Desalination and Water Treatment
www.deswater.com
11 (2009) 7–14

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Bellenden Ker tunnel, power station and a proposed east Mulgrave River water intake for Cairns

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Received 27 March 2009; Accepted 31 August 2009

ABSTRACT

The Cairns Regional Council (CRC) has identified the need to acquire an additional water source in the near future (council's corporate plan, section 5.1). Options listed include Barron River, Mulgrave aquifer, dead storage at Copperlode Dam, upgrade freshwater capacity and upgrade of Behana Ck intake. Currently the main additional water source targets are Mulgrave aquifer and Lake Placid (Barron River) water treatment plants (WTP). We present a cost and environmentally superior alternative which is to access the (East) Mulgrave River at the back of Bellenden Ker Mountain via a tunnel from the coastal plane. First we present a stream-flow model for the catchment of the East Mulgrave River above 600 m and show that sufficient water is available at that point for a water intake. This model is based on recent rainfall and cloud-stripping research by Dr David McJannet performed on Mount Bellenden Ker. Second we present a costing model for the construction of a one-lane, 6.5 km vehicular tunnel from the base of the mountain near Bellenden Ker township to the back of the mountain at 600 m, and associated infrastructure. The model incorporates a pipeline that takes water from the intake at 600 m to Gordonvale via the base of the tunnel where a power station generates sufficient electricity to run 1500+ homes. This costing model includes an option where the tunnel is the proof of concept for automated mining thereby attracting significant federal funding opportunities. The construction costs are similar to the WTP options however once in operation the tunnel power plant generates income by producing hydro-electricity while a WTP consumes large amounts of energy and other resources. As with the existing Behana Ck intake, the proposed intake only requires filtering and chlorination. Third we present an environmental impact discussion comparing our proposal to the WTP. This includes the carbon hand- versus footprints, effects of the intake on the river and effects of a bore-field and WTP on the aquifer.

Keywords: Cairns water supply; Environmental impact; Hydro power; Robotic tunneling

A banana-picking robotics project has brought about development of real-time 6-axis hydraulic motion control technology, coupled with stereo vision, 3D modelling and object recognition [1]. These robotics technologies can be applied to tunnelling and obviously there are numerous applications in the mining industry.

In this paper we focus on one specific application of that technology, one that helps open up an alternative water source which the city of Cairns must bring into production over the next decade. The Cairns Regional Council is primarily investigating whether to build a WTP at the Mulgrave or Barron River. In this paper we show that a better solution is a tunnel to access the unpolluted East Mulgrave River at 600 m above sea level where the water needs just to be filtered and chlorinated (See Figures 1 and 2). The following stream-flow analysis shows that enough water is available at that site to solve Cairns water problems for the foreseeable future.

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Presented at CESE-2009, Challenges in Environmental Science & Engineering, 14–17 July, 2009, Townsville, Queensland, Australia.
doi: 10.5004/dwt.2009.831

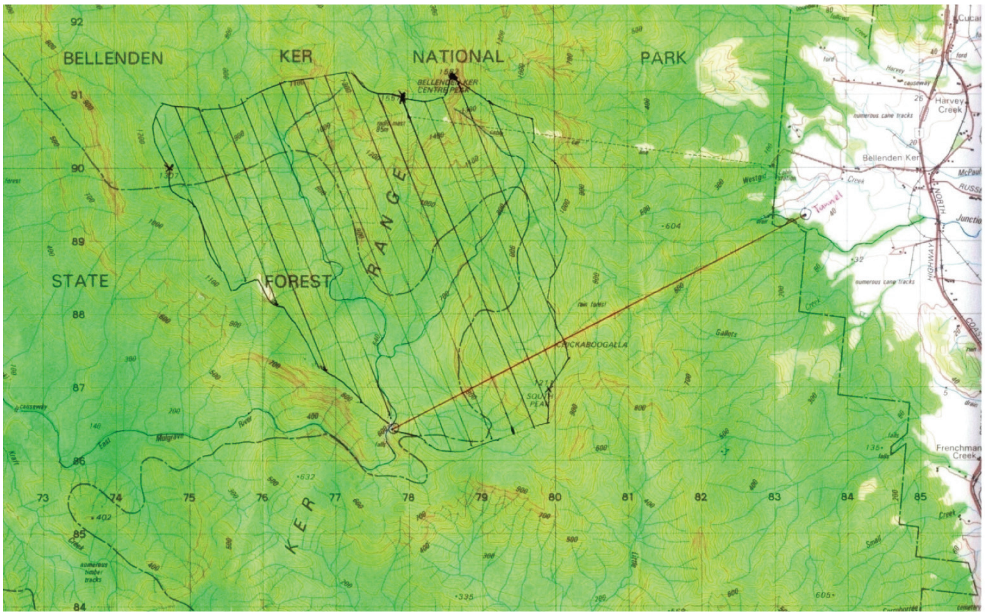

Fig. 1. Topological map and proposed 6.3 km tunnel (red line) at Bellenden Ker. The catchment area is shaded and near-perfectly oriented to capture the south-easterlies. Dr. David McJannet's hydrology research was situated inside the catchment area near the peak at the end of the cable-way (light dotted line).

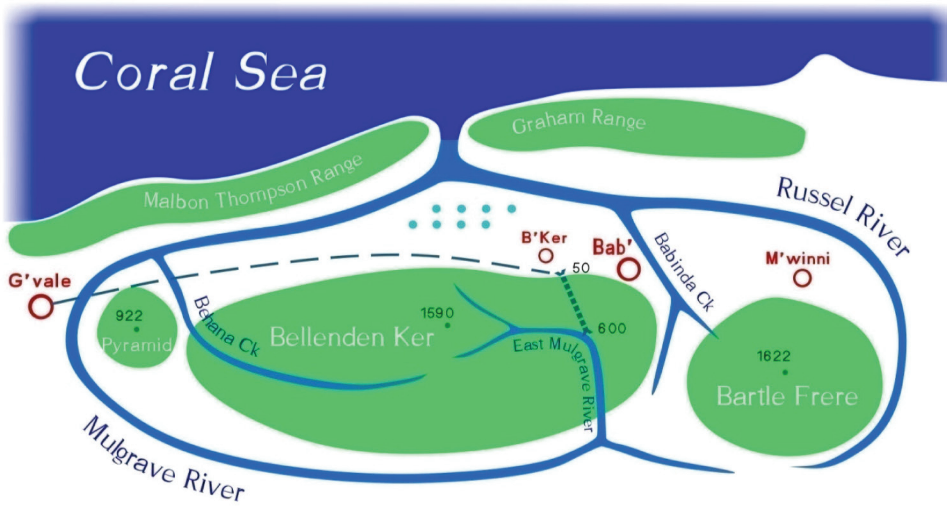

Fig. 2. The main hydrological features south of Cairns, the proposed tunnel location and pipeline to Gordonvale.

1. Stream-flow analysis

Using the best available data from rainfall and cloud interception research within the catchment area we arrive at a conservative estimate of 113 ML/day long-term average for the driest month (October) at the proposed intake, compared to 103 ML/day for the existing Behana Ck water intake. When using observed values and alternative models a value of 196 ML is arrived at. We acknowledge Dr David McJannet who by very fortunate coincidence has been researching hydrology within the catchment area. It is thanks to his work that it is possible to establish the minimum stream-flow with considerable confidence.

1.1. Water extraction

In the past the value that might have been used for water extraction has been 40% of the average daily flow in the driest month. Therefore a model is constructed to calculate the stream-flow in October.

1.2. Stream-flow model description

Initially a stream-flow analysis was commissioned from ARUP consulting Cairns [2]. It approximated the catchment area with two elevation ranges, one for all terrain below 1000 m, and one for all terrain above 1000 m. Careful estimation of each part for each square kilometer using the 1: 50 000 topological map has produced an estimate of total catchment area of 18.92 sq km, with 11.45 sq km (60.5%) being below 1000 m and 7.47 sq km (39.5%) above 1000 m. We estimate the stream-flow by approximating the run-off in each of these two areas, using an estimate of total precipitation at the mid-heights of 800 m and 1250 m. The main work presented here involves accurately estimating these averages and is different from the initial, simplistic ARUP model.

We provide two estimates. The first is a lower (conservative) limit and the second is an upper (optimistic) limit given the current data. Using work by McJannet et al [3], we used the data from Upper Barron (UB, 1050 m) and Bellenden Ker (BK, 1550 m) to calculate our estimates. BK is obviously relevant as it is situated in the catchment area and UB is deemed relevant because it represents an average height of the catchment, it is also exposed to the south-east and close-by (50 km). The next nearest site is 150 km to the north and not exposed to the same south-easterly prevailing winds. Therefore only the use of BK and UB data could be justified. We further elaborate below how the parameters were estimated; the results are presented in Table 1 for both the conservative and alternative values.

- The long term annual average rain gauge data near the top of Bellenden Ker is 8.2 m [4]. We estimate this to be 75% of total precipitation with the remaining 25% being due to cloud interception, a process that does not get captured by a rain gauge. This figure warrants extra explanation: research [3] has estimated that for the two cloudy south-easterly oriented sites at 1000 m (UB) and 1550 m (BK) the average annual precipitation due to Cloud interception for 2 overlapping 12 month periods was, BK: 30.1%, 21.2%, UB: 39.2%, 27.3%. We use 25% for the conservative limit and the observed average of 29.5% for the optimistic limit.
- A typical location at 1000 m receives about 70% of the precipitation amount at the top [5]. We use this information to calculate the total precipitation at 800 m and at 1250 m: we have a total precipitation of 8.2 m/75 * 100 = 10.9 m at 1550 m and the value at 1000 m is 0.7 * 10.9 m = 7.6 m. Using simple linear interpolation we get 9.1 m at 1250 m and 6.4 m at 800 m elevation. An alternative model uses liner interpolation of the Babinda (10 km to the SE) rainfall average of 4.2 m [4]. Using this model and 29.5% instead of 25.0% we get 10.2 m and 8.0 m which are used for the optimistic estimate.
- We assume that 1 m of total precipitation is lost to vegetation and other evaporation. The values given by McJannet [3] are 0.5 m at BK and 1.0 m at UB with an average of 0.75, used with the optimistic estimate.
- We calculate the flow in the driest month (October) from the stream-flow distribution data available for Behana Ck and the Mulgrave River at the Fisheries[1] (about 30 km downstream from the proposed intake). In those calculations we take precipitation due to cloud intercept into account according to the latest research [3]. We use 50% for the conservative value whereas the combined average of the 3 highest values (always during dry months) for both BK and UB is 58.3% which is used for the optimistic limit.

1.3. Calculations

Most calculations are rather trivial and the results for total precipitation and resulting annual stream-flow are simply presented in Table 1. Before the October average can be calculated we need to calculate the October

Table 1
The estimates and resulting flows (bold) for the conservative and optimistic limits.

	Conservative values	Optimistic values
Total % cloud intercept	25%	29.50%
Precipitation at 800 m	6.4 m	8.0 m
Precipitation at 1250 m	9.1 m	10.2 m
% Cloud I. in driest month	50%	58.30%
Loss due to evaporation	1 m	0.75 m
Cloud interception limit	1000 m/39.5%	~750 m/70% (SSE funnel)
Proportion Oct At	2.86%	3.95%
Total Annual Flow (%Fisheries)	122 337 ML (22.8%)	153 749 ML (28.8%)
Average flow/day (October)	113 ML	196 ML
40% Allocation	45 ML	78 ML

[1]Fisheries' is the name of the most up-stream gauging station in the Mulgrave River.

percentage of annual flow taking into account cloud interception [3]. The idea is to apply a measured distribution profile from 30 km further downstream to the location in question. The process of cloud interception removes water from the atmosphere by condensation on forest vegetation leading to through-fall and stem-flow that originates from 'cloud stripping' not rainfall. McJannet et al [3] have shown that up to 70% of all precipitation in one month can be the result of cloud interception. As a conservative rule of thumb cloud interception is assumed to happen upward of 1000 m although many mountains clearly less than that height are often shrouded in clouds. In our application of the distribution profile from 30 km downstream we need to account for the different amounts of cloud stripping terrain.

We wish to calculate the minimum flow F_{min} during the driest month (October). Let A% be the value for F_{min} where a catchment has no cloud stripping. Additionally we estimate that the cloud stripping proportion of the Mulgrave catchment above the fisheries is 7.5% (the calculations are not sensitive to this value). We further know that if all of a catchment is cloud stripping then the value A more than doubles, i.e. F_{min} is at least $2A$ as at this level at least 50% of total precipitation is due to cloud stripping [3]. For a catchment C_i which has a proportion k ($0.0 \le k \le 1.0$) of cloud stripping terrain the value for $A_i = (1.0 - k)A + k(2A) = A(1 + k)$. At the fisheries we estimate $k = 0.075$ and we can solve for A by using the observed value of 2.16%.

$$2.16 = (1.0 - 0.075)A + 0.075 * 2A$$
$$A = 2.01.$$

In our first model the conservative value A_t for the proposed tunnel intake is proportional to the catchment terrain above 1000 m (39.5%), in the optimistic model we assume cloud stripping on 70% of the terrain which we justify with its funnel shape which is exposed to the south-easterly prevailing winds. Table 1 summarizes the values used for both the conservative and optimistic estimates. The conservative value for the minimum October average daily stream-flow is: 0.0286 * 1 22 337/31 = 113 mega liters (ML). The numbers in table 1 were calculated as per the following examples.

$$A_t = (1.0 - 0.395) * 2.01 + 0.395 * 1.0/(1.0 - 0.50) * 2.01 = 2.86\%$$

$$P_{1250m} = (8.2/(1 - 0.295) - 4.2) \text{ m} * 1250/1550 + 4.2 \text{ m} = 10.2 \text{ m}$$

$$S_a = 11.47 \text{ km}^2 * (8.0 - 0.75) \text{ m} + 7.47 \text{ km}^2 * (10.2 - 0.75) \text{ m} = 1\,53\,749 \text{ ML}$$

1.5. Discussion—stream-flow analysis

The model depends on a number of estimates as discussed above and also on the accuracy of simplifications such as using two mid-heights. However visual inspection and comparison of the East Mulgrave River and Behana Creek confirm the relative numbers in a qualitative manner. There is no doubt that Behana creek due to its much larger catchment bears the scars of larger floods however the East Mulgrave due to its exposure catches all the south-south-easterlies in the dry season. The conclusion therefore is that the proposed East Mulgrave intake has a dry season capacity that is at least 10% larger than Behana creek intake and probably 50–100% larger. Actual numbers obtained are 113–196 ML per day in October, significantly more than Behana creek (103 ML).

The estimated totals are between 22% and 29% of the gauged water at the Fisheries. Therefore on an annual basis about a quarter of all water comes from the 5% catchment area above the intake. However 80% of that water flows in the first half of the year and 20% in the second half. Our model concludes that, because of cloud interception, about 1/5 (of 80%) comes from the intake area from Jan–Jun and about 1/2 (of 20%) from Jul–Dec.

2. Tunnel construction and costing model

In the worst case the predicted cost for a 45 ML (per day) water delivery from 2010–2030 is $47 million, about $1.1 million/ML. In the best case the cost is $4 million only, due to savings from electricity generation. The actual numbers largely depend on the ability of Cairns Regional Council to utilize the power generated. This compares with a projected cost of $64 million or about 1.5 million/ML for the Mulgrave WTP alternative [5].

2.1. Tunnel

ARUP has identified that with traditional methods the tunnel would cost between $20–35 million [5], we use $30 million. In our modeling we use the expected cost of traditional tunnel building as the worst case and the cost of a successful outcome using mining robots as the best case which we estimate at $22 million. However, as the tunnel is prototype development for robotic mining $10 million of that is factored in as Federal $–$ contribution (e.g. commercial Ready grant) and we arrive at a best case tunnel construction cost to council of $12 million.

2.2. Pipeline

We need a 3-fold capacity increase when compared to the costing given in the ARUP report [2], in our approximation model we assume this can be achieved with $\sqrt{3}$ flow speed increase and $\sqrt{3}$ increase in cross-section area. This requires a $\sqrt{\sqrt{3}}$ increase in pipe radius and strength, with a resulting increase-factor in steel of $\sqrt{3}$.

Therefore the new figures used in out-costing model are:

Pipes: $200–250/m becomes $346–$433/m, we need 30 km, makes $10 million in the best case and $13 million in the worst case. (Figures from 2006)

Installation: According to ARUP, installation would cost about $150/m inside the tunnel, makes 6300 m * $150 = approx $1 million for installation of the pipes in the 6.3 km long tunnel. From the tunnel exit to Gordonvale the cost per meter is given as $100/m, we use $125 as our worst case, 23 700 m * $125/m making about $3 million. We assume a best case where for example Ergon Energy and/or Telstra are also laying down some cable helping to share the cost, and from that a cost reduction to $40/m, i.e. approx $1 million for the best case.

So the total pipeline cost is modeled as $11–$16 million. Adding the 15–30% for control infrastructure [2] we get $12.6–$20.8 million, best and worst case. This includes the intake.

2.3. Delivery costs

From the CRC least cost planning document we know that chlorinating and filtering result in costs of $2/ML (only!). This does not include maintenance for which no accurate figures are available as it is performed by council staff as part of their general duties. Herein we assume $350/day for maintenance, making a cost of $12/ML for delivery and an annual cost of $0.18 million. Over 20 years this makes $3.5 million.

The delivery cost from a WTP depends on the amount of treatment required. CRC estimates that for a Barron river WTP this would be up to $197/ML, whereas for a Mulgrave aquifer WTP this would be about $115/ML for up to 38 ML. As we are comparing with the best alternative we use that figure to calculate the operating and maintenance cost of a WTP solution, resulting in $1.65 million per annum or $33 million over 20 years. The Least Cost Planning document puts the proportion of the electricity at 20% of cost, so the $33 million is split into $7 + $26 million. Note that these numbers agree with numbers given by the Winnipeg City Council for treating lake water [6].

2.4. Electricity

The ARUP calculates that with a 40 ML extraction 2.5 MW of power can be produced. In the worst case Council will get only wholesale prices for its power, about $0.3 million/year [4]. In the best case CRC can use the power itself for WTP and pumping stations, potentially saving up to $2.0 million/year.

Therefore, for electricity over 20 years we expect in the worst case return of $6 million, in the best case return of $40 million.

2.5. Power Station

We have reliable statistics about the sizes, distribution and cost of similar power stations throughout Australia [7].

From Table 2 [7] we can estimate our cost, note that at 2.5 MW the power station would produce about 22 GWh/year. Only three (3) out of 30 considered projects listed there would produce more electricity. The table represents "sites in the SEDA report for which a hydro installation was considered viable" [8,p.18]. The other relevant table [17,p.16] and lists actually installed projects and their sizes, but not their costs. In that table, 8 sites are larger (produce more GWh/year) and 12 sites are smaller than the power station proposed at the water tunnel.

It is stated that usually the turbine-Generator pair is imported and makes up about 30% of the cost. To estimate the power station cost we use selected entries

Table 2
Cost estimation[a,b].

Place	Capacity (MW)	Cost ($ million)	Cost/MW
Berembed Weir	1.6	4	2.5
Cochrane	2.1	2.7	1.3
Euston	3.4	6.2	1.8
Hay Weir	2.6	4.7	1.8
Maude Weir	2.2	4.8	2.2
Pindari	2	2.7	1.4
Redbank Weir	1.8	4.1	2.3
Scrivener	1.5	2.2	1.5
Rorrumbarry	2.8	5	1.7

[a]Using the Table on page 18 of the Greenhouse Office paper [7].
[b]Shown are the selected entries round the same size (2.5 MW).

Table 3
A summary of costs[a].

Costing item/project	EM-WI worst case	EM-WI best case	WTP best case
Tunnel ($ million)	30	12	0
Pipeline ($ million)	16	11	0
Delivery	4	3	26
Electricity	−6	−40	7
Power Station	5	3	0
WTP	0	0	31
Total Cost to 2030 ($ million)	49	4	64
Capacity (ML)	45	45	35
Cost per ML ($)	1.10	0.60	1.80

[a]For the worst case tunnel scenario, best case tunnel scenario and the cheapest option being pursued by Cairns Regional Council, the Gordonvale WTP.

Table 4
Comparing the tunnel with WTP options[a].

		Bellenden ker tunnel option	Water treatment plant (WTP) options 1 mulgrave aquifer & 2 lake placid
Project Basics	Parties involved	PIA Pty Ltd, JCU Student Union (ARUP, 20/20 Group)	CRC, GHD and many more
	$ so far	$30 000 (in part COMET grant)	$1 500 000 (approx)
Project Description	Drinking Water Produced	Stream abstracted 40 ML /day Behana ck type intake	1&2 A Water Treatment Plant produces 40 ML/d
	Water source	At 600 m at the East Mulgrave River	1 Pumped below sea level 2 Tinaroo vi Barron river
	Infra-structure	Tunnel (6.5 km), power station (PS) and 30 km pipeline to grid	1 Bore-field & pumps WTP to grid
	Quality of Input Water	Unpolluted Rainforest Stream	1&2 Polluted by farm, industrial and private run off or water use
	Treatment Required	Filtration and Chlorination (e.g. Behana Creek)	WTP using Membranes and reverse osmosis processes
Environment Issues	Electricity/year	Approx $2 million worth of hydro electricity produced by PS	Approx $0.5 million coal fire electricity consumed by WTP
	Operational CO_2 Impacts	Positive due to large CO_2 savings from green electricity	*Negative* due to the CO_2 impact and the cost of maintaining a WTP (overseas parts?).
	Water extraction Impacts	Reduced stream-flow (2–20%) and less water (2–5%) for aquifers (Fisheries onwards)	1 Reduction of water table at the bore-field with water extracted from below sea level
	Potential effects on Natural Balance	Minimal effects: Water abstraction mimics the natural variation and use of Lake Morris to cover driest months	1 Significant as a bore-field does not mimic natural variation leading to salt intrusion and land degradation
Social	Dis-advantaged groups		1 Cane farmers (salt intrusion) 2 Table Land farmers Food consumers
	Relevant Legislation	Environment protection laws CO_2 reduction targets	Zoning laws CO_2 reduction targets
Approximate Costs	Annual Operational Cost	$0.2 million	$2 million
	Annual Revenue/Savings	$2 million (hydro-electricity)	
	Estimated Building Cost	$50 million	$50 million
	Total Cost over 25 years	$5 million	$100 million

[a]To aid comparison we have used numbers which are 'round' and approximate but entirely reasonable and within the current range of best estimates.

from table 2. The selection is decided on the column, listing the capacity of the power station. We selected a capacity range of 1.5 to 3.5 MW to estimate the cost of the planned 2.5 MW-power station. The selected entries are shown in Table 2 above. Using those entries we arrive at an average cost/MW of $1.8 million. Therefore our estimate of the cost for our 2.5 MW-power station is about $4 million. We use $3 million for the best case and $5 million for the worst case.

2.6. Mulgrave WTP

Council has estimates that construction of a WTP and associated bores will cost $21.86 million for stage 1 and $9.17 million for stage 2, with each stage delivering 19–25 ML. We use $31 million as the cost in our comparison. This is the cheapest alternative solution listed in the least cost planning document for the initial additional water supply of between 35 M and 50 ML, corresponding to the amount that can be sourced using the proposed water tunnel.

2.7. Cost summary

Table 3 summarizes costs associated with delivery of 35 ML–45 ML/day over 20 years, (i) worst case and (ii) best case for the water intake and also the (iii) WTP.

It is also worth mentioning that the intake, water tunnel and pipelines have an expected lifespan that exceeds that of the WTP.

3. Discussion—environmental impact

The sites of tunnel entry and exit are in State Forest (~640 m) and on private land (~50 m). We argue that what determines environmental impact in the presence of large natural variability is the size of extraction during the driest months. In this regard Copperlode Dam[2] (Lake Morris) is important to ensure the East Mulgrave is only marginally affected by a potential intake. Apart from that, let us average our conservative and optimistic values to 150 ML then extracting 30 ML during October would only represent 20%, half the recommended upper limit of 40%. Taking 40–50 ML during other times would be well below 20% of stream-flow.

Other important aspects are Cairns Regional Council's CO_2 reduction targets which some claim could be as high as 40% by 2025. Generating hydroelectric power goes a long way to achieving such targets while building a WTP may make it near impossible to reduce emissions. In this respect one could build extra capacity for hydro-electricity generation in the wet season.

As this paper is being submitted events are unfolding in Cairns regarding the next water source with the perception that using the Mulgrave Aquifer is the cheapest option. However recently newspaper articles have pointed out that in Bundaberg, Mackay and the Burdekin pumping from the aquifer has damaged cane production. "It knocks the production of Cane around dramatically" (*Cairns Post*, 2009). It is not surprising that this should be the case where bore-fields are used to directly draw from an aquifer but can it occur for the tunnel-intake proposal? For the stream the main effect of an intake is reduced flow-rate not water height. In terms of the East Mulgrave, after the proposed intake location it descends about 500 m in about 5 km just before it joins with the 'West Mulgrave' and therefore flow rates are well and truly up in any case.

With aquifers the reduced stream-flow can lower the water table which relies on excess stream water to be refilled. The Mulgrave River is flanked by steep banks most of the time before reaching the gauging station at the Fisheries. At the gauging station we know the average daily stream-flow for October is 373 ML. There are minimal aquifers upstream from the Fisheries at which point a hypothetical extraction of 40 ML is 10.7% of driest month average volume, nearly four times less than the 40% threshold at which impact is deemed unacceptable. Further downstream the effect is even smaller and importantly is shared by all aquifers. Therefore no significant local lowering of the water table should occur and salt intrusion can be avoided. The main impact is on flow-rates (up to 20% less) of the East Mulgrave below the intake.

Table 4 summarizes the benefits and drawbacks of the Tunnel Intake and WTP options. Note that the most recently quoted costing figures regarding the WTP options state a minimum of $161 million [8] but it is unclear what time frame this applies to. In that light our use of $100 million for 25 years in table 4 is more than fair on the WTP options. The cost of the tunnel, power station and pipeline infrastructure is based mainly on the estimates by ARUP consulting [3].

4. Summary—environmental and social impact

A water intake mimics natural variation but a borefield does not, therefore the latter will more likely disturb the balance and lead to land degradation. A sensible intake of water has no significant effect on the river and aquifers, when compared to natural variation. The tunnel approach means forest disturbance is kept at a bare minimum. When CO_2 reductions are factored in the advantages of an intake from an environmental point of view are compelling.

Socially the tunnel and intake option pose no threat to farmers and potentially the tunnel can double as a cyclone shelter. Last but not least it is clear that over time the tunnel and intake option are far less expensive and strategically make Cairns less dependent on energy and parts produced down south or overseas.

The main points are presented in Table 4.

Acknowledgement

We thank Dr David McJannet who by fortunate coincidence had been researching hydrology within the catchment area. It is due to his work that it is possible to establish the minimum stream-flow with considerable confidence.

[2]Copperlode Dam also known as Lake Morris is Cairns' primary water storage facility (~45GL).

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