Response to feedback to FLAG by Broughton re Stewart/Thomas 2008 Model

Stewart and Thomas (2008) presented a model describing inputs and outputs to the Arthur Marble Aquifer (AMA) and in particular to Te Waikoropupu Springs in their Table 4. The model was based on a careful assessment of flows to and from the AMA including work by previous workers and more current hydrological work by the Tasman District Council, and work by GNS Science on the oxygen-18 mass balance. Andrea Broughton of Groundwater Solutions International in her Comment on the Takaka FLAG report (Appendix 1 in Broughton, 2017) pointed out that the oxygen-18 mass balance model was non-unique. She presented an alternative solution that also matched the water flows and oxygen-18 values in the springs. Having discussed our earlier work with Joseph Thomas, this is my response to Broughton's comment.

Broughton noted that there were three degrees of freedom for each spring (the three contributing recharge sources) and only two constraints (the water flows and the oxygen-18 values) in the original oxygen-18 mass balance model. However, the original model was also consistent with chloride measurements (shown in Figure 5b and Table 6 of Stewart and Thomas, 2008), which were effectively acting as a third constraint. To make this more explicit, the model has now been extended to include chloride concentration measurements as well as the water flows and oxygen-18 measurements used before. This change allows a unique best solution to be found by optimising the matches (i.e. minimising the differences) between the calculated and measured quantities for the Main and Fish Springs. The overall standard deviation of the differences is used for optimisation. The results of this optimised model are given in Table 1 (as a spreadsheet with underlying equations).

This optimised model closely reproduces the flows, $\delta^{18}O$ values and chloride concentrations of both the Main and Fish Springs. The solution is unique because the $\delta^{18}O$ values are particularly sensitive to the amount of Upper Takaka River reaching the springs, while the chloride concentrations are most sensitive to the amount of karst uplands water. The optimised model differs only slightly from the original model given in Table 4 of Stewart and Thomas (2008). The latter (in Table 2) matches the $\delta^{18}O$ values, but does not quite match the chloride concentrations.

Table 1: Optimised model of water flows within the Arthur Marble Aquifer (measured values are shown in blue and green). The contributions from the three recharge sources to each spring (yellow) were adjusted to minimise the differences between the calculated (pink) and measured (green) flows, $\delta^{18}O$ values and chloride concentrations of the Main and Fish Springs.

			Flows			
Recharge Source	$\delta^{18}O$	**Cl**	**Inputs**	**Main Spring**	**Fish Springs**	**Remainder**
	‰	**mg/L**	**L/s**	**L/s**	**L/s**	**L/s**
Karst uplands	-7.20	124	9,200	7,624	649	926
Upper Takaka River	-8.67	2	8,350	1,741	1,735	4,875
Valley rainfall	-6.00	2	2,200	635	916	649
Total flows (L/s) calculated				10,000	3,300	
Total flows (L/s) measured			19,750	10,000	3,300	6,450
Differences				0.0	0.0	
$\delta^{18}O$ (‰) calculated				-7.38	-7.64	
$\delta^{18}O$ (‰) measured				-7.38	-7.64	
Differences				0.00	0.00	
Cl mg/L calculated				95.0	26.0	
Cl mg/L measured				95.0	26.0	
Differences				0.0	0.0	
Overall standard deviation of differences =						0.0

Table 2: Original model of water flows within the Arthur Marble Aquifer (AMA) (Table 4 in Stewart and Thomas, 2008).

			Flows			
Recharge Source	$\delta^{18}O$	**Cl**	**Inputs**	**Main Spring**	**Fish Springs**	**Remainder**
	‰	**mg/L**	**L/s**	**L/s**	**L/s**	**L/s**
Karst uplands	-7.20	124	9,200	7,400	830	970
Upper Takaka River	-8.67	2	8,350	1,850	1,650	4,850
Valley rainfall	-6.00	2	2,200	750	820	630
Total flows (L/s) calculated				10,000	3,300	
Total flows (L/s) measured			19,750	10,000	3,300	6,450
Differences				0.0	0.0	
$\delta^{18}O$ (‰) calculated				-7.38	-7.64	
$\delta^{18}O$ (‰) measured				-7.38	-7.64	
Differences				0.00	0.00	
Cl mg/L calculated				92.3	32.7	
Cl mg/L measured				95.0	26.0	
Differences				-2.7	6.7	
Overall standard deviation of differences =						3.6

With the optimised model (Table 1), flows in the Arthur Marble Aquifer are only slightly different from before, with now 76% from the karst uplands, 17% from Upper Takaka River and 6% from valley rainfall. Fish Creek Spring now has 20% from karst uplands, 53% from Upper Takaka River and 28% from valley rainfall. The same proportion as before of the Upper Takaka River contribution (58%) must still bypass the Te Waikoropupu Springs and be discharged via offshore springs and seeps.

Table 3 shows the alternative solution presented by Broughton (2017) in her Appendix 1 (which was given as an example of the non-uniqueness of the Stewart and Thomas (2008) Table 4 model). This indeed matches the $\delta^{18}O$ values, but fails badly to match the chloride concentrations, and therefore is not a feasible model for the AMA.

Table 3: Broughton alternative model of water flows within the Arthur Marble Aquifer (AMA) (from Appendix 1 in Broughton, 2017).

				Flows		
Recharge Source	**$\delta^{18}O$**	**Cl**	**Inputs**	**Main Spring**	**Fish Springs**	**Remainder**
	‰	**mg/L**	**L/s**	**L/s**	**L/s**	**L/s**
Karst uplands	-7.20	124	9,200	6,438	2,299	463
Upper Takaka River	-8.67	2	8,350	2,276	990	5,085
Valley rainfall	-6.00	2	2,200	1,287	11	903
Total flows (L/s) calculated				10,000	3,300	
Total flows (L/s) measured			19,750	10,000	3,300	6,450
Differences				0.0	0.0	
$\delta^{18}O$ (‰) calculated				-7.38	-7.64	
$\delta^{18}O$ (‰) measured				-7.38	-7.64	
Differences				0.00	0.00	
Cl mg/L calculated				80.5	87.0	
Cl mg/L measured				95.0	26.0	
Differences				-14.5	61.0	
Overall standard deviation of differences =						31.3

The addition of chloride to the model removes the one degree of freedom of the original Table 4 model referred to by Broughton, 2017. The model cannot now be freely altered. The only way the model can change is by changing the inputs and outputs (which are themselves best estimates based on measurements).

The model represents an average situation, i.e. it is steady-state rather than transient. In this sense, it is conceptual rather than realistic, and its purpose was to show in general how the system works on average. More sophisticated modelling would require transient models.

References

Broughton, Andrea 2017: Comment on the Takaka FLAG “Summary of Interim Decisions for Water Quantity and Quality Management in the Takaka Freshwater Management Unit”.

Stewart, M.K., Thomas, J.T. 2008: A conceptual model of flow to the Waikoropupu Springs, NW Nelson, New Zealand, based on hydrometric and tracer (^{18}O, Cl, ^{3}H and CFC) evidence. *Hydrology and Earth System Sciences 12*(1), 1-19. http://www.hydrol-earth-syst-sci.net/12/1/2008/hess-12-1-2008.html

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