

# Using groundwater for hydro electric power generation

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## Abstract

Controlled groundwater abstraction could be used to offset the effects of drought by augmenting river discharge for power generation during times of low natural flows, such as occurred in New Zealand during the winter of 1992. Augmenting river discharge with groundwater reduces the impact of a drought by spreading its effect over the recovery time of the aquifer. Groundwater could be introduced as an operational component for hydro generation in various ways. Fast-recovery aquifers might be operated as part of normal daily hydro electric water storage and release. Existing hydro lakes might have their storage capacity increased by extending horizontal bores into the surrounding country from the lake shorelines, or by diverting any lake spillage onto artificial recharge zones. Water from deep pumped bores in vertical transmissive fault or shatter zones could augment mountain rivers for power generation. Flows might be augmented in low-relief regions by extensive fields of standard pumped bores. New kinds of hydro scheme that would allow power generation from sites where ecological or physical constraints prevent the usual forms of hydro development may be feasible. New Zealand localities for possible operational use of groundwater include the Mackenzie Basin and associated headwaters, the Volcanic Plateau, the Taupo region, and Westland. Small stand-alone groundwater power schemes may be possible in Campbell Island, the Chatham Islands, Great Barrier Island, and Stewart Island.

## Introduction

Subsurface water reserves have been utilised since ancient times to buffer against drought. With this in mind, the author (Bardsley, 1992) suggested that groundwater reservoirs in the Southern Alps might be utilised as insurance against droughts like that which caused the low inflows to New Zealand hydro lakes in the winter of 1992. Groundwater discharge schemes might also be utilised for hydro power as part of normal operations. This paper uses a water balance framework to overview possibilities for operational use of groundwater in hydro power generation in New Zealand.

Water can also be discharged from natural lakes simply by pumping out the required volume of water and lowering the lakes below their outlet levels - thinking of lakes as a special kind of aquifer with 100% porosity. This option

is unacceptable in New Zealand for environmental reasons, as would be the lowering of existing hydro storage lakes below certain levels.

## **Groundwater as Active Hydro Storage**

Groundwater has always played a role in hydro power generation by maintaining river baseflows. However, natural groundwater reservoirs are not part of the operational storage system because the stored water cannot be released as required during times of power demand.

An operational hydro groundwater system would use engineered groundwater extraction to increase discharge for a time at downstream power stations. The augmented discharges may be considerably greater than the natural river flow. During the aquifer recovery period there will be a reduction in the natural groundwater input to the river system.

The mechanism for extracting groundwater for hydro power will depend on the local topography. Groundwater in dissected regions might be released by gravity flow via modern-day qanats comprising sets of horizontal bores extending a kilometre or more beneath mountains or plateaus. Surfaces of low relief would require a grid of pumped bores and a collection system for discharging the water into nearby river systems. Pumping operations must have the obvious requirement of a low power demand compared to the extra electricity generated at the power stations i.e. the vertical distance up which the water is pumped would have to be small relative to the total fall through all downstream penstocks which receive the additional water.

Hydro groundwater schemes could operate with or without the presence of downstream storage lakes. A groundwater storage system has the advantage of avoiding land inundation, evaporation loss, and possible risks associated with dam failures in earthquake-prone localities (Matthews, 1991), and thus might be a better alternative than a hydro lake.

Augmenting low river flows with extracted groundwater is not new - Rushton and Fawthrop (1991) mention a number of such schemes in the United Kingdom. However, there appears to have been no suggestion to date that this approach might also be incorporated into hydro power generation. The difference is one of scale - the United Kingdom schemes for example are for preventing river flows from falling below critical thresholds for abstraction and water quality. The hydro power application in contrast may require groundwater extractions of sufficient magnitude to increase river discharge from low flow to bankfull for some time.

Any major hydro groundwater scheme upstream from one or more power stations requires a source of extractable groundwater, capable of yielding a considerable discharge over a period of electricity demand. The mode of scheme operation will depend on the relation between the long-term mean rates of groundwater recharge and extraction, and on the recovery time following extraction. An operational classification can be constructed as follows:

**(i) Mean extraction rate exceeds mean recharge rate (unsustainable resource utilisation)**

A groundwater reservoir may be “mined” at an unsustainable rate. This may be the only alternative if the available resource is a large store of old groundwater in hydrological isolation from the present river systems. Ancient groundwater occurs in some mountain regions (Silar, 1990), but is usually associated with extensive horizontal aquifers with low head gradients. Old water might be deliberately extracted for power generation at a constant rate until depleted, or it could be held in reserve as a buffer against a finite number of hydro electric droughts. The mining of previously isolated groundwater increases power output because new water is being introduced to the hydro river system.

**(ii) Mean extraction rate equal to mean recharge rate (sustainable resource utilisation)**

*(a) Slow recovery*

The recovery time following major groundwater extraction to offset a hydro drought may be about the same as the return period of the drought. Such extended recovery times imply a low rate of recharge relative to the volume extracted. The natural recharge may, nonetheless, be sufficient for drought insurance, provided major extractions are not permitted in normal years. This is the groundwater equivalent of melting part of a glacier to obtain emergency water supplies. It would be interesting to evaluate the cost-effectiveness of slow-recovery drought insurance against the alternative of constructing reserve thermal power stations.

The groundwater discharged from slow-recovery schemes would have entered the river system sooner or later. There is thus no overall increase in power output unless the groundwater is imported from outside catchment boundaries. Rather, the effect is to manage dry-year hydro generation problems by spreading their impact over the aquifer recovery time.

*(b) Seasonal recovery*

If the recovery time following extraction is measured in months, a groundwater reservoir can be used as part of seasonal power generation operations.

One mode of seasonal operation would be for groundwater recharge and discharge to be related to the seasonal fluctuation of existing hydro lakes. A series of horizontal bores could be extended beneath the surrounding countryside from the lowest seasonal shoreline level of the lakes. This would initially lower the local water tables which would then become synchronous with the lake levels ie the bores would recharge the adjacent aquifers as the lake levels rose and discharge back when lake levels fell. The hydro lakes

would thus behave as if they had a larger surface area. Additional power could be generated if the increased storage capacity produced less spillage from the lakes during times of high inflow. The reduced seasonal fluctuation of lake levels might be an ecological improvement - a partial return to pre-hydro water level variations.

Another method of seasonal recharge would be seasonal pumping of groundwater from vertical bores located along existing hydro canals or tunnels. The use of such linear borefields would increase power output if the extracted groundwater would not otherwise have entered the water supply of the power scheme.

Particularly favourable aquifers may allow some existing hydro schemes to obtain additional storage capacity and increased seasonal water supply by constructing new canals supplied entirely by pumped groundwater. Detailed pumping tests would be needed to verify the resource and check environmental impacts prior to canal construction. One possibility with minimal environmental impact would be to intercept only that groundwater which would otherwise have drained directly into the ocean or a lake. This might allow an increase in both hydro storage capacity and power output without any impact on the visible surface hydrology.

Seasonal groundwater storage might be enhanced by artificial recharge of the aquifers during months of water surplus. Such schemes are currently in operation in Southern California to maximise urban water supply in dry seasons (Matthews, 1991).

### *(c) Rapid recovery*

Some groundwater reservoirs may recover rapidly, within hours or weeks, due to natural hydraulic connection with river systems, or through the use of artificial rapid recharge systems. Such aquifers could be used for day-to-day hydro operations in much the same way as a hydro lake behind a dam.

One simple type of rapid-recovery scheme might be based on the diversion of the normal discharge of a river into a canal which runs parallel to the channel before rejoining it further downstream. The canal discharge is augmented at times of power demand by bores pumping from the alluvial floodplain aquifer. Extraction could be enhanced by horizontal extensions of the bores beneath the river channel. The capacity of the canal will be exceeded during times of high river discharge and the excess flow will recharge the now-dry channel gravel aquifer.

The use of this type of channel aquifer storage and extraction was proposed for rural water supply by Rajagopalan and Prasad (1989), who noted the advantage of storing some monsoon discharges which would otherwise have been lost down the river.

There is clearly an environmental price to be paid for channel aquifer storage: a section of river is converted to a semi-permanent dry bed. This may

still be a better environmental alternative than a hydro lake which would have inundated the entire surrounding flood plain. A variation on the same theme would be to utilise a gravel-filled former hydro lake. Pumping into a canal constructed on this new aquifer might be sufficient to restore viability to a zero-storage power scheme.

Another type of rapid-recovery system might be created by emplacing a sufficiently large number of recharge bores into an existing unconfined aquifer, which then in effect behaves as a hydro lake (Bardsley, 1994a).

There is every intergrade between aquifers with "slow" and "rapid" recovery, but the classification is convenient. The time to recovery is just the waiting period before the accumulated volumetric recharge equals the water volume discharged in the last extraction. The natural volumetric recharge of a groundwater reservoir from precipitation increases with the surface extent of the aquifer. The size of the region of extraction may therefore be as important as climatic and geological factors in determining the appropriate aquifer management for hydro power generation.

### **Stand-Alone Groundwater Power Schemes**

The discussion thus far has centred on the use of aquifers as alternative water stores for supply to one or more hydro power stations located further down a river system. However, it may be possible to directly couple groundwater extraction and power generation, avoiding the intermediate river stage.

The simplest system would be to generate power by pumping groundwater from a single bore and piping the discharge directly to a generator at a lower elevation than the bore water level. Net power will be produced after subtracting some of the power to maintain pumping. Small power schemes of this type might be useful in isolated islands with limited surface streams and high infiltration rates. These simple generating systems provide interesting problems of resource optimisation as there is a trade-off between pumping rate and power generation (Bardsley, 1994b).

A more ambitious scheme might involve an extended elevated canal or mountain tunnel with the discharge supplied entirely by numerous bores. At the end of the tunnel or canal the discharge would be passed down to a power station at a lower elevation.

### **Possibilities for New Zealand**

One task which could be carried out immediately would be to check all existing hydro lakes to see if their storage capacity could be increased through the use of horizontal bores. Any such investigation would have to include the environmental impact of the initial lowering of the water table in the new storage areas.

Evaluation of hydro groundwater possibilities within New Zealand requires detailed knowledge of local hydrogeology and climatology. In some localities the volume of potential hydro groundwater can be estimated from the volume and porosity of saturated rock at a given altitude. Dell (1982, p.84) estimated the groundwater volume in the ignimbrites of the Mamaku Plateau near Rotorua to be as much as 16 times the volume of Lake Tarawera. An even larger volume could be demonstrated for aquifers in the Taupo basin. In the light of limited current knowledge, quantification beyond this simple approach would create a false impression of accuracy. Instead some speculations are offered as to how hydro groundwater schemes might function in a few selected New Zealand localities.

### **(i) Mackenzie Basin**

The Mackenzie Basin in South Canterbury includes a considerable land area of low relief underlain by fluvioglacial alluvium. Precipitation is low, but the large areal extent of the basin suggests the possibility of constructing a slow-recovery scheme with pumped groundwater augmenting the Tekapo and Pukaki rivers in times of drought. This would serve to maintain power output at Benmore, Aviemore and Waitaki. Some 4500 vertical bores distributed over 250 square kilometres and pumping at a mean rate of 1500 m<sup>3</sup>/day would generate a discharge of almost 100 m<sup>3</sup>/s. This implies removing 1 metre of groundwater from the area concerned for every month this discharge was maintained. A scheme of this size could forestall any repeat of the 1992 electricity crisis. Each metre of extracted water might require 10 years of recovery, assuming 10 cm annual recharge from precipitation and from leakage from streams originating in the surrounding hills.

A more modest development would be to construct artificial recharge systems for subsurface storage of spillage from the Mackenzie lakes in wet years. This water could then be later extracted by pumping during times of water demand.

Any scheme in the Mackenzie plains would involve considerations of bore locations, depth, and spacing. Some relevant papers have appeared recently which investigate the catchment areas of individual bores (Akindunni and Gillham, 1992; Lerner, 1992; Narasimhan and Zhu, 1993).

### **(ii) Southern Alps east of the main divide**

The schists and greywacke ranges in the headwaters of the Clutha and Waitaki may contain a considerable store of water as a consequence of the large volumes of rock involved. However, any comments on development options are clearly speculative in the absence of firm data on the hydraulic properties of the faults and shatter zones which are likely to be the main extraction sites.

A series of long horizontal bores could be extended beneath uplands for at least a kilometre - now possible with current technology (Cooper, 1994). Each bore would need to intercept a sufficient number of transmissive zones along this length to provide gravity flow water yields in the order of 10,000 m<sup>3</sup>/day. It was noted by Bardsley (1992) that some 430 such bores would be sufficient to offset a 5 cm/day fall in the level of Lake Tekapo. The diameter of the bores would probably be in the order of centimetres: theory and experience indicates that widening rock drill-holes to full tunnel diameter need not greatly increase the water inflow (Zhang and Franklin, 1993). The traditional qanats of ancient Persia were quite large in diameter, but this was related to their construction by human labour rather than to any hydrological considerations (Beaumont, 1971).

An alternative method would be to cluster fields of deep vertical bores to tap transmissive zones associated with faults or intense jointing near the main divide. A promising fault runs north through the mountains just west of the Hopkins River and extends across the main divide through to the headwaters of the Landsborough River (Gair, 1967). If this fault zone proves to be transmissive, then bore fields emplaced into it along the upper Hopkins valley might yield significant discharges. The induced pressure gradient could be sufficient to cause some migration of groundwater along the fault from the Landsborough catchment. An initial deep trial bore might be attempted at the most accessible part of the fault where it crosses Elcho Stream, almost on the floor of the Hopkins valley.

Economic aspects as well as hydrogeological factors will determine optimal bore locations for hydro power use within the Southern Alps. For example, the mountains in the headwaters of the Godley River would probably yield groundwater of greatest value as the extracted water passes through the most power stations. Groundwater schemes constructed in the catchments of lakes Wanaka and Wakatipu could increase the relatively small amount of total controlled storage in the Clutha catchment.

The rate of recharge would determine whether Southern Alps aquifers would be used as drought insurance or as part of day-to-day hydro operations. The number of operational options increases with the recovery rates, suggesting that the optimal locations for groundwater extraction should be as close to the main divide as possible to take advantage of the rapid westward increase in precipitation (Chinn, 1979; Griffiths and McSaveny, 1983; Henderson, 1992). Groundwater recharge in mountain environments, however, is not always a simple function of precipitation (Forster and Smith, 1988).

The scientific analysis associated with the development of "hard rock" alpine groundwater systems in New Zealand would touch upon a number of areas of active hydrological research. Mountain hydrology is still poorly understood and special care is required when constructing hydrological

models in heterogeneous steepland regions (Klemes, 1990). Much also remains unknown about crack flow and various models are still being proposed (Bai et al, 1993). The extent of current research in hard-rock groundwater hydrology is evident by the range of papers presented at a recent international symposium on this subject (Banks and Banks, 1993). Even such apparently mundane topics as optimal siting of bores with respect to joint location and orientation have been the subject of recent analyses (Yin and Brook, 1992; Banks, 1992).

### **(iii) Westland**

The unique scenic and ecological character of Westland can lead to conservation-related rejection of hydro schemes which require land inundation, and high bedloads can lead to rapid siltation of any hydro lakes constructed to smooth discharges in flood-prone rivers.

The West Coast could thus be an ideal region for rapid-recovery groundwater storage schemes. The Blackburn flats near Buller was tentatively suggested by the author as a possible site for a fast-recovery scheme based on gravity-flow artificial recharge (Bardsley, 1994a). Most of the storage in this scheme would be in sediments beneath native forest, a less destructive alternative than the original controversial proposal to flood native forest in the adjacent Ngakawau valley.

A diligent search of the West Coast catchments might reveal other sites for fast-recovery hydro power developments. One possibility might be the extensive fluvioglacial deposits beneath the forested region between Lakes Ahaura and Hochstetter. If these sediments proved suitable for storage they could form the basis of a hydro power scheme on the Ahaura river with a power station located near Ahaura township.

### **(iv) Central North Island**

Water released from groundwater storage via slow-recovery schemes would be of particular value for the Tongariro scheme during drought. Such schemes might be located in the Rangipo Desert or in the upper Moawhango Catchment. The maximum augmented discharges might be less than those of the Mackenzie basin, but the higher rainfall would allow faster recovery from greater drawdowns. The recovery time for the Rangipo aquifers might be reduced by enhancing groundwater recharge of the local ephemeral streams using techniques developed for arid regions (Cochran et al, 1989; Abdulaziz, 1991).

Because of the small amount of operational storage in the Tongariro scheme, a hydro groundwater system could operate on a seasonal recharge basis with low-flow augmentation being part of the ordinary seasonal cycle of operations. Existing canals and tunnels could be used as a basis for linear



fields of extraction bores. For example, bores might be established along the line of the Wahianoa Aqueduct on the southeast of Mt Ruapehu to intercept groundwater which would otherwise have been lost to the south.

The Tongariro scheme also offers some interesting possibilities for groundwater-based extensions with minimal environmental impact. An ideal extraction process intercepts just that groundwater which would otherwise discharge as sub-lake springs and seeps. This principle might be applied to Lake Taupo by supplying the Tokaanu hydro via some new canals or tunnels along the east and west sides of the lake, at the elevation of Lake Rotoaira. These canals would extract only deep groundwater destined for Lake Taupo, provided aquifers with sufficiently high water pressure to make the pumping operation economical could be located. The volumes of groundwater extracted would probably not be large in terms of sustainable yield, and some energy would be lost in the pumping process. The cost of canal construction therefore may or may not be offset by the increase in storage capacity and power output from Tokaanu.

One further environmental modification to the Tongariro scheme might be to construct a fast-recovery groundwater store in the vicinity of Lake Rotoaira. This would act as an alternative store should the lake be restored to its natural state in response to requests from the local Maori people.

Outside of the Tongariro region a major slow-recovery groundwater scheme could be established in the ignimbrite aquifers beneath the upper Rangitaiki River to the east of Lake Taupo. This would be the North Island equivalent of the Mackenzie slow-recovery scheme. A canal capable of carrying up to 100 m<sup>3</sup>/s would be required to transport the extracted groundwater to Lake Taupo for subsequent power generation on the Waikato River.

#### **(v) Offshore islands**

Small direct-generation groundwater hydro schemes may be feasible on a number of New Zealand's smaller islands using a few deep pumped bores coupled to a power plant at sea level. In island environments traditional hydro schemes often cannot store sufficient water in small stream valleys to maintain power generation during times of low flows. Groundwater hydros have an advantage in that their built-in aquifer storage may involve considerable volumes of water relative to the power output. Also, no scarce land is lost beneath a storage lake.

Chatham Island is attractive from the viewpoint of groundwater power in that the gentle topography of the southern uplands should encourage recharge, and the volcanic bedrock may contain a large groundwater store. Groundwater piped to a sea level power station sited near Ko Oreao Point on the south coast could produce power using an operating head of 260 metres. A much smaller scheme may prove feasible on nearby Pitt Island.

Campbell Island has a small power requirement, and a single-bore groundwater power scheme there may prove more cost effective in the long term than regularly transporting diesel fuel from the mainland. A bore pumped at 450 m<sup>3</sup> per day would produce about 2kW if the equilibrium bore water level was 50m above the generator. The much greater population of Great Barrier Island means that groundwater power could at best meet only part of the demand there.

Finally, a low-head groundwater power scheme could supply Stewart Island. One option which would be to construct bore-supplied collection canals in the lowlands around Island Hill in the west of Stewart Island, supplying water to a sea level power house at Mason Bay with an operating head of about 50 metres. This scheme might produce up to 0.3 MW depending on the water table elevations. Smaller schemes on the island might be possible from bores extracting water from the upper weathered zone of the granitic base rock.

An unfortunate problem in establishing the viability of small direct-generation hydro schemes is the high cost of the evaluation phase. The only means of establishing the equilibrium bore water levels for various extraction rates (Bardsley, 1994b) is by direct measurement from pumping tests after first going to the expense of drilling the bore - in which case the scheme is already well on the way to completion. In contrast, preliminary evaluation of a stream-based hydro scheme requires little more than topographic maps and a sufficiently long discharge record.

## **Environmental Impacts**

Hydro power schemes utilising groundwater components should have less environmental impact than traditional schemes of the same size. However there will inevitably be some alteration of subsurface water balances. Slow-recovery schemes might have the greatest impact, as they will reduce baseflow during the extended replenishment periods. Spalding and Khaleel (1991) discuss predicting the extent of streamflow depletion caused by nearby bores. Water quality is also important for the operation of all groundwater schemes. It would be necessary to verify that pulses of extracted groundwater would not significantly modify the chemistry of existing surface ecosystems. Hellawell (1988) discusses the environmental effects of augmenting river discharges with groundwater inputs.

The extraction of large volumes of groundwater does not always imply a widespread environmental impact. In a dry area like the Mackenzie basin, the natural water tables are deep below the ground surface, so dewatering need not affect the land surface. Even the few wetland areas there would suffer minimal impact if they were supported by a perched water table.

A very large groundwater store may act as an environmental buffer against even major extractions. For example, the suggested slow-recovery scheme in

the upper Rangitaiki may not have too great an impact on stream discharges if the groundwater is replaced by lateral migration of water from the extensive adjacent ignimbrite aquifers.

An additional environmental factor for a slow-recovery scheme on the volcanic plateau would be the possibility of surface subsidence associated with dewatering buried paleosols. Prior to any exploitation it would be desirable to evaluate the subsidence potential - a discussion of techniques is given by Prokopovich (1991). Modification of the groundwater balance of Lake Taupo should have little surface environmental impact if carried out with care. Streams feeding into the lake would need constant monitoring to ensure that groundwater extraction was not depleting baseflows.

Ecological impact is likely to be low for any groundwater hydro schemes in the Southern Alps. Discharge from high altitude mountain streams might be reduced. A more significant ecological impact could arise from discharging large volumes of extracted groundwater to valley streams which normally have much lower flows. If the bores could be distributed over a wide area, no single mountain stream need experience too great a discharge increase during an extraction phase.

Small direct-generation power schemes carry their own environmental risks. Groundwater should not be diverted into power plants at the expense of depleting local water sources. In the Chatham Islands particular care would be required to avoid draining any wetlands of the southern uplands not supported by perched water tables.

Direct-generation schemes might be used as a reliable source of good-quality reticulated water for island communities and elsewhere. On the New Zealand mainland a bore-supplied pipeline might be extended along the length of the Mamaku Plateau to supplement Rotorua city water and power, although the power contribution would be minor.

## **Economic Aspects**

Any hydro groundwater development in New Zealand must be economically viable. A candidate scheme must therefore provide optimal water yield for minimum establishment costs. This concept has been considered for standard bore fields by Rostock et al (1977), but preliminary geophysical investigations will be required for optimal placement of bores in upland terrains such as the Southern Alps.

On the national level hydro groundwater operations would need to be integrated into the New Zealand power generation system. This would raise the profile of groundwater to an integral part of the national resource base, as it is in Israel today (Hamberg, 1989). Enhancing the status of groundwater might serve to avoid the temptation to simply deplete the resource for short-

term gain in power yield. It is worth noting the criticism of Glasby (1991) that geothermal power utilisation in New Zealand appears to have been carried out without regard to sustainability.

## Conclusion

The operational use of groundwater has the potential to contribute to both hydro storage and direct power generation in New Zealand and elsewhere. Most of this paper has been unashamedly speculative but it is hoped that it might stimulate feasibility investigations at some of the localities mentioned.

## References

- Abdulaziz, S.A. 1991: Effectiveness of recharge from a surface reservoir to an underlying unconfined aquifer. *International Association of Hydrological Sciences Publication no. 206*: 191-196.
- Akindunni, F.F.; Gillham, R.W. 1993: Unsaturated and saturated flow in response to pumping of an unconfined aquifer: numerical investigation of delayed drainage. *Ground Water 30*: 873-884.
- Bai, M.; Elsworth, D.; Roegiers, J. 1993: Multiporosity/multipermeability approach to the simulation of naturally fractured reservoirs. *Water Resources Research 29*: 1621-1633.
- Banks, D. 1992: Optimal orientation of water supply boreholes in fractured aquifers. *Ground Water 30*: 895-900.
- Banks, S.; Banks, D. (eds) 1993: *Hydrogeology of Hard Rocks*. Memoires of the XXIVth Congress, International Association of Hydrogeologists, Oslo, parts 1 & 2, 684p.
- Bardsley, W.E. 1992: Groundwater hydro resources. *New Zealand Science Monthly*, July Issue, p.11.
- Bardsley, W.E. 1994a: Underground hydro lakes. *New Zealand Science Monthly*, April issue, p.8-9.
- Bardsley, W.E. 1994b: Power from groundwater. *Journal of Hydrology*, (in press).
- Beaumont, P. 1971: Qanat systems in Iran. *Bulletin of the International Association of Scientific Hydrology XVI*: 39-50.
- Chinn, T.J. 1979: How wet is the wettest of the wet west coast? *New Zealand Alpine Journal 32*: 85-87.
- Cochran, G.F.; Barry, J.R.; Dale, M.W.; Sones, P.R. 1989: Harvest of ephemeral runoff for artificial groundwater recharge: feasibility evaluation using hydrological and hydrogeochemical models. *International Association of Hydrological Sciences Publication no. 188*: 471-485.
- Cooper, G.A. 1994: Directional Drilling. *Scientific American 270*: 56-61.
- Dell, P.M. 1982: *The effect of afforestation on the water resources of the Mamaku Plateau region*. Unpublished M.Sc. thesis lodged at the University of Waikato library 319pp.

- Forster, C.; Smith, L. 1988: Groundwater flow systems and mountainous terrain 2. Controlling factors. *Water Resources Research* 24: 1011-1023.
- Gair, H.S. 1967: *Sheet 20 - Mount Cook. Geological Map of New Zealand 1:250 000.* Wellington, New Zealand. Department of Scientific and Industrial Research.
- Glasby, G.P. 1991: A review of the concept of sustainable management as applied to New Zealand. *Journal of the Royal Society of New Zealand* 21: 61-81.
- Griffiths, G.A.; McSaveney, M.J. 1983: Distribution of mean annual precipitation across some steepland regions of New Zealand. *New Zealand Journal of Science* 26: 197-209.
- Hellawell, J.M. 1988: River regulation and nature conservation. *Regulated Rivers* 2: 425-443.
- Hamberg, D. 1989: The role of groundwater in Israel's integrated water system. *International Association of Hydrological Sciences Publication no. 188*: 501-514.
- Henderson, R.D. 1992: Extreme rainfall in the Southern Alps is simultaneous over 500 km and the maxima are 10km upwind of the highest ground. *Abstracts of DSIR/CSIRO Chief Executives Symposium on Atmospheric Research*: 22-24.
- Klimes, V. 1990: The modelling of mountain hydrology: the ultimate challenge. *International Association of Hydrological Sciences Publication no. 190*: 29-43.
- Lerner, D.N. 1992: Well catchments and time-of-travel zones in aquifers with recharge. *Water Resources Research* 28: 2621-2628.
- Matthews, C.A. 1991: Using ground water basins as storage facilities in Southern California. *Water Resources Bulletin* 27: 841-847.
- Narasimhan, T.N.; Zhu, M. 1993: Transient flow of water to a well in an unconfined aquifer: applicability of some conceptual models. *Water Resources Research* 29: 179-191.
- Prokopovich, N.P. 1991: Detection of aquifer susceptibility to land subsidence. *International Association of Hydrological Sciences Publication no. 188*: 27-33.
- Rajagopalan, S.P.; Prasad, N.B.N. 1989: Subsurface water in river beds as source of rural water supply schemes. *Journal of Water Resources Planning and Management ASCE* 115: 186-194.
- Rostok, C.A.; Simpson, E.S.; Roefs, T.G. 1977: Minimizing costs in well field design in relation to aquifer models. *Water Resources Research* 13: 420-426.
- Rushton, K.R.; Fawthrop, N.P. 1991: Groundwater support of stream flows in the Cambridge area, UK. *International Association of Hydrological Sciences Publication no. 202*: 367-376.
- Silar, J. 1990: Time and its meaning in groundwater studies. *International Association of Hydrological Sciences Publication no. 190*: 281-289.
- Spalding, C.P.; Khaleel, R. 1991: An evaluation of analytical solutions to estimate drawdowns and stream depletions by wells. *Water Resources Research* 27: 597-609.
- Yin, Z.; Brook, A.B. 1992: The topographic approach to locating high-yield wells in crystalline rocks: does it work? *Ground Water* 30: 96-102.

Zhang, L.; Franklin, J.A. 1993: Prediction of water flow into rock tunnels: an analytical solution assuming an hydraulic conductivity gradient. *International Journal of Rock Mechanics and Mining Science & Geomechanics Abstracts* 30: 37-46.

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