# Modeling the feasibility of tapping artesian flow to augment winter baseflows in a hydropower catchment in New Zealand

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## Abstract

This paper shows the possibility of tapping artesian water of an ignimbrite aquifer for generating addional power during low streamflow seasons. After the hydrogeological factors are considered which determine the feasibility of releasing artesian groundwater at optimal times to supplement hydro-electric generation, aquifer parameters are determined in a hydrogeological field study and used to set up a steady state groundwater model of the catchment area. The calibrated model indicates low values for the aquifer recharge, which in addition to the rather small values of the estimated transmissivities result in relatively poor yields of the artesian aquifer. Using transient simulations of pump-drawdown for a single well various pumping/canalised discharge scenarios are performed. The subsequent cost–benefit calculation show that hydraulic power generation by tapping artesian water is economically well feasible. Depending on the value of the storativity chosen which, unfortunately, is poorly known, an additional income between approximately NZ$ 16,500 and NZ$ 19,500 during one winter season seems to be possible.

## 1. Introduction

The operation of a free electricity market in New Zealand and a number of other countries means that electricity selling prices fluctuate over time. In particular, prices tend to be highest in winter when demand is greatest. Large power schemes with seasonal storage capacity can develop optimal strategies in this economic environment, by storing summer inflows for winter power generation. This is not an option for small schemes which may have only a few days of available storage in small hydro lakes. However, it may sometimes be possible for small schemes to

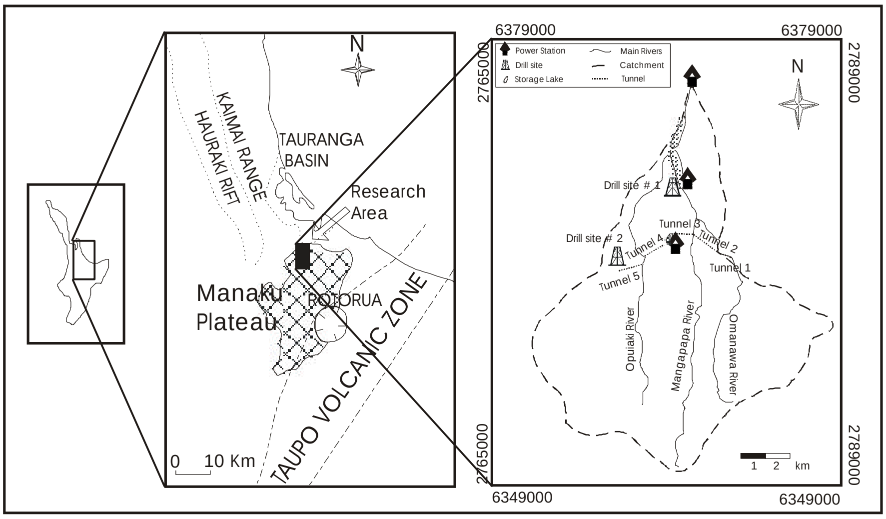

***Fig. 1:*** *Study area with main rivers of the Kaimai Hydro Power Scheme.*

achieve a component of seasonal storage by making winter groundwater extractions from underlying aquifers. Given suitable hydrogeological conditions, such aquifers could play the economic role of small seasonal storage lakes. The ideal situation is for artesian flow conditions which reduce ongoing pumping costs.

In this regard, the Kaimai power scheme which drains a catchment area of 240 km$^2$ and is situated in the eastern site of the Kaimai Ranges at the Northern Island of New Zealand (*see Fig. 1*) has the unusual feature of an artesian head at a higher elevation than the level of the topmost hydro storage lake. The hydro-electric power scheme involves the diversion of water from the headwaters of several rivers via a system of tunnels, dams and canals that direct water through a cascade of three power stations and small storage lakes. The average annual energy output of the complete hydropower scheme is approximately 165 GWh per year.

However, during winter months high electricity needs cannot be met because of low streamflow (*Ward, 1993*). The abstraction of deeper, underpassing artesian groundwater which does not normally contribute much to streamflow, could produce some extra hydroelectric power and income. The present paper will investigate this possibility. Using transient numerical models, pump-drawdowns are simulated for various hydrological scenarios and a hydraulic enery balance is carried out to estimate the amount of net turbine power that can be gained from the artesian water extracted.

## 2. General geological and hydrological setting

### 2.1 Geology

The <u>Mamaku Ignimbrite</u> is generally fine-grained with a severely variable degree of welding. It forms the upper surface of the northern Mamaku Plateau and dips

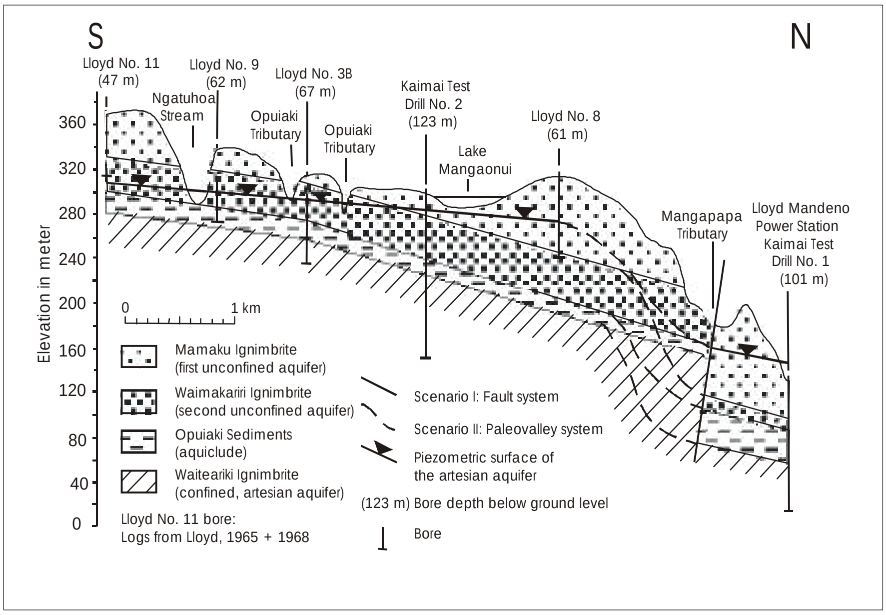

***Fig. 2:*** *Geological cross-section of the area along a south-north profile.*

about 2° to the north. The thickness at the northern Plateau is 70 - 80 m, decreasing to 40m further north.

The Waimakariri Ignimbrite or Lower Mamaku Ignimbrite is an extremely variable lithostratigraphic unit. The rocks dip with 1 - 4° towards north and north-east. It is a poorly to moderately-welded pumiceous and fine grained ignimbrite. Its thickness thins to the north and to the east.

The Opuiaki Sediments, are a sequence of pumiceous lacustrine or fluviatile sediments (silts and clays with minor sands). They are widespread throughout the northern Mamaku Plateau and are interpreted as lake basin sediments *(Carryer, 1975)* or as a meandering river system associated with lakes *(Morgan, 1986)*.

The Waiteariki Ignimbrite is an intensely welded, hard, dacitic ignimbrite. It reaches a thickness in the northern Mamaku Plateau of about 50 m *(Morgan, 1986)*. This thickness was also confirmed in the two testdrills. The north-trending streams dissecting the Mamaku Plateau have exposed the Waiteariki Ignimbrite in the steep valleys of some rivers.

The two top ignimbrites act as an unconfined aquifer, with the Opuiaki sediments as the confining layer. The average vertical distance from the ground surface to the Waiteariki Ignimbrite is about 60 - 80 m (see *Fig. 2*).

## 2.2 Hydrology

### 2.2.1 Rivers

A large number of streams drain the Mamaku Ignimbrite plateau. The streams and rivers are enclosed in vertical or deep sided gorges and valleys 60 - 110 m deep and flow in roughly parallel directions to the north whereas their tributaries tend to flow north east. This drainage pattern have imparted a distinctive dendritic pattern and is considered to be the result of the Mamaku Ignimbrite dipping to the north. Since a considerable proportion of run-off in the area is from ground water source of the unconfined aquifer, stream flows are fairly constant over long periods.

### 2.2.2 Rainfall

The mean annual rainfall is closely related to the topography of the Kaimai Ranges and varies 2500 mm in the Upper Kaimais and 1250 - 1500 mm in the Tauranga Region. Rainfall data at five rain gauges *(Fig.*3) show large seasonal variations with lows beneath normal during the winter months.

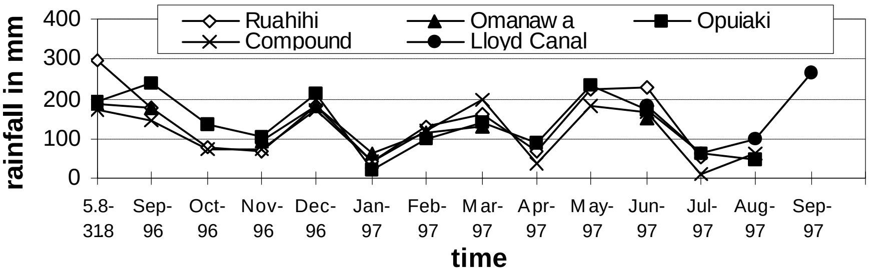

***Fig. 3:** Monthly rainfall between August 1996 and September 1997 for five stations*

## 2.3 Hydrogeology

The confined aquifer in the study area is formed by the Waiteariki Ignimbrite. Ignimbrites act as hard rock aquifers where jointing performs the primary control on drainage. The jointing of ignimbrites is strongly related to the process of welding which promotes the union or cohesion of glassy fragments. The degree of welding controls the hydraulic conductivity in an inverse manner. Conversely densely welded material is more likely to contain cooling fractures giving rise to hight bulk conductivities *(Tracey, 1986)*. Pumping test data from various ignimbrites indicate a high degree of uniformity and also fairly consistent values for transmissivity and storativity for ignimbrites. Highly jointed zones, densely welded zones and inter-ignimbrite contacts are the dominant and most efficient ground water paths, whereas the poorly welded zones typically have very little ground water movement, despite their high (50-60%) porosities. *Hind (1985*) showed that densely welded ignimbrites have hydraulic conductivities of approximately 3 * $10^{-3}$ m/s and poorly welded ignimbrites of approximately 6 * $10^{-6}$ m/s.

# 3. Field investigations

## 3.1 Test drills

Two test drills took place, one at the Lloyd Mandeno Power station and the second close to the tunnel 5 outlet (*Fig. 1*). At the lower drill site artesian water was found (with a water pressure of 20 m above lake level), the water level at the upper drill site was approximately 5 m above the upper lake surface. A pumping test was carried out in order to calculate the hydraulic conductivity (K) and transmissivity (T) of the Waiteariki aquifer. From the pumping test T was calculated to 0.001 $m^2/s$. This equates to a hydraulic conductivity (K) of $2 * 10^{-5}$ m/s, with the assumption of a thickness of the Waiteariki aquifer of 50 m. This pumping test was carried out with a narrow diameter bore and a low pumping rate. The hydraulic estimates may increase somewhat for a production bore with a large diameter pumped at a higher rate and fully penetration to the base of the aquifer.

## 3.2 Artesian head

The piezometric surface of the artesian aquifer slopes gently towards the north and follows the general trend of the topography. The piezometric surface exceeds topographic elevation in some places, particularly at some valley floors. Therefore there is the potential for simple groundwater release by gravity flow from localized artesian bore fields.

A map of the estimated locations for artesian flows from the Waiteariki aquifer was created while the constructed piezometric surface of the artesian aquifer was first estimated using water head measurements from the two test bores, together with earlier water head measurements reported by *Lloyd (1965; 1968)*. Potential artesian regions were then delineated wherever this estimated piezometric surface exceeded the land elevation. As expected, most of the artesian localities are associated with relatively low elevation regions in the incised valleys in the western part of the study area, such as the river valleys of the Omanawa River, the Ngatuhoa Stream and the Opuiaki River. The artesian head around the Omanawa River is likely to be up to 5 m above ground surface, up to 10 m above ground surface at the Ngatuhoa River and along part of the Opuiaki River.

## 3.3 Location of artesian bore fields

For optimal location for a drill site it is very important that the groundwater is tapped at a high enough elevation to pass through as much turbines as possible and preferably through all the power turbines in the sequence. Only then it can be made for sure that the additional groundwater would make a viable contribution to the hydropower production. The best place for a trial production bore would be along the Ngatuhoa Stream in order to trap the artesian water at the highest possible head and supply it into the diverted tunnel system.

There are different scenarios about the possible flow of the artesian groundwater of the artesian aquifer. The best situation would be when the groundwater currently underpasses all three power schemes as will be investigated in Section 4.

### 3.4 Tritium age of groundwater

For groundwater in the Mamaku Plateau *Dell (1982)* calculated from tritium data a residence time of 50 - 100 years. A tritium age determination on the artesian water indicates that most of the water is in excess of 40 years old, suggesting a large groundwater store. The tritium concentrations show probably that deep fluid and diluting groundwater derive from large reservoirs in ignimbrite.

# 4. Numerical modeling of the artesian aquifer

### 4.1 Steady state groundwater model of the catchment area

Using the groundwater flow model MODFLOW (McDonald and Harbaugh, 1984) we have set up a steady- state groundwater flow model for the artesian aquifer (see *Fig. 2*) using the previously measured aquifer parameters. Dirichlet boundary conditions for the piezometric head were used at the southern and northern boundaries and no-flow bondary conditios at the eastern and western boundaries of the model region.

The model was calibrated on observed heads collected from the field investigation and from historical records by mainly adjusting the effective recharge rate due to rainfall infiltration. With an annual rainfall of 2000 mm the optimal recharge rate was found to be only 100 mm/a which is indicative of the small amount of leakage from the unconfined aquifer into the artesian aquifer. Therefore it is to be expected that most of the artesian water to be used for augmenting the baseflow will come from areas up-gradient where the confining upper clay layer appears to thin out. This is also indicated by the long tritium water age of 40 years. *Fig. 4 (left panel)* shows the calibrated model together with the observed piezometric heads.

### 4.2 Transient models of pump drawdown

With the transient version of the MODFLOW model we have simulated the maximum discharge of artesian water that could be extracted through one particular well during the assumed 120 days of the winter session. The calculations were done under the hydrogeological constraint that the maximum drawdown reached during that time interval should not fall below the upper confining layer of the artesian aquifer, that is between 50 and 70 m. This results in a maximum pumping rate of Q ranging between 0.07 $m^3/s$ and 0.09 $m^3/s$, without avoiding the danger for the aquifer to dry out during this time.

*Fig. 4 (right panel)* shows the drawdown cone for a particular simulation with a discharge rate $Q = 0.075\ m^3/s$ and a storativity $S = 5 \times 10^{-3}$. *Fig. 5* shows that there is a significant sensitivity of the drawdown cone to the values of the storativity which are only poorly known. Increasing the latter yields in a range that is typical for unconfined aquifers *(Fetter, 1994)* results in a higher productivity (yield) of the well or, for the same discharge rate, results in a smaller drawdown. As will be seen in the following section, this has an effect on the economice benefit of the proposed artesian water extraction scheme.

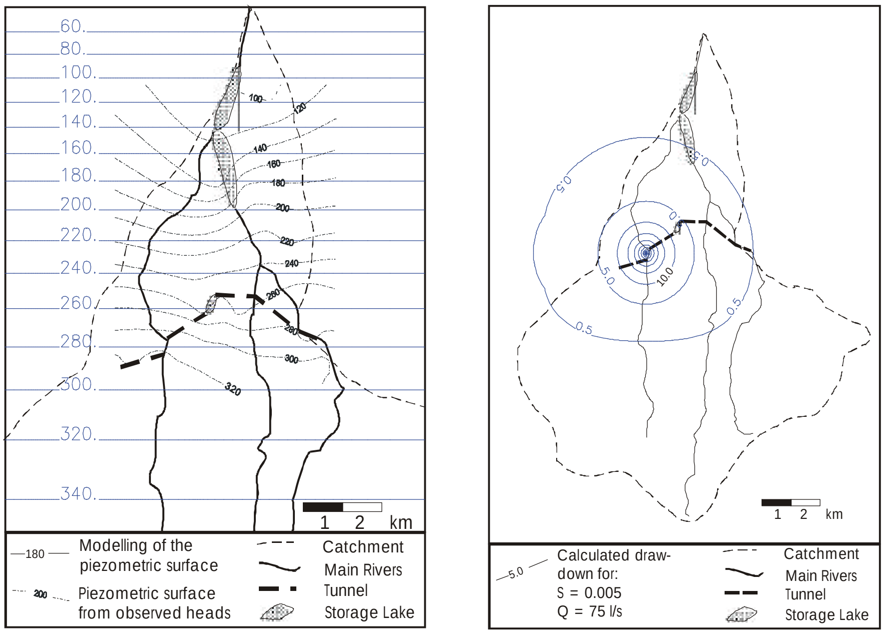

***Fig. 4***: *Left panel: Calibrated piezometric surface, Right panel: Drawdown cone after 120 days of pumping.*

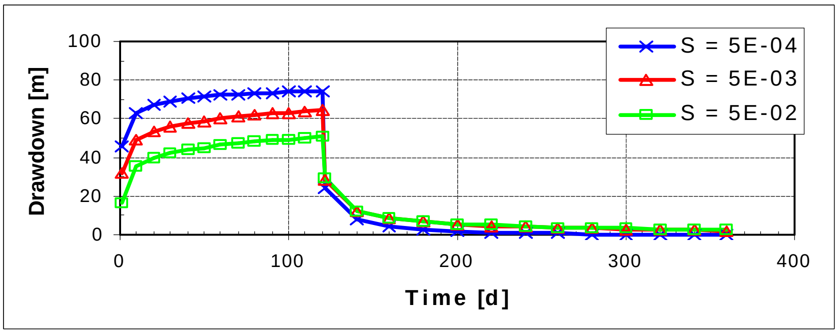

***Fig. 5:*** *Drawdown versus time for different values of storativity.*

# 5. Hydraulic and economic analysis of tapping the artesian aquifer

## 5.1 Theoretical energy balance of pumping versus power generation

To lift the water from the pump inlet to the ground surface the pump has to overcome the total drawdown. The effective power $P_{peff}$ required for this purpose is calculated using the following well-known formula for a pump (cf. *Roberson and Crowe, 1993*):

$$P_{peff} = 1/ \cdot_p * h_p * D * g * Q \qquad (1)$$

where $\cdot_p$, efficiency of the pump (~0.9); $h_{p,}$ lift height which is a variable in the following calculations; D, density of water (= 1,000 kg/m³); g, gravity acceleration (= 9.81 m/s²) and Q, discharge rate.

The additional hydraulic power $P_{Teff}$ produced at a turbine is calculated using the turbine power formula (cf. *Roberson and Crowe, 1993):*

$$P_{Teff} = \cdot_T * h_T * D * g * Q \qquad (2)$$

where $\cdot_T$, efficiency of the turbine (~0.9); $h_{T,}$ total falling head, which for the three turbines of the Kaimai Hydro Power cascade system is $h_T$ = 266 m.

It follows from (1) and (2) that the effective net power gained is:

$$P_{gain} = P_{Teff} - P_{Peff} \qquad (3)$$

## 5.2 Economic benefits (income generation) of tapping the artesian aquifer

Using Eqs. (1) to (3), the pumping power used, the turbine power gained and the net power gained, respectively, and the corresponding economic benefit (income generation) can be calculated for different drawdown or lift heights $h_p$ obtained for various pumping scenarios. The latter are selected based on the results of the transient drawdown modeling of Section 4.2.

*Fig. 5* showed that, for a given pumping discharge Q = 0.075 m³/s , the maximally obtained drawdown height $h_p$ obtained during a three-month winter period pumping depends on the value of the storativity S which, so far, could not be determined. Based on these values, a total falling head $h_T$ = 266 and a selling price of 0.05 NZ$/kWh for electricity, *Table 1* for the total power budget and the net income generation can be constructed.

***Table 1:*** *Analysis of income generation for various drawdown heights*

| Storativity S | Pumping height $h_T$[1] [m] | Pumping power $P_{peff}$ [kW] | Turbine[2] power $P_{Teff}$ [kW] | Net power gained $P_{gain}$ [kW] | Net income gener. per day [3] [NZ$] | Net income gener. per winter season [4] [NZ$] |
|---|---|---|---|---|---|---|
| $5*10^{-2}$ | 50 | 40.9 | 176.1 | 135.2 | 162.2 | 19,464 |
| $5*10^{-3}$ | 65 | 53,1 | 176.1 | 123.0 | 147.6 | 17,712 |
| $5*10^{-4}$ | 75 | 61,3 | 176.1 | 114.8 | 137.8 | 16,531 |

[1] based on a pumping discharge Q = 0.075 m³/s,
[2] based on a total falling head for the turbine system $h_T$ =266m
[3] based on an electricity price of 0.05 NZ$/kWh
[4] based on 120 days of winter season

*Table 1* illustrates that, owing to the fixed falling height of the turbine‘s headwater pipeline, the power generated is invariant and depends only on the discharge rate Q, which is fixed here. However, the pump power required to lift the artesian groundwater to the surface depends on the values of the storativity, i.e. it is related to the yield of the aquifer. With this, the last column of *Table 1* shows that the net income generated in NZ$ for the given winter session of 120 days is NZ$ 19,464, NZ$ 17,712 and NZ$ 16,531, respectively, for the three values of the storativity assumed. Surprisingly, the relative large uncertainty in the storativity appears to not have a large impact on the outcome of the economic benefit.

It should be noted, however, that the true benefits will be somewhat lower if one takes into account the installation costs for the well and the pump and, to a lesser degree, the maintenance costs. From this point of view, the practical implementation of a such a water diversion scheme would only be profitable in the long run.

## 6. Conclusions

In a small hydropower catchment an investigation took place to study the possibility of using the underpassing artesian groundwater as an additional source for generating power and thus extra income during winter seasons when low streamflow reduces normal power generation . The hydraulic analysis, based on the scarce hydrological field investigation and numerical models that allow to mimic different scenarios, shows a certain economic benefit in doing this.

The main restriction to a practical implementation of the project is the low average yield of the artesian aquifer which, for a maximally possible drawdown of about 60 m, results in an upper limit for the discharge rate Q between 0.07 $m^3/s$ and 0.09 $m^3/s$, depending on the value of the storativity chosen. With a typical uncertainty range assumed for the latter, an additional income between approximately NZ$ 16,500 and NZ$ 19,500 during one winter season appears to be realistic.

Performing additional pump tests with various observation wells should better constrain the storativity and thus provide a better estimate of the net income generated. Another approach which might provide higher benefits would be the installation of an additional well sufficiently upstream of the suggested well-site, in order to obtain more artesian water. However, this has to be weighted against higher installation and maintenance costs.

It should be noted that the model calculations have been performed under the assumption of an homogeneous porous media aquifer. In fact, the ignimbrite is a fractured aquifer with variable local hydraulic properties. This means that well efficiencies might be much larger in some areas as assumed in the analysis above. Eventually, only a long-term practical test can verify the feasibility of our suggestion of additional hydraulic income generation from artesian groundwater.

## Acknowledgements

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