BEFORE CANTERBURY REGIONAL COUNCIL
AT CHRISTCHURCH

In the matter of	the Resource Management Act 1991
And	
In the matter of	Proposed Variation 2 to the Proposed Canterbury Land and Water Plan
And	
In the matter of	a submission by Te Rūnanga o Ngāi Tahu

STATEMENT OF EVIDENCE OF M.D. GOFF
ON BEHALF OF TE RŪNANGA O NGĀI TAHU
Dated 15 May 2015

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INTRODUCTION

Qualifications and Experience

1. My full name is Michael David Goff. I am an Associate - Hydrogeologist employed by the multidisciplinary consulting firm Beca Limited. I have some 29 years' experience in the field of hydrogeology.

2. I am a graduate of Western Michigan University with a Bachelor of Science degree majoring in Geology awarded in 1986.

3. My work at Beca has involved technical and managerial roles in groundwater related projects including water resource development, catchment surface and groundwater assessment, saline intrusion monitoring and consent compliance for large water utilities.

4. Previously, I have worked at Schlumberger Water Services in the USA, Saudi Arabia and the United Arab Emirates, the Las Vegas Valley Water District/Southern Nevada Water Authority, Boyle Engineering Corporation and Missimer & Associates Inc. in the USA. Of particular relevance is my experience with the Southern Nevada Water Authority as Technical Manager of the largest artificial recharge programme in North America at that time, while working there from 1994 to 2007.

5. In the course of my work, I have provided technical management of the Las Vegas Valley Artificial Recharge Program which has banked nearly 475 million cubic metres of water in the Las Vegas Artesian Basin. I have also conducted feasibility, pilot studies and programme development for artificial recharge schemes including those in Florida, California, Abu Dhabi Emirate and the Kingdom of Saudi Arabia.

6. Managed Aquifer Recharge (MAR) is the application of technology to increase the natural rate of recharge and the volume of stored water of an aquifer and/or improve water quality through natural aquifer treatment processes. MAR is a powerful water resource management tool that has been successfully implemented in many locations around the world. Success of MAR depends on many factors including establishing appropriate and attainable goals, proper planning, suitable geology and hydrogeology, availability of surplus water and availability of aquifer storage capacity.

Code of Conduct for Expert Witnesses

7. I confirm that I have read and am familiar with the Code of Conduct for expert witnesses contained in the Environment Court consolidated Practice Note 2011. I have also read the Code of Conduct for expert witnesses contained in the recently released Environment Court Practice Note 2014. I agree to comply with those Codes. Other than where I state that I am relying on the evidence of another person, my evidence is within my area of expertise. I have not omitted to consider material facts known to me that might alter or detract from the opinions that I express.

Scope of Evidence

8. I have been asked by Te Rūnanga O Ngāi Tahu to give evidence about the Hinds Plains proposed Managed Aquifer Recharge (MAR) scheme.

9. My evidence addresses the proposed use of MAR as set out in the following reports:

   (a) Managed Aquifer Recharge (MAR) as a tool for managing water quality and quantity issues. Report No. R14/80, ISBN 978-1-927314-41-8, 2014

   (b) Hinds plains water quality modelling for the limit setting process, Report No. R13/93, ISBN 978-1-927274-37-8, 2013

   (c) Integrated catchment modelling of the Hinds Plains Model development and scenario testing Report No. R14/64, ISBN 978-1-927314-06-7 2014

   (d) Economic impact assessments of the Hinds water quantity and quality limit setting process, Report No. R14/82, ISBN 978-1-927314-47-0, June 2014

Background

10. Managed Aquifer Recharge (MAR) is the application of technology to increase the natural rate of recharge to increase the volume of stored water and/or improve water quality through natural aquifer treatment processes. MAR can be implemented with a variety of goals in mind including storage of water for later extraction and use by the project owner, storage of water to the benefit of other users, recharge of water for environmental benefit and recharge of water for treatment by natural processes occurring within the

aquifer. These goals are not all inclusive and can be further refined and in some cases combined to meet multiple goals. MAR of recycled wastewater to replenish an aquifer and benefit groundwater users is one example.

11. MAR does not work in all situations. Several criteria must be met in order for MAR to be a feasible approach. There must be room in the aquifer for storage of the water. In an unconfined aquifer this means that groundwater levels must be deep enough below land surface to allow storage of the water. If water rises above land surface it is lost to runoff or evaporation and causes environmental and social/infrastructure problems by water logging the affected area. In a confined aquifer the water must be recharged at a head greater than the aquifer hydraulic head[1]. MAR water will displace aquifer water and increase hydraulic head within the aquifer. Depending on the situation this could cause wells and dry springs to flow which can be problematic in some areas such as urbanized areas where buildings have been constructed over the previously dry springs.

12. The aquifer transmissivity[2], or ability of the ground to transmit water must be high enough to allow the recharge water to enter the aquifer system whether through surface application such as ponds and infiltration galleries or through injection wells.

13. In some cases the transmissivity is too high. If the transmissivity is too high, the water may not be available for later recovery because it may be lost to mixing with lower quality groundwater or travel away from the intended storage area. High transmissivity may also limit or disallow the increase of hydraulic head in the aquifer. If the transmissivity is too high and the water moves away from the intended storage area there will be no increase in water levels, or hydraulic head, within the aquifer. The transmissivity must be appropriate for the goals set out for the project.

14. Aquifer geometry must also be appropriate for the goals set out in the project. An aquifer with high transmissivity that is open to the sea is unlikely to meet the goals of storing water for later extraction or raising groundwater levels for environmental benefits requiring higher groundwater levels. The water will flow away from the area of intended benefit, and increased storage and water levels will be temporary, likely occurring only during recharge operations.

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[1] Hydraulic Head - The height above a datum plane of a column of water. In a groundwater system, it is composed of elevation head and pressure head (WSP 2220, USGS 2004)

[2] Transmissivity is the rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. It equals the hydraulic conductivity multiplied by the aquifer thickness (WSP 2220, USGS 2004)

15. Water for recharge must be available in sufficient quantity and have suitable water quality to meet the goals of the project. MAR is very useful for seasonal or long term storage and has flexibility to accommodate seasonal variations in recharge flow in many cases. Some applications require a consistent recharge schedule to maintain conditions created within the aquifer. MAR for control of saline intrusion is an example of an approach requiring consistent addition of recharge water.

16. The quality of MAR water must be compatible with the aquifer materials and receiving waters of the aquifer. Chemical reactions between recharge water and aquifer materials and/or aquifer water can have undesirable results such as precipitation of minerals resulting in reduction of hydraulic conductivity. In some cases recharge water has resulted in the mobilization of arsenic from geological materials in which it was held, resulting in undesirable water quality in the aquifer. Geochemical modelling can be used to predict possible reactions between recharged water and the receiving environment.

17. MAR projects have been successfully planned and implemented with the goal of storing high quality water in aquifers of lower water quality for later extraction and use. Although the recovery is typically not 100% of the water recharged, the projects are successful when compared to other options for storage of the water. For example at least 6 sites have been operating in the State of Florida, USA for over 5 years successfully storing freshwater in a brackish water aquifer[3].

18. There are examples of water of higher quality (including treated wastewater) being used to replenish aquifers by raising aquifer water levels. The goal of this approach is to increase water levels and groundwater storage and to not adversely affect groundwater quality. The recharged water is mixed with the aquifer water until it cannot be chemically distinguished when it reaches the extraction wells.

19. I do not know of examples where the goal has been to use higher quality water to improve the water quality within an aquifer of poor quality water as is proposed here for the remediation of nitrates. In my experience I have not seen high quality recharge water used to dilute poor quality groundwater. I believe that in most cases the volume of water required to dilute an aquifer would be too great to be cost effective and may ultimately be unsuccessful.

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[3] Water Quality in Aquifer Storage and Recovery (ASR) Wells, R. David G. Pyne, P.E., 2003

Water Balance

20. When recharge results in an increase in hydraulic head within the aquifer, the increase propagates down-gradient of the recharge area. Increase in hydraulic head occurs down gradient from the recharge area as a pressure response which moves faster than groundwater flow. Figure 3[4] (below) indicates that MAR will increase spring flow as a result of increased hydraulic head in the aquifer. An increase in hydraulic head in the aquifer will also increase discharge to the ocean. Raising hydraulic head up-gradient will raise hydraulic head down gradient. Increased hydraulic head at the foot of the basin will increase flow to the ocean. This increase is not apparent in the graphical representation.

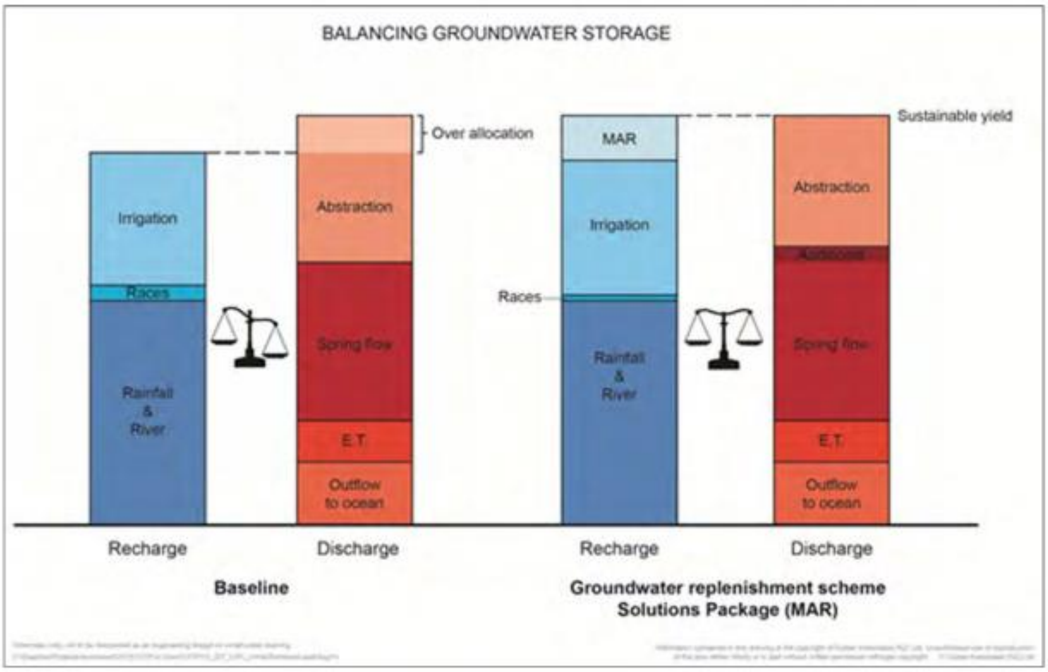

Figure 3: Contrasts in the water balance of a catchment, showing the effectiveness of MAR.

21. Preparation of a groundwater budget should balance known or estimated inputs with outputs. Measured or carefully estimated inputs and outputs are required to utilize the budget for planning and determination of goals for the project. Large inaccuracies in the water budget results in errors in assessment of the water balance for the catchment which can lead to poor selection of methods to balance the water budget. Table 3[5] (below) entitled *"Analytical steady-state groundwater budget for the Hinds/Hekeao Plains"* shows large variations in outputs of Coastal Drains, Groundwater Abstraction and Offshore Groundwater flow. These variations amount to 45% of the total

[4] Managed Aquifer Recharge (MAR) as a tool for managing water quality and quantity issues. Report No. R14/80
[5] Managed Aquifer Recharge (MAR) as a tool for managing water quality and quantity issues. Report No. R14/80

output from the groundwater budget. These values can be interpreted to show there is a large surplus or deficit of water in the groundwater system. For example taking the total of the average inputs as stated at 20 m^3/s and the lower end of the range of average outputs, which totals 15.5 m^3/s, results in a surplus of 4.5 m^3/s. Taking the upper end of the range of average outputs results in a deficit of 4.5 m^3/s. This range totals 45% of the balance which is a significant uncertainty.

22. Within the narrative of the report describing this table[7] it states that the offshore discharges of groundwater are calculated by balancing the other measured components. I suggest that estimation of offshore discharge using groundwater gradient and estimates of hydraulic conductivity should be used to check the reliability of such an approach. Coastal drains and groundwater abstraction have a wide range in the estimates provided and may benefit from more detailed analysis. In my opinion, the estimates for planning must be more accurate for a MAR project of this size and importance.

Table 3: Analytical steady-state groundwater budget for the Hinds/Hekeao Plains.

Average inputs (m^3/s)		**Average outputs (m^3/s)**	
Land surface recharge (1)	15.5	Coastal Drains	3.0 – 7.0
River recharge		Groundwater abstraction	3.0 – 7.5 (2)
▪ Rangitata River	<1	Discharge to Rangitata River	0.3
▪ Hinds/Hekeao River	0.3	Offshore groundwater flow	9.2 – 9.7
▪ Ashburton River/Hakatare	1		
Water race losses	3.2		
Total inputs	20	Total outputs	20

Notes: 1) LSR = (precipitation + irrigation – evapotranspiration – run-off).
2) Maximum possible abstraction is 7.5 m^3/s averaged over a year, 2011/2012 consumption is approximately 40 %.
Source, Durney (2014).

MAR Goals and Targets

23. Goals and targets for MAR schemes are very important and provide key criteria for design and measures of success or failure. In following paragraphs, I provide some comments on the goals[6] set out for the project.

b) Manage groundwater storage levels to maximise base flows to spring-fed water bodies while minimising drainage issues.

24. I agree that this is an important goal and must be carefully thought out and refined throughout the process. In my opinion, analysis of detailed groundwater level data across the project area must be coupled with

6 Managed Aquifer Recharge (MAR) as a tool for managing water quality and quantity issues. Report No. R14/80

evaluation of the influence of recharge and discharge. Balancing groundwater levels to provide spring flow while not creating drainage issues is a complex and delicate matter especially within an unconfined aquifer. The MAR report[7] has not detailed how groundwater storage levels will be managed and how drainage issues will be minimized. In my view a significant monitoring effort will be required, over as long a period as feasible (minimum 24 months) prior to implementation and throughout operations, to accomplish this goal.

c) Manage groundwater dilution to ensure the nitrate-N goal of 6.9 mg N/L is achieved, while targeting specific land use activities and / or known hot spots.

25. In determining problem areas, clear and reliable data must be available for the decision making process. In the MAR report[8], Figure 25 shows variations in Nitrate concentration from "low to high". Numerical values are needed here to assess where the critical areas are located. Low to high is subjective and may lead to application of remediation technologies in areas that do not warrant attention.

26. Furthermore, modelling of the groundwater system as a mass dilution situation is unrealistically simplistic. Geochemical and mixing models simulate interactions of recharge water with aquifer materials and aquifer water quality as well as factors of dispersion and density flow. In my opinion, the modelling of water quality effects requires a more sophisticated approach that considers the physical and chemical interactions of the recharge water with that present within the aquifer.

27. MAR requires room within the aquifer for the volume of water being recharged. The "high" nitrate areas, shown in Figure 25, correspond to the shallow water level areas shown in Figures 26 and 27[9]. MAR, within an unconfined aquifer, requires an unsaturated zone to be successful, as pointed out in Sec 2.4 page 12 of the same report. In my opinion, application of additional recharge to unconfined aquifers with water levels near land surface may lead to water logging and consequent damage to infrastructure and crops, in addition to not meeting the planned recharge quantities and project goals.

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[7] Managed Aquifer Recharge (MAR) as a tool for managing water quality and quantity issues. Report No. R14/80.
[8] Managed Aquifer Recharge (MAR) as a tool for managing water quality and quantity issues. Report No. R14/80
[9] Managed Aquifer Recharge (MAR) as a tool for managing water quality and quantity issues. Report No. R14/80

28. MAR requires sufficiently high transmissivity to enable the recharge to occur at the required rates as stated in Sec 2.4 pg 12[10].The "high" nitrate areas, shown in Figure 25, also correspond to areas of low hydraulic conductivity as shown in Figure 28 of the same report. Application of additional recharge directly to or up-gradient of areas of low permeability aquifer materials may result in fresh water by-passing the area of poor quality aquifer water by taking a higher transmissivity path, the path of least resistance.

d) Real time monitoring of recharge operations and groundwater conditions with key measures of flows and drainage.

29. In addition to monitoring of the quantity and quality of water recharged under this scheme, a significant groundwater monitoring programme should be anticipated for this project. Required groundwater monitoring will likely include a network of monitoring wells at multiple depths located up and down gradient of recharge facilities. Data collected at these monitoring wells will include real-time water level and scheduled sampling of water quality. These data will be critical in operations of the recharge volumes, schedules and locations. Based on conditions within the aquifer the location and volumes of recharged water may need to be adjusted. Establishment of MAR to sites spread across the project area will further complicate the monitoring and increase costs. It is not clear in the discussion on costs of the programme what level of monitoring was considered. Monitoring should be conducted in dedicated bores prior to final MAR design to better assess water level, flow and quality conditions as discussed in paragraph 24 of my evidence. These bores can then be used during operational monitoring.

f) Use of catchment-scale modelling (MIKE SHE) to test the suitability of recharge sites, as a tool to extrapolate pilot test results into catchment scale context, and to help provide predictive information relative to recharge operations and seasonal water level changes.

30. The Hinds Plains geology consists of coalescing alluvial fan deposits that are characteristically heterogeneous and anisotropic. The resulting groundwater flow system is complex in that down gradient flow will be greatest, in terms of volume and velocity, in buried channel deposits that meander as did the streams and rivers that deposited these materials. Representing these variations in hydraulic conductivity in a numerical flow model must be

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[10] Managed Aquifer Recharge (MAR) as a tool for managing water quality and quantity issues. Report No. R14/80

carefully considered. The modelling report[11] describes a model that is oversimplified with reference to vertical and horizontal heterogeneity of the aquifer system. The Figures in Appendix 4 and 5 do not follow well with the hydrogeological system described in the MAR report[12]. Buried channel geometry is not apparent and a significant number of observed transmissivities differ dramatically from those used in the model zonation (Figure A4-2). Extrapolating pilot study results to catchment scale is not likely to be representative based on the current model. The conclusions drawn from using the current model, even after consideration of pilot study results, will be flawed as the model does not appear to provide a reasonable representation of aquifer conditions.

Design

31. Design of a pilot test and full scale MAR requires careful planning with a solid understanding of the hydrological and hydrogeological system being augmented. The narrative on design[13] is a collection of issues which are not fully addressed and does not present a conclusion on a preferred design. The approaches considered include large recharge facilities in areas of deep groundwater and small facilities in areas of nitrate issues. These approaches conflict with each other in that raising water levels throughout the basin is likely to increase spring flow but may also increase nitrate loading.

32. Increasing spring flow from a nitrate laden groundwater source could result in a greater total load. Attempting to raise water levels in high nitrate areas is not envisioned to be successful because these areas correspond to shallow water levels, particularly in the winter months when recharge water for MAR is most likely to be available.

33. The concept of diluting nitrates by nearby recharge is further handicapped by the lack of understanding of the complexities of mixing of recharged water within the aquifer, and the influence of low hydraulic conductivity in “high” nitrate areas, and subtleties of spring geometry and travel paths and times. These specifics are not addressed in the “whole bucket” mixing model utilized.

34. In most MAR systems, surplus water is stored within aquifers for later use or other benefits. Surplus surface water in the Hinds/Hekeao Plains is available

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[11] Integrated catchment modelling of the Hinds Plains Model development and scenario testing Report No. R14/64
[12] Managed Aquifer Recharge (MAR) as a tool for managing water quality and quantity issues. Report No. R14/80
[13] Managed Aquifer Recharge (MAR) as a tool for managing water quality and quantity issues. Report No. R14/80

during the wet winter months. The MAR report[14] states that "One rule of thumb for MAR site placement is to ensure that the baseline depth-to-water in rural areas is more than 4 m to avoid flooding and lateral movement of groundwater mounding (AGWR 2009)". Looking at winter water levels (Figure 26) and nitrate monitoring results (Figure 25), in the same report, it becomes apparent that few if any areas close to nitrate affected areas offer water level conditions that will meet this "rule of thumb".

35. Raising hydraulic head in a coastal aquifer will increase hydraulic head at the saltwater interface, and increase discharge to the ocean. The MAR report[15] indicates that "*Although a small increase in offshore groundwater discharges should be expected, this increase is proportionally much smaller than the increases to spring-fed water body discharges. This is because the speed of water moving deeper through the saturated flow pathway in the groundwater system is constrained significantly by lower permeability and slower flow velocities*." In my view, this line of thinking ignores the effect of hydraulic connectivity and pressure effects within the aquifer. If head levels in the upper basin increase, then the heads at the shoreline will also increase which increases ocean outflow. The converse would show that declining heads up gradient will reduce the head at the saltwater interface, potentially resulting in seawater intrusion.

Costs

36. I agree with Section 5.4 of the MAR report[16]" in that the viability of the MAR solution requires consideration of cost. This section presents high level estimates of cost. In assessing even high level costs some detail on what is being proposed must be presented. The discussion indicates that large scale recharge facilities as well as small scale facilities are being considered. Without a quantity of either of these facilities or a rough idea of location it is not possible to determine even a high level estimate.

37. In developing a cost for MAR it is necessary to include those costs that would not otherwise be necessary if MAR is not implemented. For instance scientific studies, groundwater modelling of MAR options and maintenance costs required to rehabilitate a recharge basin periodically in order to maximise infiltration. These costs would not be required in other

[14] Managed Aquifer Recharge (MAR) as a tool for managing water quality and quantity issues. Report No. R14/80
[15] Managed Aquifer Recharge (MAR) as a tool for managing water quality and quantity issues. Report No. R14/80
[16] Managed Aquifer Recharge (MAR) as a tool for managing water quality and quantity issues. Report No. R14/80

approaches. The MAR report[17] does not consider these and other costs specific to MAR.

38. No details on the basis for cost estimation is given further than "*These estimates were based on a recharge goal of 4.0 m³/s, using both large-scale infiltration basins (flagship sites) and smaller distributed galleries (to target water quality objectives*)". The difference in costs between a few large sites and numerous small sites will be significant in construction and operation.

39. Cost estimates in each case should include capital costs[18]:

- Land;
- Testing costs, long term monitoring of water quality and level, feasibility analyses;
- Consulting services for the design, permitting, and supervision of the construction;
- Construction costs (e.g., roads, piping, instrumentation, controls, and pre-treatment systems); and
- Regulatory testing requirements during construction and operational testing.
- Cost estimates should also include operation and maintenance costs:
- Labour (system operation, regulatory requirements, administration);
- Electricity;
- Consulting services;
- Regulatory testing requirements (e.g., water level monitoring and water quality testing);
- Maintenance costs (e.g., parts replacement, well and basin rehabilitation);
- Pre-treatment costs (additional treatment prior to recharge);
- Post-treatment costs (e.g., chlorination); and

[17] Managed Aquifer Recharge (MAR) as a tool for managing water quality and quantity issues. Report No. R14/80
[18] Economics of Managed Aquifer Recharge, Robert G. Maliva, ISSN 2073-4441, www.mdpi.com/journal/water, May 2014

- Raw water costs.

40. While all of these elements of cost do not apply in all cases, the cost estimates for Hinds/Hekeao Plains have not included some significant elements including the studies and monitoring needed to plan and design the system and operational issues. The discussion is not specific on construction costs including roads, piping and instrumentation or the operational issues of regulatory monitoring and testing. If costs cannot be estimated upfront it may result in a failure in the project due to economics.

41. In my opinion the cost estimate is low and may be misleading. When the noted elements are considered the cost will be significantly increased. During detailed design, following the pilot test, more detail should be given to cost estimates to fully determine cost benefit.

Conclusions

42. Implementation of MAR to dilute groundwater in high nitrate areas is unlikely to be successful for reasons of shallow groundwater levels and areas of low hydraulic conductivity coinciding with high nitrates. Other factors that threaten the success of the MAR project include issues associated with spatially variable mixing and dispersion, and raising nitrate laden shallow groundwater toward springs and increasing nitrate loading to the springs and streams.

43. Further issues that need consideration include the accounting for ocean discharge and other uncertainties in the water balance that may indicate that the proposed rate of MAR is not sufficient.

44. Application of MAR in an effort to dilute groundwater is not an established practice in NZ and I am not aware of examples of MAR projects with the goal of diluting groundwater elsewhere outside of NZ.

45. MAR can play an important role in managing groundwater in the Hinds/Hekeao Plains. Application of additional recharge to benefit areas of declining groundwater levels can help to stabilize and prolong the usefulness of the resource. Focus should be given to implementing MAR in areas with storage capacity and using surplus water.

46. Supply of MAR water using surplus from stormwater/high flows should be investigated – diversion of stormwater flows to off stream infiltration basins and/or existing water race systems may be an effective way of increasing

basin storage with water that would otherwise not enter the groundwater system. Capture of stormwater would allow planned MAR water, if available, to be used in other manners such as targeted stream augmentation. Capture of high flows for MAR has been successful in Orange County, California as implemented by the Orange County Water District[19].

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[19] Orange County Water District Application to Appropriate Santa Ana River Water, Draft Program Environmental Impact Report, March 2006