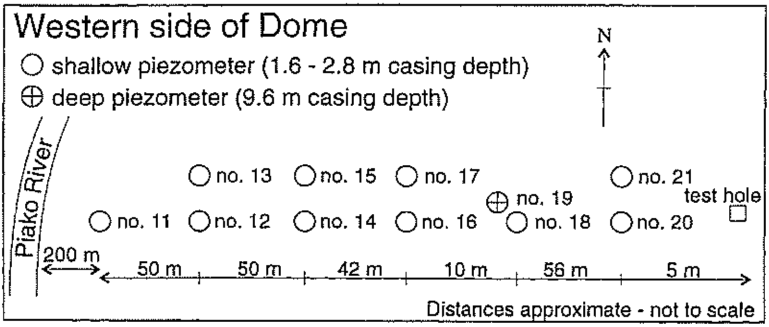


Figure 3 - Schematic diagram showing piezometric monitoring networks on the eastern and western margins of the Kopouatai Dome.

technique were also available for Williamson's (1995) field site located approximately 2 km north-west of the piezometric network at Carters Canal.

Errors in the estimation of daily rainfall across the Dome are likely to be substantial, particularly during summer when showers produce an uneven rainfall distribution. Monthly and annual rainfall data (Table 1) vary less than the daily data for the three main sites used in this study. Using the period with overlapping rainfall data for the three sites (April 1992 to June 1994), monthly rainfall totals showed a mean difference of 0.5 ± 12.7 mm (n=27, Carters Canal cf. Maukoro Landing) and a mean difference of 1.0 ± 15.2 mm (n=27, Blake's Farm cf. Maukoro Landing).

For the main study period (September 1991 to August 1994), annual rainfall totals differed by 3 mm, 28.5 mm and 45.5 mm at Blake's Farm (eastern margin of Dome) and Maukoro Landing (western margin).

Stewart and Rouse (1976) found that the Priestley-Taylor method may be used to estimate the daily potential evaporation of a shallow lake within an error margin of 5%. Williamson (1995) discussed errors associated with the Bowen ratio method. The typical error for a dry canopy day is likely to be between 10 and 20 %.

Runoff is estimated using flow data from the Carters Canal hydrometric site, which has a catchment area of c. 3 ± 1 km^2 (determined using historic peat survey data and field reconnaissance).

Table 1 - Monthly and annual rainfall and evaporation (September 1991 to August 1994) (mm)

	1991/92			1992/93			1993/94		
	Rain	Evap^1	Evap^2	Rain	Evap^1	Evap^2	Rain	Evap^1	Evap^2
Sep	125.0	75	49	86.5	77	50	50.5	75	49
Oct	86.5	95	63	139.0	96	63	32.0	108	71
Nov	81.0	131	70	72.0	120	64	97.0	129	69
Dec	52.5	151	83	97.5	147	81	60.0	141	77
Jan	115.5	137	75	20.5	166	91	59.5	166	91
Feb	73.5	125	65	33.0	126	63	68.5	134	67
Mar	31.0	100	55	73.5	106	58	46.0	120	66
Apr	66.5	70	37	61.0	66	35	102.5	67	36
May	168.5	42	28	112.5	47	31	76.5	51	34
Jun	48.0	35	23	160.5	33	21	99.0	39	25
Jul	144.0	36	24	9.5	36	24	151.5	42	28
Aug	184.0	54	36	92.0	53	35	92.5	53	35
Total	1176	1051	608	957.5	1073	616	935.5	1125	648

Rain: rainfall at Maukoro Landing

Evap^1: evaporimeter at Carters Canal

Evap^2: adjusted for 15 and 20 dry-canopy days (refer text)

The piezometric network (Fig. 3) comprised 19 shallow P.V.C. piezometers with a casing depth of 1.6 to 2.8 m and two deep galvanised iron piezometers with a casing depth of 9.6 m. No ground water enters the piezometers above the bottom of the casing. Seven of these piezometers were used for falling head tests. Core samples, taken using a D-section manual corer, were obtained at most of the piezometer sites.

Numerous temporary piezometers were installed on the eastern and western margins of the Dome, located about 120 m west of Carters Canal, 1 km west of Carters Canal, and 430 to 470 m east of the Piako River. Table 2 shows the intake depths of all piezometers used for falling head tests.

Piezometric levels were measured manually using a purpose-built, lightweight electric probe or tape measure, with recordings made fortnightly or monthly for a period of two to three years—October 1991 to November 1993 (western margin of Dome) and August 1991 to August 1994 (eastern margin of Dome). Care was taken to minimise disturbance to water levels when observers walked on the bog surface near the piezometers (which typically extended 0.3 to 0.5 m above ground so that they could be measured from a greater distance). During the study, piezometers were surveyed annually (approximately) to determine any rise or fall of the piezometer casings. Survey information was also used to determine the hydraulic gradient of shallow ground water at both margins of the Dome.

Ground water levels were monitored intensively, using two adjacent piezometers, for a 34 day period beginning 29 September 1993, using Kainga 5 m range pressure transducers. A datalogger was used to store measurements recorded at 15 minute intervals. This work was undertaken to examine possible evaporation effects and response to rainfall.

Ground water levels were recorded to a precision of 1 mm. Replicate measurements indicated that manually read levels were repeatable at most sites and differed by < 5 mm at remaining sites. Some systematic error may occur for manual measurement of ground water levels despite the precautions taken. If observers stand immediately beside a piezometer, ground water levels may show a quick response, typically of about 10 mm; a worst-case measurement error of 10 mm is thus likely for manual ground water level measurements.

Falling head (slug) tests were carried out to estimate the hydraulic conductivity of peat at different depths within the peat profile. The test results principally reflect horizontal hydraulic conductivities, although there was a small component of vertical conductivity. In saturated peat,

Table 2 - Estimates of hydraulic conductivity (K) (m s^{-1}) at various depths within peat at Kopouatai.

Depth Tested (m)	Cooper *et al.* method	Hvorslev method	Bouwer and Rice method	Average
0.15-0.30	...	...	2.5×10^{-4}	
0.30-0.45	...	...	6.4×10^{-4}	
0.30-0.45	...	...	7.8×10^{-4}	
0.45-0.60	...	...	6.4×10^{-4}	
0.45-0.60	...	...	5.4×10^{-4}	
0.45-0.60	...	...	5.3×10^{-4}	
0.60-0.75	...	...	2.4×10^{-4}	
0.65-0.80	...	...	6.7×10^{-4}	
0.75-0.90	...	...	8.3×10^{-4}	
0.85-1.00	1.7×10^{-4}	1.9×10^{-4}	8.4×10^{-5}	1.5×10^{-4}
0.85-1.00	6.7×10^{-5}	1.3×10^{-4}	3.0×10^{-5}	7.6×10^{-5}
0.90-1.05	...	...	6.9×10^{-4}	
1.05-1.20	...	...	3.9×10^{-4}	
1.05-1.20	...	...	7.0×10^{-4}	
1.20-1.35	...	...	5.1×10^{-4}	
1.35-1.50	...	...	1.1×10^{-4}	
1.50-1.65	2.2×10^{-5}	8.2×10^{-5}	1.0×10^{-5}	3.8×10^{-5}
1.65-1.80	...	...	2.4×10^{-4}	
1.65-1.85		2.7×10^{-7}	5.8×10^{-8}	1.6×10^{-7}*
1.85-2.00	9.3×10^{-7}	4.9×10^{-7}	2.3×10^{-7}	5.5×10^{-7}
2.00-2.15	1.6×10^{-4}	6.9×10^{-4}	1.6×10^{-5}	2.9×10^{-4}
2.00-2.65	1.0×10^{-5}	2.9×10^{-6}	4.1×10^{-6}	1.4×10^{-5}
2.00-2.65		4.4×10^{-7}	2.4×10^{-7}	3.4×10^{-7}*
2.00-2.65		2.4×10^{-7}	1.6×10^{-7}	2.0×10^{-7}*
2.05-2.20	4.1×10^{-7}	7.6×10^{-7}	4.1×10^{-7}	5.3×10^{-7}
2.15-2.30	6.5×10^{-6}	1.4×10^{-6}	4.7×10^{-7}	2.8×10^{-6}
2.30-2.45	1.2×10^{-5}	2.9×10^{-5}	6.8×10^{-6}	1.6×10^{-5}
2.50-3.15	6.1×10^{-9}	8.3×10^{-8}	2.7×10^{-8}	3.9×10^{-8}
2.50-3.45	3.5×10^{-5}	2.4×10^{-5}	1.8×10^{-6}	2.0×10^{-5}
2.54-3.65		4.2×10^{-9}	4.9×10^{-8}	2.7×10^{-8}*
2.60-3.65	...	...	2.6×10^{-4}	
2.77-3.15	7.5×10^{-9}	1.5×10^{-8}	1.6×10^{-8}	1.3×10^{-8}

* average value from the Hvorslev, and Bouwer and Rice methods. The Cooper *et al.* method was not used because the test data showed a poor match with the type curves.

... the short duration of these tests prevent the use of analytical methods in their standard form, so the Bouwer and Rice formula (Bouwer, 1989) was used for calculating the time $t_{90\%}$ required for the water level to fall 90% of the initial raising of the water level in the piezometers.

the differences between horizontal and vertical conductivities are usually small, and for practical purposes a non-directional value of hydraulic conductivity may be adopted for each sample depth and location. Data from 32 tests were analysed using the Hvorslev (1951) method, the Bouwer and Rice (1976) method, and the Cooper *et al.* (1967) method. An average value was determined using these methods, except for several tests for which the Cooper *et al.* method was inappropriate due to the poor match between test data and the type curves, and short duration tests for which only the Bouwer and Rice method was used (Table 2).

Hydraulic conductivities control the infiltration rates of water in surface peat deposits (Rycroft *et al.*, 1975). However, the emphasis for determining hydraulic conductivity is to estimate lateral throughflow, and to estimate any vertical seepage to or from aquifers underlying a peat deposit. Hydraulic conductivity values are characteristically low (10^{-10} to 10^{-5} m s^{-1}) for peat materials, but several overseas studies have found relatively high hydraulic conductivity and infiltration rates in the upper horizons of peat bogs. High horizontal conductivities in the unsaturated zone may reflect the fibrous structure of poorly decomposed plant remains (e.g. intact *Sphagnum* leaves) (Rycroft *et al.*, 1975).

Hydraulic conductivity tests measure the ability of water to flow through the peat under artificially-created differences in head. The spatial and vertical variability of the peat, the artificial nature of the hydraulic conductivity tests, and problems with the tests (for example, possible air entrapment or compression of the peat) suggest that the results are only indicative. Furthermore, hydraulic conductivity changes when the pressure on the solid peat matrix is altered by fluctuations in the water table (Ivanov, 1975).

Details of the analysis of selected peat properties (e.g. bulk density, degree of decomposition, and moisture content) are presented in Maggs (1995). These studies suggest that average available storage is 10% for unsaturated peat above the water table. A specific yield of 0.1 implies that a rise or fall in water level of 10 mm is equivalent to a water gain or loss of 1 mm.

The water balance of Kopouatai was examined using a simplified water balance model:

$$P = E + R + \Delta S \qquad (1);$$

where P = precipitation;
E = evapotranspiration;
R = runoff; and
ΔS = change in ground water storage.

Surface water inflow from adjacent waterways and ground water throughflow were also assessed. Relationships between ground water levels and rainfall were examined for selected piezometers on each side of the Dome. Relationships between rainfall and the flow of adjacent rivers and drains were also examined.

Results and discussion

Rainfall and evaporation

Based on comparisons between the monthly rainfall at Maukoro Landing during the study period and long-term normal (1961-1990) rainfall data (Tomlinson and Sansom, 1994) at Elstow (approximately 5 km south-west of Kopouatai), the study has included a period of relatively low rainfall (July 1993 to June 1994) and several months with relatively high rainfall. For example, rainfall in August 1991 and 1992, January 1992, and October 1992 was 50 to 70% greater than normal at the Elstow site. Assuming long-term mean annual rainfall for the calendar year at Kopouatai (1150 mm; Jones and Maggs, 1990) is similar to the September to August water balance period used in this study, two (1992/93 and 1993/94) of the three water balance periods were drier than normal and 1991/92 received about average rainfall.

Theoretically, daily evapotranspiration losses for a peatland catchment may be greater than that for a catchment with drought-prone mineral soils, because a high water table and capillarity maintain the moisture content of the peat. However, evaporation measurements at Kopouatai obtained using the Bowen ratio energy balance technique showed that the average summer dry-canopy daily evaporation above vegetation dominated by the lesser wire rush (*Empodisma minus* (Hook. F., Johnson and Cutler)) was about 1.5 mm (Williamson and Campbell, 1994). This value is equivalent to about 30% of the summer evaporation (Kelliher and Scotter, 1992) that would normally be expected from a mineral soil with a non-limiting soil moisture content. Consequently, monthly estimates of Priestley-Taylor evaporation for November to April have been adjusted using a multiplier of 0.3 to correct for overestimated daily values (assuming 20 dry-canopy days per month and an average daily Priestley-Taylor evaporation value for each month). Evaporation estimates for May to October have been adjusted similarly, but assuming 15 dry-canopy days per month (Table 1).

Daily evaporation data estimated for the 54 day period 4 November 1993 to 29 March 1994, using the Bowen ratio technique (Williamson, *pers. comm.*, 1994) and the Priestley-Taylor method, show a moderate positive correlation ($r = 0.695$; $p < 0.01$). Dry-canopy evaporation at

Kopouatai appears to depend primarily on plant physiology (canopy resistance) and vapour-pressure deficit (Williamson and Campbell, 1994). Dry-canopy evaporation at Kopouatai may be overestimated substantially (e.g. > 200 mm per annum) using the Priestley-Taylor method. However, the Priestley-Taylor method appears adequate for modelling evaporation at Kopouatai for periods when the canopy is wet (Williamson, 1995).

Hydraulic conductivity

Tests indicated that peats at Kopouatai have a wide range of hydraulic conductivities. Estimates of conductivity range from 1.3×10^{-8} m s^{-1} for silty peat at depths between 2.77 and 3.15 m to 8.3×10^{-4} m s^{-1} for a peat layer at a depth of 0.75 to 0.9 m. Sixteen tests carried out on peat at depths of between 0.15 and 1.5 m (all using a cavity length of 0.15 m) indicated hydraulic conductivities between 7.6×10^{-5} m s^{-1} and 8.3×10^{-4} m s^{-1}. Deeper peat deposits (over 1.5 m below ground) typically showed a wider range of conductivities, from 1.3×10^{-8} m s^{-1} to 2.9×10^{-4} m s^{-1}.

Evidence of preferential flow paths (natural water pipes) within surficial peats was indicated by the relatively clean water infilling shallow holes excavated in the peat during the coring and installation of piezometers.

The range and distribution of hydraulic conductivities for shallow to deep peat agree with typical values found in other overseas and local studies of peat deposits, especially the relatively high values in the upper horizons of the peat bog. For example, McLay (1986) found an average hydraulic conductivity (below the water table) of 1.02×10^{-5} m s^{-1} at a depth of 1 m to 1.1 m. This figure compares favourably with an average hydraulic conductivity of 4.2×10^{-4} m s^{-1} for six tests carried out on peat at depths between 0.85 m and 1.35 m (Table 2) in the present study.

Overall, the hydraulic conductivity test results and core samples indicate that water transfer from the peat to deep alluvial sediments and vice versa is restricted: finely structured silts and clays underlie the peat deposit, and the strongly decomposed peat layers towards the bottom of the peat deposit and interbedded silt and clay layers within the peat have inherently low permeability. Therefore, most water exchange probably occurs within a 1.5 m layer of peat immediately below the surface of the Kopouatai Dome.

Ground water levels

Ground water levels measured at the eastern and western margins of the Kopouatai Dome are shown in Figure 4. Water levels measured at any piezometers that subsided by more than 25 mm per year or more than 40 mm over the study period have been omitted from most analyses. The

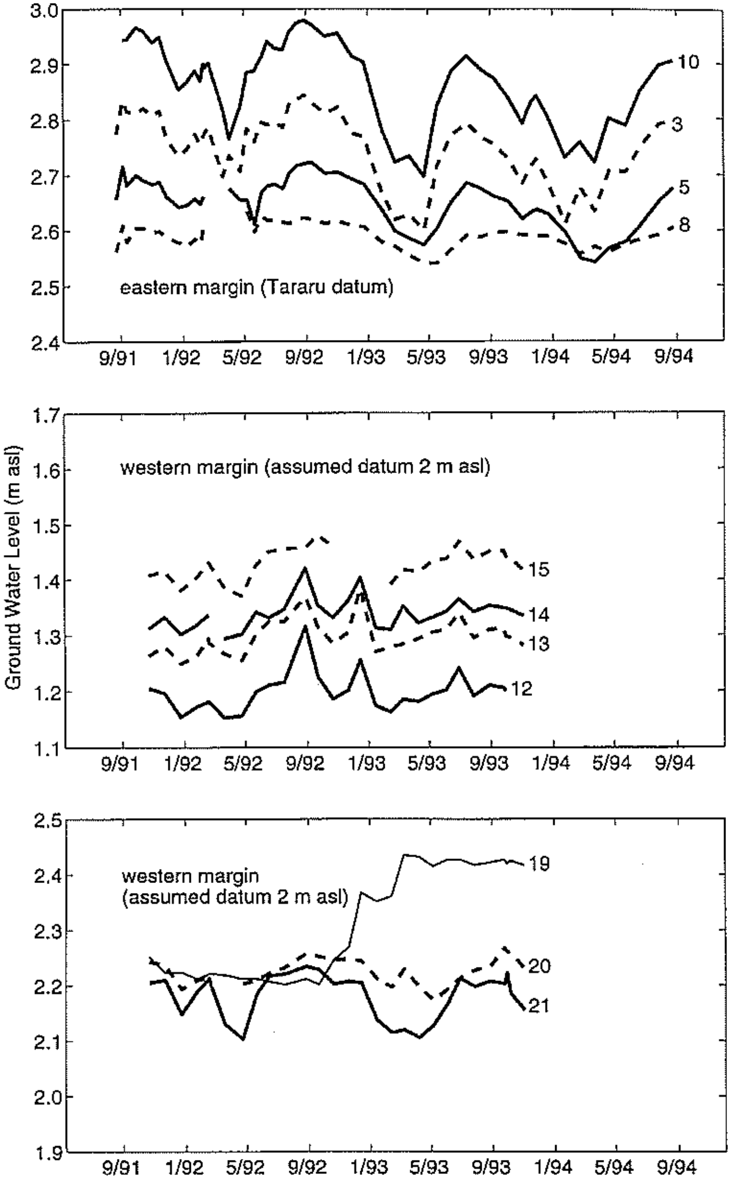


Figure 4 - Ground water level variation at piezometric monitoring sites on the eastern and western margins of the Kopouatai Dome.

water level at piezometer no. 9 (deep) is omitted because this piezometer may have been constructed poorly (with an initial (4/9/91) water level of 9.555 m below the top of the casing).

Most of the piezometers subsided or became elevated by less than 10 mm over the study (Maggs, 1995). This variation is smaller than the annual oscillation reported for raised bogs overseas (e.g. Königsmoor: 15 mm and 30 mm in 1956 and 1957 respectively; Ingram, 1983). Water level measurements affected by hydraulic conductivity tests have also been omitted from Figure 4.

Water levels at Kopouatai fluctuate seasonally, with high ground water levels typically occurring during July to September and low levels during February to April. A rise in water levels at piezometer no. 19 during 6 months after September 1992 may be attributable to the delayed effects of recharge of ground water beneath the peat.

Maximum water level variation was about 300 mm at the eastern margin of the Dome and 150 mm at the western margin. This difference may reflect lower hydraulic conductivities at the western margin. Alternatively, piezometers nearer the Piako River showed less seasonal and annual variation than those further from the river, suggesting that the piezometers near the river are affected by surface ponding during floods. Furthermore, sharp peaks in ground water levels at piezometers no. 12, 13 and 14 (Fig. 4) may have been caused by the direct entry of floodwaters (loose-fitting piezometer caps provided no seal against the entry of floodwaters).

Annual changes in ground water level for piezometers no. 3 and 10 are 0.010 and 0.035 m (1991/92); -0.090 and -0.105 (1992/93); and 0.043 and 0.032 m (1993/94) (these piezometers are selected because they cover the full study period, show minimal subsidence and a smooth pattern of water level change, and indicate a range of aquifer transmissivities). The ground water level changes represent an increase or decrease in water storage of up to 4 mm (1991/92), 11 mm (1992/93), and 5 mm (1993/94).

The Piako River may control the fall of the water table at adjacent sites during summer, and similarly Carters Canal may control ground water levels at nearby sites (e.g. piezometer no. 8). A more extensive ground water monitoring network would be required to determine if the seasonal ground water variation in shallow piezometers is controlled by adjacent waterways.

Ground water levels were monitored intensively at piezometer no. 12 and 13 at the western margin of the Dome. At piezometer no. 12, insertion and withdrawal of the pressure transducer caused immediate ground water level displacements of 140 and 115 mm respectively, whereas the apparent displacement (1 mm) at piezometer no. 13 was well within the measurement error for the pre- and post-installation and withdrawal observations. The inferred high hydraulic conductivity at piezometer no. 13 is consistent with results for the falling head test undertaken at this site.

Until an instrumentation check on 6 October 1993, it was assumed that the pressure transducers were either stabilising or reaching a new equilibrium level to compensate for the volume displaced during transducer installation (piezometer no. 12 only). Depths to water (Figs. 5 and 6) relate only to data after 6 October 1993. At piezometer no. 13, the ground water level dropped by 13 mm from 6 October to 2 November 1993, but the pressure transducer recorded an apparent rise in ground water level (raw data; Fig. 6) for the same period. Consequently, assuming linear drift, the raw data have been corrected using the start (6/10/93) and end (2/11/93) water level measurements, which were recorded manually.

Ground water levels at piezometer no. 13 (Fig. 6) responded rapidly (within several hours) to rainfall (recorded at Maukoro Landing, approximately 4 km to the south-west of the monitoring network on the western side of the Dome) (Fig. 1). At piezometer no. 12 (Fig. 5), the low hydraulic conductivity of the peat (as indicated by the marked response to the installation and withdrawal of a pressure transducer) may explain a weaker response to rainfall (reflected by a change in the slope of the water level recession) there than at piezometer no. 13, where hydraulic conductivity is relatively high (2.6×10^{-4} m s^{-1}).

At piezometer no. 13, rainfall (12.5 mm at Maukoro Landing and 9 mm at Carters Canal) on 11 October 1993 caused a rapid change in water level of about 10 mm within 12 hours of the start of rainfall. Following 9 mm rainfall at Maukoro Landing on 19 and 20 October 1993, water level rose about 30 mm at piezometer no. 13. This marked difference in the water level variation for apparently similar rainfall may be attributable to differences in the rainfall received at the study site compared with Maukoro Landing. However, water level changes for rainfalls of similar magnitude are more likely to vary due to the duration of such events (e.g. at Maukoro Landing, 8 mm rainfall occurred over 2.5 hours on 11 October and over 6.25 hours on 19-20 October 1993.

Assuming 9 mm rainfall on 19 and 20 October 1993 (cf. 8.5 mm at Carters Canal): a temporary increase in ground water storage accounts for about 3 mm (0.030 m x 0.1) of this total, but net change in storage is negligible by 21 October 1993 (Fig. 6); evaporation loss on 19-20 October accounts for up to 7 mm of the total rainfall (peak evaporation rates may

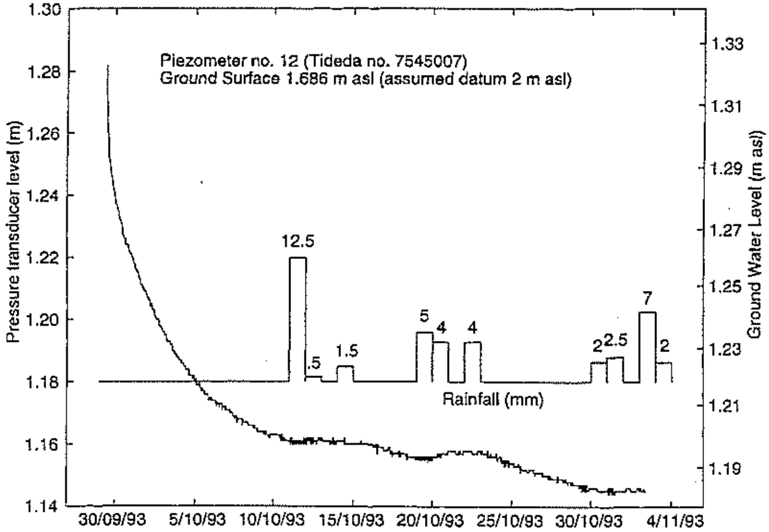


Figure 5 - Comparison of rainfall with shallow ground water at piezometer no. 12, 29 September 1993 to 2 November 1993.

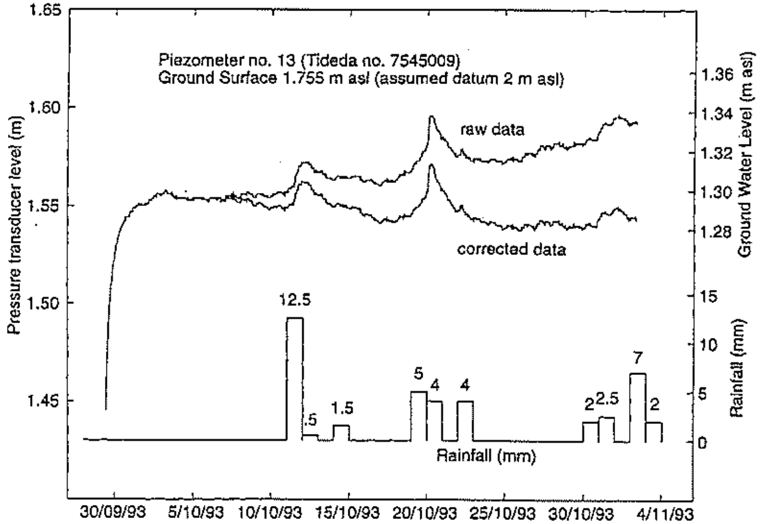


Figure 6 - Comparison of rainfall with shallow ground water at piezometer no. 13, 29 September 1993 to 2 November 1993. Data corrected for linear drift of the pressure transducer record.

be sustained during wet-canopy days (Williamson, 1995)); and up to 2 mm may be removed as surface runoff and throughflow (average daily flow at Carters Canal increased by about 9 l s^{-1} (0.3 mm d^{-1}) during these two days).

Horizontal ground water gradients have been estimated for both margins of the Dome using water level data (m asl) for two pairs of piezometers (no. 8 and 10, and no. 12 and 21). Assuming maximum water levels occur in September and minimum water levels in April, horizontal gradients have been calculated for five sampling dates (30/9/91, 10/9/92, 21/4/93, 8/9/93, and 21/4/94) for the eastern margin of the Dome and three sampling dates (21/09/92, 8/4/93, and 24/9/93) for the western margin. Using these data, horizontal gradients vary from about 0.001 (21/4/93) to 0.004 (30/9/91 and 10/9/92) at the eastern margin, but are consistently about 0.006 at the western margin.

The water table typically mirrors the general topography of an area, so horizontal gradients are probably steeper near the margins of a peat dome, where the rate of peat decomposition is greater. However, gradients at the eastern margin of the Dome may be shallower than the western margin, because of water level control by Carters Canal.

Relationships between monthly net rainfall and changes in water level were analysed for piezometers no. 10 (eastern margin) and 21 (western margin), to further study the pattern of water level variation on either side of the Dome, and to estimate runoff during a winter month.

Rainfall data were obtained from Blake's Farm (eastern margin) and Maukoro Landing (western margin). Evaporation data (Table 1) were obtained from the Carters Canal evaporimeter, adjusted for dry-canopy days. Using water level data for the period 31 October 1991 to 31 October 1993 (piezometer no. 21) or 31 October 1991 to 31 July 1994 (piezometer no. 10), water levels were estimated by interpolation for the end of each month. Interpolated ground water levels are likely to be either underestimates or overestimates during some months, because the rate of ground water level rise and fall is likely to vary between observations. For example, the depth to water (interpolated value) on 30 April 1992 may have been an underestimate, because the following observed level followed more than 70 mm rainfall recorded after 30 April.

Monthly changes in ground water level were calculated from the interpolated water level data, and the following curvilinear and linear relationships were determined:

$$\Delta h(a) = -0.0011 \times (P - E)^2 + 0.507 \times (P - E) - 13.4 \quad (2);$$

$$\Delta h(b) = 0.653 \times (P - E) - 22.6 \quad (3);$$

where $\Delta h(a)$ = monthly change in ground water level (mm) at piezometer no. 21; and

$\Delta h(b)$ = monthly change in ground water level (mm) at piezometer no. 10.

These relationships have a coefficient of determination (R^2) of 0.55, indicating a moderate relationship between monthly changes in water table height and net rainfall. The very low coefficient (0.653) in Equation 3 indicates that only 6.5 % of the average monthly net rainfall (P-E) appears as a change in ground water level. Remaining net rainfall is discharged as ground water throughflow and surface runoff.

Equations 2 and 3 support the previous observation that water level variation is typically greater at the eastern margin of the Dome (piezometer no. 10) compared with the western margin (piezometer no. 21). Further work would be required to determine if this small difference in sensitivity to net rainfall is statistically significant.

Runoff, throughflow and seepage

Using a simplified water balance equation, annual runoff (including throughflow) for the period September to August was 564 mm (1991/92), 353 mm (1992/93), and 282.5 mm (1993/94). Alternatively, runoff may be roughly estimated using flow data from the Carters Canal hydrometric site. Using this method, annual runoff at Kopouatai was 668 mm (1991/92), 393 mm (1992/93), and 287 mm (1993/94).

Percentage runoff data (48 to 57% of rainfall) for 1991/92 are comparable with values found in several overseas studies of raised bogs (e.g. Robertson *et al.*, 1968; Nicholson *et al.*, 1989). Runoff from Kopouatai is not distributed evenly, with most runoff typically occurring in the June to November period when ground water levels are close to the surface and there is little available storage. During the latter two years of the study, runoff percentages (30 to 41%) were smaller than during the first year, which was probably due to lower rainfall throughout these years, but particularly during the spring and winter periods. Combined winter and spring rainfall percentages were similar for all three years of the study.

During the period January 1992 to December 1993 at Kopouatai, annual runoff determined from monthly water balance totals was 578 mm (1992) and 199 mm (1993). Runoff during January to March and October to December accounts for about 26% of the annual total in 1992. Evaporation exceeded rainfall during these periods in 1993, and ground water levels dropped at most sites. Negative monthly discharge totals were calculated for the January to March and October to December periods in 1993. Consequently, the simplified water balance method is unreliable for estimating seasonal differences in discharge at Kopouatai. Similarly, summation of monthly runoff totals as a residual of the water balance is likely to underestimate annual runoff, especially for dry years such as 1993.

Assuming an available porosity of 10% (Maggs, 1995) and using either Equation 2 or 3, maximum monthly (August 1992) change in ground water storage during the study was about 7 mm (recharge equivalent). Net rainfall was about 140 to 150 mm (Table 1) during August 1992, and most of this net rainfall would have contributed to runoff from the Dome. Runoff during August 1992 from part of the adjacent Waitoa catchment (predominantly low-lying) was approximately 1.7×10^7 m^3, which is equivalent to a specific discharge of about 130 mm $month^{-1}$. Consequently, runoff from the Dome during most winter months with at least average rainfall may be similar to runoff from adjacent farmed areas with mineral soils.

Several studies of peatland catchments have shown that overland flow typically forms a small proportion (< 10%) of total runoff. At Kopouatai, there is some evidence that overland flow occurs when the water table is at the ground surface, particularly at the western margin of the Dome, where ephemeral discharges occur within microchannels and shallow rills during and after significant rainfall.

Rapid ground water flow from ephemeral zones of saturation (interflow) may contribute a large proportion of peatland runoff. However, stream base flow may be negligible after a prolonged dry period. A raised peat bog does not behave like a sponge (e.g. McCraw, 1979; Thompson, 1983) sustaining stream flow by slowly releasing water (a theory, attributed either to A. von Humbolt or F. Hochstetter, which dates back to the 1850s (Ivanov, 1975)). Runoff from a peatland may cease completely during summer (Bay, 1967; 1969). Heikurainen (1976) suggested that, for an undrained peatland during summer, no runoff occurs when the water level is below a threshold depth of 100 mm. At Kopouatai, the water table is typically below 100 mm for most of the summer and autumn.

Lateral throughflow typically forms a large proportion of the runoff component of a peatland water balance, because peatlands usually form over a relatively impermeable stratigraphic layer, and because surface runoff (overland flow) is usually low due to shallow ground surface gradients and water storage in many small depressions.

Throughflow at Kopouatai may be estimated using Darcy's law:

$$v \quad = Q/A \quad = -K(\Delta h/\Delta l) \qquad (4);$$

where Q is throughflow;
A is cross-sectional area (average thickness of saturated strata multiplied by unit width of 1 m);
$\Delta h/\Delta l$ is the hydraulic gradient; and
K is hydraulic conductivity.

Using an average hydraulic conductivity of 4.5×10^{-4} m s^{-1} determined from 16 shallow slug tests, a hydraulic gradient of 0.001 (eastern margin of the Dome) to 0.006 (western margin of the Dome), and assuming the average saturated thickness of the shallow peat is 1.5 m, gives the following estimate of throughflow at Kopouatai:

$$Q = 4.5 \times 10^{-4} \times 1.5 \times 0.001 \text{ (or } 0.006) = 6.75 \times 10^{-7} \text{ to } 4.05 \times 10^{-6} \text{ (m}^3\text{s}^{-1})$$

The Darcy velocity (v_d) or specific discharge from the shallow peat is 4.5×10^{-7} to 2.7×10^{-6} m s^{-1}. Hence, assuming lateral throughflow is discharged along the entire boundary (40 km) of the Dome and assuming an exact oval boundary (semi-major axis = 8 km, semi-minor axis = 4 km, area = 100 km^2), throughflow from a discharge area of 60 000 m^2 (1.5 m x 40 000 m) is about 2 000 to 14 000 m^3 per day. Spread over a recharge area of 100 km^2, this discharge is equivalent to a water loss of 0.02 to 0.14 mm per day from the Dome. Annual water loss via throughflow is about 5 to 50 mm, and therefore is a small to moderate proportion of the runoff component of the simplified water balance. Throughflow is less than 5% of long-term, mean annual rainfall.

Vertical piezometric gradients may be used to evaluate ground water recharge from deep aquifers to the overlying peat. Artesian bores located near the Kopouatai Dome indicate that the lower Piako catchment is a discharge zone, but the depth of water within surficial peat deposits may modify local piezometric gradients. At Kopouatai, the very low transmissivities of deep peat deposits and interbedded silt and clay layers indicate that ground water recharge from deep aquifers is unlikely to contribute significant volumes of water to the shallow peat deposits. Similarly, ground water seepage loss from surface peat to deeper ground water is likely to be negligible, especially at the low-lying margins of the Dome.

River flow interactions

A raised peat dome receives water primarily from rainfall, but this water supply is augmented by floodwaters from adjacent rivers. Floodwaters may become "trapped" in open water depressions. Novitzki (1979) plotted relative flood flows in a basin versus different percentages of lake and wetland area. He reported that basins with 5% of their area covered by wetlands or lakes have flood peaks 50% lower than basins without them.

Wetlands cover approximately 110 km^2 (7%) of the Piako catchment, so the theoretical effect of this area is to reduce major flood flows by approximately 55% (Novitzki, 1979). This value compares favourably with Harris' (1979) estimate of a reduction of at least 40% for the Piako River. However, the percentage reduction in flood peaks may vary for different floods and may depend on antecedent rainfall in the catchment. Furthermore, ponding in areas of the catchment other than at Kopouatai have a major role in reducing peak flood flows of the Piako River.

The Dome will be only partially flooded during events with a low (e.g. < 2 y) return period. For example, a typical flood in the Piako River (Tideda no. 9140) during August 1992 (maximum average daily flow = 75.3 m^{3}s^{-1}; Environment Waikato, 1993) appeared to extend only several hundred metres inwards towards the centre of the Dome, and a similar flow of shorter duration in October 1992 caused even less surface water ponding at the western margin of the Dome. During major floods the Dome is important in attenuating flood flows in the Piako River, acting as a natural flood barrier between the Piako and Waihou Rivers. However, surface water ponding due to flooding of adjacent rivers is not a significant source of water input at the Dome during most years, so floodwaters are unlikely to contribute sediment and nutrients to much of the Dome area except during major floods.

During winter and spring, the surface flow of Carters Canal responds rapidly to both small (e.g. < 10 mm) and large (e.g. 70 mm) daily rainfalls. Stream flow response to similar rainfalls during summer and autumn is often much smaller (Fig. 7) as rainfall infiltrates the surface peat and raises ground water levels. During winter and spring, ground water levels are high and ground water outflow provides a continuous source of water for some surface streams. By comparison, reduced ground water levels during summer and autumn correspond with very low rates of surface flow from the Dome.

Seasonal differences in surface water outflow indicated that, for a given storm (e.g. 20 mm rainfall), the Peat Dome will be more effective in reducing flood flows of adjacent rivers in summer and autumn than in winter and spring. However, the Dome has some beneficial effects in reducing flood peaks throughout each year.

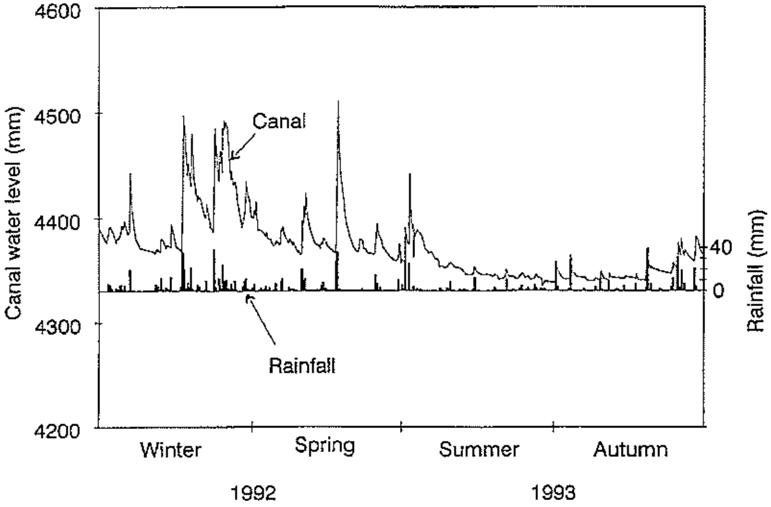


Figure 7 - Comparison of rainfall with water level at the Carters Canal monitoring site.

Conclusions

This paper has described components of the water balance at Kopouatai. The hydraulic conductivity of peat materials is variable, from highly permeable for fibric (weakly decomposed) horizons to negligible for sapric (strongly decomposed) horizons. The hydraulic conductivity of peat at Kopouatai is comparable with peats both in New Zealand and overseas. This implies that the hydrological characteristics of peat at Kopouatai may be expected to be similar to those for peat bogs in other parts of the world with similar climates. Further work will be required to assess the available porosity or specific yield of peat in the zone of water table fluctuation and the unsaturated zone, and to assess differences in ground water throughflow and evapotranspiration due to vegetation cover at Kopouatai.

Rates of water movement within the peat varied by several orders of magnitude, with most water exchange within the upper 1.5 m layer of peat and plant cover.

Seasonal variation of ground water levels occurs at both the eastern and western margins of Kopouatai, but maximum variation was greater at the eastern margin of the Dome than at the western margin. There is a moderate relationship between monthly changes in water table height and net rainfall at both margins of the Dome.

A simplified water balance for 3 years showed that annual runoff was highly variable (283 - 564 mm). Alternatively, surface flow measurements indicated that annual runoff for a small part of the Dome was 668 mm (1991/92), 393 mm (1992/93), and 287 mm (1993/94). Runoff varies as a proportion of rainfall, probably due to seasonal and annual rainfall differences during the study period. Annual water loss via throughflow was about 5 to 50 mm, and therefore forms a small to moderate proportion of the runoff component of the simplified water balance.

The Kopouatai Peat Dome is particularly important in attenuating floods generated by long duration rainfall and floods with a high return period. During major floods the Dome acts as a natural flood barrier between the Piako and Waihou Rivers. However, surface water ponding due to flooding by adjacent rivers is not a significant source of water input at the Dome during most years.

During winter and spring, ground water levels are high and ground water outflow provides a continuous source of water for some surface streams. Runoff from the Dome during most winter months with at least average rainfall may be similar to that from adjacent farmed areas with mineral soils. By comparison, reduced ground water levels during summer and autumn correspond with very low rates of surface flow off the Dome. Several small streams located at topographic lows at the margins of the Dome may continue flowing during summer and autumn, but such streams on the western margin of the Dome are affected by tidal backwater in the Piako River and little outflow is apparent for much of the tidal cycle. Several streams cease flowing during dry periods in summer and autumn.

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