Fall 2009

Investigating the Technical Feasibility of Utilizing Aquifer Storage and Recovery to Supplement the Public Water Supplies in Evans Head and Ballina

Brandon Cohen
SIT Study Abroad

Investigating the Technical Feasibility of Utilizing Aquifer Storage and Recovery to Supplement the Public Water Supplies in Evans Head and Ballina

Cohen, Brandon
Academic Director: Brennan, Peter
Project Advisor: Meyers, Donald
Dartmouth College
Environmental Engineering
Lennox Head, New South Wales, Australia
Submitted in partial fulfillment of the requirements for Australia: Sustainability and the Environment, SIT Study Abroad, Fall 2009

Abstract

At a time when the future of fresh water resources in Australia becomes more unpredictable as a result of global climate change, it will become necessary to look for new alternative sources of fresh water. Reclaimed wastewater is an important fresh water resource that will become increasingly important. One strategy to augment the public water supply is to inject and store reclaimed water underground, then to pump it out of the aquifer and treated to drinking water standards. This is known as *Aquifer Storage and Recovery* (ASR) and similar schemes have been established in the United States, United Kingdom, Canada, Australia, South Africa and Israel.

This report examines the feasibility of using ASR to supply water to the towns of Evans Head and Ballina. Using available hydrogeological data, I analyzed the potential for each aquifer to transport the flow of wastewater. I also determined adverse interactions that may take place between the injected reclaimed wastewater and ambient groundwater, and how to treat these problems. Basic plans for treatment are advised.

Based on the data I have analyzed, I have determined that pending further study, ASR is feasible in this region. While this report is by no means comprehensive, it provides a starting point for designing an ASR scheme in this area.

Comment [MSOffice1]: It is very important to describe the water correctly. Otherwise, readers will conclude that sewage is being injected into the aquifer.

ISP Topic Codes: 625 (Geology), 819 (Sanitary, Municipal, and Waste Management), 812 (Civil Engineering)

Keywords: Aquifer Storage and Recover, ASR, Groundwater, Wastewater, Reclaimed Water

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

I would like to thank first and foremost Craig Zerk and Duncan Thompson at GeoLINK, and the rest of the office staff at GeoLINK. I conducted this project under the direction of Craig and Duncan, but everyone around the office was extremely helpful and welcoming during the five weeks I spent there. I'd like to thank Catherine Cheyne at GeoLINK for giving me rides to and from Byron Bay. I would like to thank my advisor Dr. Donald Meyers, whose extensive knowledge of environmental waste management was extremely helpful and relevant to this project. I would like to thank Peter Dillon of CSIRO who has done extensive work on ASR in Australia and provided me with one of his reports for guidance. I would also like to thank Peter Brennan, Dave Brown, and the rest of the SIT Australia: Sustainability and the Environment students for their support and guidance during the ISP period and the entire semester.

LIST OF FIGURES, TABLES, ABBREVIATIONS

Figures

Tables

Abbreviations

AGT- Australian Groundwater Technologies

ASR- Aquifer Storage and Recovery

ASTR- Aquifer Storage Transfer and Recovery

BOD- Biological Oxygen Demand

cfu/100mL- Colony-forming unit per 100 milliliters of water

CSIRO- Commonwealth Scientific and Industrial Research Organization

DO- Dissolved Oxygen

m- meters

mg/L- milligrams per liter

NFR- Non-Filterable Residue

TSS- Total Suspended Solids

WWTP- Wastewater Treatment Plant

1. INTRODUCTION

1.1 Theory

Aquifer Storage and Recovery (ASR) is the process of recharging of an aquifer by injecting water into it through wells or by surface spreading and infiltration and then pumping the water out when it is needed. The aquifer functions as a water bank. The aquifer is recharged in times of surplus, typically during the rainy season and water is extracted when available water storages cannot meet demand.

ASR schemes commonly operate in conjunction with wastewater treatment plants, by injecting the treated waste water into the aquifer, and recovering the water after a determined transport time (and distance) in the aquifer, depending on local hydrogeology and water quality standards.

There are many advantages to using this type of system to store water. It may reduce the need for surface reservoirs, which are expensive and resource intensive to build and maintain, are left vulnerable to tampering (which would be more difficult with an underground reservoir), and are prone to losing water due to evaporation. According to the *United States Ground Water Association*, ASR not only provides water for human consumption by recharging aquifers but also prevents salt-water intrusion in coastal aquifers and helps maintain base stream flow levels (Pyne, undated). As global climate change affects the hydrologic cycle and more is understood about the harmful effects of damming waterways, groundwater will become an increasingly important source of fresh water. Since most aquifers are well protected from surface pollution, in most instances the water only requires disinfection to become drinking water.

ASR systems cost about half that of traditional surface storage systems for equal storage volumes. When the cost of water treatment plants and other infrastructure required to deliver potable water from surface storages is considered, ASR systems can deliver water for as little 10% of the cost of traditional storage and treatment systems (Pyne, undated).

1.2 A Typical ASR Scheme

Figure 1 below shows a diagram of a general ASR scheme. There is also a general schematic of an ASR scheme available in Appendix E. The quality of the ambient groundwater in these storage zones ranges from pure to brackish, with a concentration for total dissolved solids of up to 5000 mg L^{-1}. Almost all aquifers have at least one water quality problem (e.g. raised levels of Fe, Mn, Fl, H_2S, SO_4^{2-}, Cl, ^{224}Ra, alpha radiation or other elements that may be displaced by recharging depleted aquifers) that necessitates some form of treatment after withdrawal if the water is to be used for human consumption. The potential for recovery varies based on the hydrogeology of the region. In some areas it may even be feasible and cost-effective to store water in an aquifer containing sea water, while in other areas it may not be possible to recover as much water as was previously injected. While ~~image below~~Figure 1 shows a confined aquifer, it is also possible to use unconfined aquifers. The aquifers generally occur within strata containing sand, clay sand, sandstone, gravel, limestone, dolomite, glacial drift~~,~~ and basalt. When the water is injected into the existing aquifer, it slowly displaces ~~that~~ the resident groundwater, creating a "bubble" of fresh water. In current schemes, the volume of these "bubbles" can range from about 50 ML to 10,000 ML.

Figure 1. Diagram of Aquifer Storage and Recovery. Source: Parliament of Victoria (2004).

1.3 ASR Schemes Worldwide

The United States Geologic Survey began conducting tests on ASR technology in the 1940s, and the first well in the United States was constructed in Wildwood, New Jersey in 1969. In 1983, Manatee County, Florida began using ASR technology, and since then, ASR schemes have been constructed in the United States, United Kingdom, Canada, Australia, South Africa and Israel. The Netherlands, New Zealand, Thailand, Taiwan and Kuwait are all in the process of developing ASR. There are currently wells with recovery capacities that range from 2 ML d^{-1} ~~-~~(from single wells) to wellfields with recovery capacities upwards of 400 ML d^{-1}. There is currently~~oy~~ a proposal to create a large wellfield in the Florida Everglades, which would have a total recovery capacity of 8,000 M~~l~~L d^{-1}.

There are a few schemes that are used for indirect potable water use (as in the case of this project). Examples of this type of scheme in the United States include a project in Denver, CO, the Potomac Estuary, VA, Los Angeles and Orange County, CA, El Paso, TX, San Diego, CA, and Tampa, FL (Metcalf and Eddy 2003).

1.4 ASR Schemes in Australia

There are currently four ASR systems operating in Australia, and several more are proposed. Figure 2 below shows where these systems are located. There are currently no ASR systems on the East Coast of Australia.

Figure 2. Distribution of ASR schemes in Australia. Source: Pyne (undated).

A very large system operates in Salisbury, SA, near Adelaide. During high periods of high rainfall in the winter, water is naturally filtered by the wetlands and deposited 164 meters underground for storage. In the summer, the water is recovered to irrigate sports fields. Due to the success of the Salisbury ASR scheme, several small and large scale ASR systems have been established in South Australia.~~,~~ These types of schemes can reduce the burden on surface water systems such as the Murray River, which has seen reduced flows and increased salinity recently due to poor management in Queensland, New South Wales, Victoria, and South Australia. CSRIO is currently investigating the possibility of an ASR system in Melbourne~~,~~ and the possibility of using ASR at the domestic level (Dillon 2006). In 2007 CSIRO began investigating the world's first ASTR scheme, where the water is transported through the aquifer a distance from the injection point to the recovery point (Dillon et al. 2007).

The success of the Salisbury scheme has also prompted scientists to investigate the possibility of using ASR to store and treat reclaimed water. This~~at~~ will be the focus of this study. In 2003 Dillon et al. (2003) conducted a study on ASR using reclaimed water from the Bolivar sewage treatment plant in South Australia. This scheme involved the use of secondary treated wastewater from the Bolivar sewage treatment plant~~,~~ which was stored before being pumped into the limestone aquifer. It was found that the water was able to travel up to 200 m over at least 12 months, and at the time of removal was found to be suitable for irrigation. The passage of the treated water through the aquifer resulted in reduced concentrations of suspended solids, organic carbon, some metals and E. Coli from the water. The system that this paper will investigate may include the use of tertiary treated wastewater to simplify the treatment processes that will be needed to further reduce public health risks.

Comment [MSOffice2]: Is this what you mean?

Comment [MSOffice3]: Name the acuifer and give basic details

Comment [MSOffice4]: Over what time period?

Comment [MSOffice5]: It is very unlikely that these were "removed". At best they would have been below the detection limit.

1.5 Water in Northern NSW

ASR is a cost-effective way to meet the water demands of regions without reliable water resources. it is likely to be especially effective in areas such as northern New South Wales, with long periods of drought and periodic flood events. There has never been an ASR scheme proposed in Northern NSW~~,~~ but there has been some investigation into the possibility of discharging treated wastewater into aquifers ~~under~~ in the Evans Head region for the purpose of disposal (Coffey 1997; Coffey 2003).

According to Rous Water, the provider of drinking water in this region, their "existing water sources can comfortably meet demand for water in the short to medium term. However it's essential to plan for the future so we are prepared for future water needs in the region" (Rous Water, undated). ~~They~~ Rous Water is also proposing the construction of a new dam in Dunoon, NSW to meet future demand for water. Ballina, Lennox Head, and Evans Head wastewater treatment plants currently discharge 20,816,400 L d~~ay~~$^{-1}$ of water to nearby surface waters. Very little of this water is reused. Ballina Council is planning a ~~massive~~ major augmentation ~~overhaul~~ of their treatment plants and infrastructure to recycle an~~d~~ increasing amount of water in the coming years (Hess & Balandin 2009).

1.6 Study Goals

The goal of this study ~~is~~ was to determine the feasibility and potential environmental impacts of using Aquifer Storage and Recovery (ASR) to meet the growing demand for fresh water in Ballina and Evans Head within Northern New South Wales. This report will assess the hydrogeologic suitability of the aquifers ~~under~~ in the Ballina and Evans Head regions to support an~~d~~ ASR scheme~~,~~ and to design a feasible system.

2. METHOD

This study was conducted entirely from the GeoLINK office in Lennox Head, NSW Australia.

2.1 Desktop Compilation of Geology and, Groundwater Hydrology ~~ology~~

I followed the procedure for developing an aquifer storage and recovery project outlined ~~by~~ in the *Australian Guidelines for Water Recycling* (2009), as published by the Natural Resource Management Ministerial Council. I conducted the Entry-level, or Stage 1 assessment. The goals of the Entry-level assessment are to determine whether or not there is likely to be a suitable aquifer, to assess the level of difficulty that the project will ~~be~~pose, and to determine which aspects of the project require further study.

To determine whether or not there exists a suitable aquifer in Ballina and Evans Head, I consulted geologic maps, groundwater bore data, and ~~old~~ existing reports of projects concerning the groundwater in this region. From ~~this~~ these data, I was able to create images of the aquifers underlying Ballina and Evans Head. Using hydrogeolog~~y~~icaly data from various sources, I located three aquifers of sufficient size ~~have been~~ in close proximity to the Ballina and Evans Head Wastewater Treatment Plants. One of the aquifers, however, located North of Evans Head, would

Comment [MSOffice6]: What does this mean?

require infrastructure built in Broadwater National Park, so it is not considered viable to ~~design~~ establish a scheme in that region at this time.

2.2 Calculations

Using flow data from the wastewater treatment plants, known properties of each aquifer, and Darcy's Law I was able to determine flow rates of water through the aquifers. The cross sections only provide speculation as to what the true shape of the aquifer may be, so only bore hole depth data is used in the calculations of groundwater flow. Using a modified version of Darcy's Law, it is possible to calculate flow rate on a "per width" basis, which is known as the *transmissivity*, to find the maximum flow rate for the aquifer. Darcy's Law is a relationship that describes fluid flow through a pourous medium.

$$Q = -Khw\frac{\partial h}{\partial x} \qquad [1]$$

$$T_x = -Kh\frac{\partial h}{\partial x} \qquad [2]$$

The quantity $\partial h/\partial x$ is also known as the gradient (i), which can be calculated using the following formula:

$$i = \frac{\partial h}{\partial x} = \frac{h_1 - h_2}{L} \qquad [3]$$

where h is the head at a given point, $\partial h/\partial x$ is the change in head over L~~,~~ and L is the distance between the two head points taken along the direction of the flow of groundwater. K is the hydraulic conductivity, Q is the flow rate, and T_x is the transmissivity, in units of L d^{-1} m^{-1}~~/day/m~~. Coffey (2002) contains the experimentally laboratory determined hydraulic conductivity values and the transmissivity values for the aquifer. I have chosen to use the conductivity values for calculations, because these transmissivity values have been determined for the existing depth of the groundwater (regions that have been labeled as "water bearing") and I wish to model the entire layer of Woodburn Sand. This equation is used to calculate a flow rate for both the injection point and the recovery point at each site. In both cases, the flow rate at the recovery point was found to be less

Comment [MSOffice7]: What does this mean?

Comment [MSOffice8]: Transmissivity is a measure of the flow through a strip of aquifer one unit wide (i.e. 1 m) that extends for the full depth of the aquifer.

Comment [MSOffice9]: Define K

than at the injection point, so the rate of injection is limited by the flow rate of the aquifer at the recovery point.

To find the width that the aquifer must be to accommodate a certain flow rate of water, the following equation is used:

$$w = n\frac{Q_{TW}}{T_x} \qquad [4]$$

where Q_{TW} is the flow rate of reclaimed water through the aquifer, and T_x is the transmissivity calculated above. This equation states that the theoretical required width is equal to the percentage of reclaimed water flow being injected into the aquifer (n) multiplied by the ratio of the total flow to the "per width" flow. Although this model ignores ambient groundwater flow, other simple models also ignore the ambient flow (Dillon 2002, p. 2) so I feel comfortable ignoring it at this stage.

2.3 Groundwater Chemistry

Once I had concluded that based on available data there are sufficientwere aquifers with sufficient storage and appropriate hydrogeological characteristics present for a scheme of this type, I investigated the water chemistry of the effluent and groundwater to identify possible the potential for adverse reactions following mixing of these waters and advise identify treatment strategies for the effluent prior to injection. My analysis of the water quality data is mainly derived from reading other reports written about injecting wastewater into groundwater (Coffey 1997; Coffey 2002; AGT 2002; Dillon 2002; Dillon et. al 2003).

3. RESULTS

3.1 The Evans Head Aquifer

Comment [MSOffice10]: Try using subsections to deal with the different types of data

The land in consideration for ASR development here lies to the North of Evans Head, east of the Richmond River. Figure 3 below shows the location on a map.

Figure 3. The blue line is the line that the hydrogeological cross sections have been adapted from. The dotted black line represents a divide in the flow of the Woodburn Sand Aquifer. The black dot indicates the location of the Evans Head WWTP. Source: Central Mapping Authority of NSW 1987.

Under this land there are two main aquifer systems; a semi-confined aquifer of Woodburn Sand and a confined aquifer of South Casino Gravel. Figure 4 below shows a cross section (taken along the blue line in figure 3) created from interpolating stratigraphical data taken from bore hole data.

Figure 4. A Cross Section of the Evans Head aquifer systems, with the Woodburn Sand (large region with dots) and South Casino Gravel aquifers shown. Source: Coffey (2002)

In 1997 and 2002, Coffey Partners International conducted a study to determine the feasibility of injecting reclaimed water into both of these aquifers for disposal as opposed to reuse. This study is only targeting the Woodburn Sand Aquifer because it is large and close enough to the surface that it will not be too difficult to inject and recover the reclaimed water. As can be seen from figure 4, there are four regions of Woodburn Sand (Figure 4, I-IV), which all formed at different times, and "no single feature distinguishes each of the four units, however they could be tentatively separated by a combination of different textures, sieve analysis, lithology, heavy mineral concentration and quartz surface textures" (Coffey 1997, p. 10). For the purpose of basic groundwater flow calculations though, I will not differentiate between the four units.

There are three basic subdivisions of the Woodburn Sand aquifer. Around bore 39152, there is a divide in the flow of the groundwater~~ through the Woodburn Sand aquifer~~. East of the divide, the water flows toward the Pacific Ocean, and w~~W~~est of the divide it flows toward the Richmond River. To the east of the divide, there is a layer of Broadwater Sandrock Member, which is a semi-confining layer, and has a vertical hydraulic conductivity of at least one order of magnitude less than the Woodburn Sand (Coffey 1997, p. 17). There is a layer of Woodburn Sand above the Broadwater Sandrock Member, but this study is concerned with the aquifer that is below the semi-confining layer. To the w~~W~~est of the divide, the Woodburn Sand aquifer is either semi-confined by floodplain soils or unconfined.

The bore log data include the depths at which water was found, but for this study I am taking the thickness of the aquifer to include the entire Woodburn Sand layer. Figure 5 below shows the flow of groundwater as modeled by the *New South Wales Water Resources Comission* (Drury 1982) using the values for conductivity of each layer shown below.

Figure 5. Groundwater flows and equipotential lines for the Evans Head cross-section. Source: Drury (1982).

Each side of the divide will be analyzed separately, as two distinct possiblities for ~~an~~ ASR schemes in this area. Using Darcy's Law, it is possible to calculate the flow rate that the aquifer could possibly accomidate (see Method Section 2.2). Since the width of the aquifer is unknown, it is not feasible to determine the volume of these aquifers~~ with the given data~~. Although the ~~explicit~~ width of the aquifer is not known, based on additional geological cross sections of the region I have estimated that the aquifer extends fairly uniformly for at least 1 km to the South and 3 km to the North, with no major confining boundaries within 10 km (Drury 1982).

3.1.1 Boundary Conditions

There is no bore data or other explicit hydrogeological data for the region surrounding the cross section shown in Figure 1, but the topography and landscape north of the Evans River is homogenous, so I will assume that the hydrogeology is somewhat homogenous is well. This assumption is supported by the bore data from the Rileys Hill cross section in Figure 6 (Drury 1982, p. 22), as it shows very similar geology to the Evans Head section further south, including the Woodburn Sand layers and the Broadwater Sandrock Member.

> **Comment [MSOffice11]:** Is this Figure 5? If not, you should include a figure showing this cross section.

Figure 6. Rileys Hill Cross Section. Source: Drury (1982).

The heathland that covers this aquifer at Evans Head over ~~the first~~ layer I of Woodburn Sand extends North nearly ~~all the way~~ to Ballina. However, s~~S~~outh of the Evans River the topography and geology is different, and without more complete geologic information about this region, I will assume that this is the Southern boundary of the Woodburn Sand aquifer. This boundary is approximately 2 km s~~S~~outh of the cross section. Thus, ~~so~~ the theoretical maximum width of this aquifer would be approximately 4 km.

3.1.2 Evans Head Flow Calculations (for the Aquifer that drains to Pacific Ocean)

Comment [MSOffice12]: This should be 3.2.1 as it is a subsection of 3.2.

The limiting flow rate for groundwater in the side of the aquifer that drains to the ocean is 319.04 L d^{-1} m^{-1}. The tables below display the results of Equation 4, for using various fractions of the available reclaimed water being injected to the ground. The Evans Head WWTP produces 2,643,840 L d^{-1} during summer and dry weather (Richmond Valley Council 2009). The results show the theoretical required width of the aquifer required to accommodate a given percentage of the reclaimed water flow.

To Inject (%)	Q_{TW} (L d^{-1})	Width (m)
100%	2643840	8290
75%	1982880	6220
50%	1321920	4140
25%	660960	2070
20%	528770	1660
15%	396580	1240
10%	264380	830
5%	132190	410
4%	105750	330
3%	79320	250
2%	52880	170
1%	26440	80

Table 1. Results for Evans Head Aquifer (draining to ocean)

Table 1 is a summary of the calculations for the side of the aquifer that drains to the Pacific Ocean. Based on the estimated boundary conditions from section 3.1.2, the section of the Woodburn Sand aquifer under Evans Head would be able to store 50% of the reclaimed water from the Evans Head WWTP in an ASR scheme. The travel time from the injection site to the shore would be between two and nine years (Coffey 1997, p. 21).

3.1.3 Evans Head Flow Calculations (Aquifer that drains to Richmond River)

The limiting flow rate for groundwater in the side of the aquifer that drains to the Richmond River is 543.73 L d^{-1} m^{-1}. Table 2 shows the same calculations data for the section of the Evans Head aquifer that drains to the Richmond River.

To Inject (%)	Q_{TW} (L d^{-1})	Width (m)
100%	2643840	4860
75%	1982880	3650
50%	1321920	2430
25%	660960	1220
20%	528770	970
15%	396580	730
10%	264380	490
5%	132190	240
4%	105750	190
3%	79320	150
2%	52880	100
1%	26440	50

Table 2. Results for Evans Head Aquifer (draining to Richmond River)

This side of the aquifer also has a similar hydrogeological profile nNorth all the way to the cross section at Rileys Hill, as well as a similar floodplain surface sSouth to the Evans River. Assuming that the flow of groundwater in this area is perpendicular to the Richmond River, the width of the aquifer in this region could be upwards of 4000 m wide. An ASR scheme utilizing this aquifer could therefore , which means that this design could potentially store up to 100% of the reclaimed water.

3.2 The Ballina Region Aquifer

There are much less data available for the aquifer in the Ballina region~~,~~ but the hydrogeology of the ~~two~~ Ballina and Evans Head regions are similar enough ~~that we can~~to enable ~~make~~ a ~~legitimate~~ reasonable comparison. Figure 7 below shows the location of the relevant aquifer which is located ~~that we are targeting in Ballina. It is~~ to the n~~N~~orth of Lennox Head, near Lake Ainsworth. ~~Out o~~Of several potential aquifers ~~sites~~ in the Ballina region, this site was the only ~~one to show~~that has the potential for the storage of large volumes of water. ~~The~~ An obvious ~~downside~~ difficulty ~~to~~ with this site is ~~its~~ the distance from the Ballina and Lennox Head WWTPs ~~and distance from~~to the Ballina CBD. ~~, but t~~The scheme could, however, be used to provide water for Lennox Head instead of the Ballina ~~CBD~~.

Figure 7. Shows the two cross sections that were analyzed. The horizontal section, #27, is shown in detail in Figure 8. Source: Ballina Topo Map.

This large aquifer near Lake Ainsworth is similar in its geologic composition to the aquifer in Evans Head. Figure 8 shows that in the section of the aquifer closest to Lake Ainsworth, the geology is almost identical to Evans Head, with the Broadwater Sandrock Member as a semi-confining layer over the Woodburn Sand.

Figure 8. Shows two cross-sections for the aquifer below Lake Ainsworth. Note that to the South-East there is a very similar composition to Evans Head. Source: Drury, 1982.

Information about the direction of flow in this aquifer is not available, but I am assuming based on the data from Evans Head that the water flows towards the Pacific Ocean. Though the aquifer is close to North Creek, the creek is tidal for nearly the entire extent of the study area, so without more information it is not known whether the groundwater flows n~~N~~orth or s~~S~~outh.

3.2.1 Ballina Region Flow Calculations

~~The actual conductivity values for the Woodburn Sand in this case.~~ In a Hydrogeological Report (Drury 1982) for the Richmond River Valley, values of 8-60 m d^{-1} for hydraulic conductivity (K) are cited for various bores ~~containing~~ that penetrate Woodburn Sand. Employing the same method used to calculate flow rates in the Evans Head aquifer, the limiting flow rate in the aquifer was found to be 305.78 L $d^{-1}m^{-1}$ width using an hydraulic conductivity value of 8 m d^{-1}, and 2290 L $day^{-1}m^{-1}$ width using a ~~conductivity~~ value of 60 m d^{-1}. Based on cross section #26 in Figure 8, the aquifer is at least 1 km wide, so a good estimate for the limiting flow rate in the aquifer would be 305780 L d^{-1} for K = 8 m d^{-1} and 2293000 m d^{-1} for K = 60 m d^{-1}, which is equal to just over 3% and 27% of the rate of recycled water produced by the Ballina and Lennox Head WWTPs. There is potential for an ASR scheme using this aquifer, but further samples are needed to determine whether more precisely what flow rates ~~of water~~ will be able to be injected into the aquifer.

3.3 Safe Yield

Comment [MSOffice13]: Which aquifer(s)?

The flow rates calculated in this paper will increase the safe yield of each aquifer, which is equal to the average replenishment rate of the aquifer (Bouwer 1978, p. 32). The safe yield of the aquifer is the amount of water that can be recovered without causing a long-term decline of the water table or piezometric surface. As a result, in times of greater water need it would be possible to withdrawal a flow of water equal to the sum of the injection rate and the natural rate of recharge, and still be withdrawing within the safe yield. These calculations account only for withdrawal equal to the rate of injection though.

4. DISCUSSION

This section will focus on the basic design of an ASR scheme and the associated treatment strategies in the aquifers Ballina and Evans Head as discussed in section 3, and the potential problems with such a scheme.

4.1 Proposed Scheme (Evans Head)

Appendix A contains a map of the proposed scheme at Evans Head. In Evans Head there is the possibility of using the aquifer on both sides of the groundwater flow divide, which is marked on the map roughly by the dotted black line. Using a single pipeline, the water would be transported to a site that sits roughly on the divide, with injection facilities on both sides. There would be two recovery points, one at the Evans Head WWTP and one just outside ~~of~~ Woodburn. Placing one of the recovery points on the same site as the WWTP reduces the footprint of the project. To bring the water to drinking water standards, this project would necessitate pumping to a centralized treatment facility that would preferably be located at one of the recovery points. The water recovered could possibly be pumped directly into the existing transfer main between Woodburn and Evans Head.

4.2 Proposed Scheme (Ballina/Lennox Head)

Appendix B contains a map of the proposed scheme in Ballina/Lennox Head. The local council has already considered constructing a pipeline for the transport of recycled water ~~pipes~~ to location (1) on the map, and north of location (8) in close proximity to the proposed recovery point. There are several possibilities for the location of treatment facilities. The effluent from the Ballina and Lennox Head plants could either be treated on site at the WWTP or remotely at the injection point. One problem with treatment at the WWTP is that if water were taken from both the Ballina and Lennox H~~h~~ead plants, then treatment facilities would be required at both plants, substantially increasing project costs. The advantage to this scheme would be that the reclaimed water leaving the plant and traveling across town would be of a higher quality than the effluent, and could be used for irrigation or livestock, as it will be treated to those standards. The recovery point for this water would be to the n~~N~~orthwest of the Lennox Head CBD, and after additional treatment at the recovery site could be connected directly to the municipal water supply.

4.3 Injection Wells

The Coffey (1997) report concluded that 8 wells would be needed to handle the peak season flows and accommodate the predicted future flow increases. It was also recommended that the wells should be spaced at least 50 m apart and drilled to a depth of 22 m to reach the Woodburn Sand Aquifer. According to AGT (2002), more analytical modeling is needed to determine the proper spacing of the injection wells. These studies are relevant to the design of the injection manifold for any ASR scheme at Evans Head because they relate to the Woodburn Sand Aquifer. None of these studies included recovery of the injected water, so further work is needed to determine the most appropriate recovery system. There have been other studies about ASR in Australia that include discussion of recovery systems (Dillon et. Al 2003), but additional work is needed to design a system appropriate for the Woodburn Sand aquifer.

4.4 Environmental Values of Groundwater and End Uses

“Environmental values” of water refer to specific guidelines ~~set forth~~prepared by the governments of Australia and New Zealand. The *Australian Guidelines for Water Recycling, 2004* gives six different environmental values of water: aquatic ecosystems, aquaculture, recreation, livestock, drinking, and irrigation. The aquifers in this region are not used to obtain drinking water for the public (the though private wells may exist) nor for aquaculture. Given the land uses in the

Northern New South Wales region, the groundwater could be used for aquatic ecosystems (the groundwater flows to the ocean and the Richmond River), recreation, livestock, and irrigation. A summary of these guidelines, as well as water quality data for the effluent from each WWTP and the ambient groundwater is ~~available~~ contained in Appendix A.

4.5 Treatment Prior to Injection

The wastewater should be treated to meet the environmental guidelines described above, but more importantly must also be compatible with the chemistry of the groundwater. I have summarized the environmental values for lowland river, estuarine, and marine aquatic ecosystems, irrigation, livestock, and recreational uses as outlined in the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality* (National Resource Management Ministerial Council 2000) and the targets for injection water quality as outlined in Coffey~~,~~ (2002) and reviewed by Dillon (2002). The injection water quality targets, drinking water standards, and effluent quality data ~~is~~ are shown in Table 3 below:

Table 3. Water Quality Data Summary

Parameter	**Units**	**Woodburn Sand Aquifer**	**Effluent (Evans Head)**	**Effluent (Ballina)**	**Effluent (Lennox)**	**Injection Target**	**Drinking**
Temperature	*˚C*	25	25			15 - 35	
Ph		7.03	6.5			6.5 - 7.5	6.5 - 8.5
Redox Status	*mV (pe)*	-180 (-3)	700 (12)			-200	
DO	*%*	< 0.1 %	115%			90 - 100%	> 85 %
Ca	*mg/L*	30	23			1000	
Mg	*mg/L*	22	4.9			2000	
Na	*mg/L*	110	66			300	180
K	*mg/L*	8.5	11				
Fe (soluble)	*mg/L*	1.1	0.04			1.5	0.3
HCO_3^-	*mg/L*	170	110				
SO_4^{2-}	*mg/L*	21	62			400	250
Cl	*mg/L*	190	60			400	250
P	*mg/L*	0.01	0.82	0.39	5.1	0.02	
NH_3-N / NH_4-N	*mg/L*	0.9	4	2	0.04	0.015	
NO_x	*mg/L*	< 0.01	20	2	2.1	NO_3 + NO_2 < 0.1	50 NO3
BOD	*mg/L*	< 2	9	4	7		
TSS/NFR	*mg/L*		25	11	14	1	

Total N	*mg/L*		12	6	4	0.12	
Oil and Grease	*mg/L*		0	4	5		
Faecal Coliform	*cfu/100mL*		568	100	46	0	0
Chlorophyll A	*mg/L*			74	80		
TDS	*mg/L*	262		1834		1000	500

Table 3.For the "Injection Target" and "Drinking" categories, unless otherwise indicated, all values are upper limits for each criteria. Values marked with a "greater than" (>) sign indicate that the value is the lower limit. pH is given as a range of values. Any values marked with a "less than" sign indicate that the concentration is less than the precision of the measuring equipment.

Though the Injection Target takes into account various guidelines for use, the most important criteria to meet are those that match the quality of the ambient groundwater. Since ASR with reclaimed water involves injecting reclaimed water into the ground, the public may require that the water be treated to drinking level standards prior to injection, though this will vary by location.

A common problem when injecting water into aquifers is the question of clogging. Clogging can occur as a result of precipitation of carbonates and hydroxides, bacterial growth, and siltation with colloids and fine silt/clay particles (Coffey 2002, p. 20). Clogging reduces the rate at which water can be injected to the aquifer. While there was no additional study for this project on aquifer clogging, based on previous studies clogging is not anticipated to be a problem in this ASR scheme. In 2002, Coffey concluded that based on their work in similar sand aquifer systems with injected wastewater, that clogging would only affect an area less than 1 m away from the injection site (Coffey 2002, p. 21).

4.5.1 Redox Potential and Heavy Metals

The Australian Groundwater Technology (AGT) report on wastewater injection into the aquifer at Evans Head concluded that metal precipitates from iron and other heavy metals will not be problematic (AGT 2002, p. 16). The concentration of soluble iron in the effluent from Evans Head is just 0.04 mg L^{-1}. To reduce the possibility that adverse reactions will take place, the redox status of the effluent must be altered. The effluent is in a highly oxidized state (E_h = + 700 mV from Evans Head WWTP), while the Woodburn Sand aquifer is in a reduced state (E_h = -180 mV). In a reduced aquifer, oxidized iron species (Fe^{3+}, Fe_2O_3, FeO) will become Fe^{2+} and dissolve, thereby lowering the risk of clogging the aquifer from iron precipitates.

4.5.2 Biological Oxygen Demand (BOD) and Dissolved Oxygen (DO)

The Woodburn Sand Layer under the Broadwater Sandrock Member is under very high reducing conditions~~,~~ and has almost no dissolved oxygen. Adding injectant with relatively high BOD (average effluent BOD is approximately 7 mg L^{-1}) compared to the groundwater (<2 mg L^{-1}) would remove the remaining dissolved oxygen, thereby enhancing the reducing state of the water, and would reduce the potential for precipitation of iron oxides which ~~would~~ might lead to clogging (Coffey 1997, p. 30). However, with the addition of effluent with relatively high BOD there remains a risk of clogging due to the development of biofilms, or bioclogging.

A biofilm is a group of microorganisms in which cells ~~are stuck~~adhere to each other or a surface. The development of biofilms cannot be modeled in the same way as chemical clogging, so Dillion (2002) advises that a laboratory and field study of how to avoid bioclogging must be done before this scheme could be built. ~~, and t~~The AGT (2002) report proposes that the effluent may require further disinfection before injection to reduce the potential for clogging by destroying a proportion of the microorganisms in the water. Additional testing is needed to confirm the fate of injectant with relatively high BOD.

It is worthy of note that the level of dissolved oxygen for the Evans Head effluent ~~given by the most recent report~~most recently reported (Australian Groundwater Technologies 2002) is ~~quite~~ high for treated ~~sewage~~ effluent at 10 mg L^{-1} or 115%. Levels of dissolved oxygen in the effluent for the Ballina and Lennox Head plants were not available. Naturally, in a subsequent study the quality of the effluent would have to be very well defined for the design of proper treatment strategies.

4.5.3 Nitrogen and Phosphorus

The Coffey (1997) report concluded that the nitrogen and phosphorus ~~species~~ in the effluent would not affect the system's operation. The AGT (2002) report also concluded that precipitation of nitrates would be problematic if they were present at concentrations over 50 mg L^{-1}. However, since the reclaimed water must meet the environmental values of water for aquatic ecosystems (lowland river, estuary, and marine), irrigation, recreation, and livestock, the concentrations of nitrates must be below 10 mg L^{-1}. Currently, the Evans Head, Ballina, and Lennox Head Wastewater Treatment Plants (WWTPs) all produce effluent with total nitrogen concentrations of less than 10 mg L^{-1}, which is a general limit outlined in the *Australian Guidelines for Water Recycling* for the level above which there is a high risk of clogging. Though the effluent does not meet target levels for either total nitrogen and oxidized nitrogen (NO_3 and NO_2), additional treatment may not be required. Nitrogen and phosphorus can be decreased by passing the effluent through a wetland, though this may increase concentrations of coliform bacteria. Nitrogen can also be reduced by changing the water to reducing conditions and denitrification prior to injection.

4.5.4 Total Suspended Solids (TSS), Oil and Grease

There is also an increased risk of clogging if the treated effluent contains high levels of Total Suspended Solids (TSS). According to Coffey (1997), TSS (identical to NFR) should be below 5 mg L^{-1}, and possibly as low as 1 mg L^{-1} to minimize the potential for serious clogging. Based on October 2007 – March 2009 averages, TSS levels in the Evans Head WWTP effluent was 25 mg L^{-1} and as of September 2009, NFR levels in the Ballina and Lennox Head WWTP effluent was 11 mg L^{-1} and 14 mg L^{-1} respectively. Oil and grease should also be kept to a minimum to reduce clogging, though no quantitative limit has been set. Suspended solids can be removed by chemical precipitation, depth filtration, flotation, microfiltration, microscreening, reverse osmosis, sedimentation, and surface filtration.

4.5.5 Faecal Coliform Bacteria

The AGT (2002) report advised that all effluent should be disinfected prior to injection. There are other reports available, such as Dillon (2003) that study the fate of pathogens and other bacteria after injection into the aquifer. Faecal coliform levels in the effluent ranges from 46 cfu/100mL in Lennox Head to 568 cfu/100mL in Evans Head. Even if the effluent is disinfected prior to injection, I suspect that disinfection will be required in treatment after recovery to meet drinking water standards.

4.5.6 Total Dissolved Solids (TDS)

Total dissolved solids in the Ballina effluent was 1834 mg L^{-1}, and the target level is 1000 mg L^{-1} for injection and 500 mg L^{-1} for drinking water. Though our target level is 1000 mg L^{-1}, the ASR scheme in Bolivar, South Australia used effluent with a TDS level of 1267 mg L^{-1} without any problems. In Bolivar the aquifer was a limestone aquifer, and the ambient groundwater contained 2006 mg L^{-1} of TDS compared with 262 mg L^{-1} in the Woodburn Sand aquifer, so additional study is needed to determine any potential problems with high concentrations of TDS in the injectant.

4.6 Post-Recovery Treatment

After the water is recovered from the aquifer, it will have to be treated to drinking water standards to be added to the public water supply. Save for one case in Namibia, there are no cases in the world where wastewater is *directly* reused as drinking water, but as discussed in the introductions, there are several examples of *indirect* potable water reuse. Groundwater recharge schemes are considered *indirect* potable reuse, and are more common. Since the injected influent is treated to match the groundwater as closely as possible, and there will be mixing of the injectant and groundwater, the post-recovery treatment will not differ greatly from traditional drinking water treatment for groundwater. The treatment must reduce concentrations of iron, sulfates, chlorine, sodium, TDS, and will most likely require disinfection to address public concern over drinking recycled wastewater. For potable reuse, the three main concerns in the wastewater would be enteric viruses, organic constituents (both industrial chemicals and household products and medicines), and heavy metals.

4.7 Salinity

There is cause for concern if the salinity of the effluent is above 10,000 mg L^{-1} (17,300 µS cm^{-1} at 25 ˚C in conductivity). All values of conductivity for Woodburn Sand as cited in Drury, 1982 and Coffey, 1997 are well below this number. Careful analysis of the Woodburn Sand aquifer will be required to determine the placement of the recovery points for Evans Head and Ballina that are near the ocean, so as to not be affected by salt-water intrusion.

4.8 Additional Treatments

In addition to the implementation of appropriate source controls to limit the risk of contamination by toxic chemicals, additional treatment measures that may be required prior to injection include (Metcalf and Eddy 2003):

- Primary sedimentation and secondary biological treatment,
- Chemical coagulation,
- Clarification,
- Granular-medium filtration,
- Activated-carbon adsorption,
- Removal of volatile organics,
- Reverse osmosis,

- Disinfection.

It is beyond the scope of this study to determine the most appropriate methods of treatment for each of the measures stated above. Once the water is in the ground, it is recommended that the water be retained in the ground for at least 12 months, and travel a horizontal distance of 300 – 600 m with a direct injection scheme. During the ASR trial in Bolivar, South Australia, the secondary treatment was achieved by activated sludge reactors. The water then passed through a water reclamation plant which used dissolved air flotation ~~filtration~~ separation and disinfection using chlorine (Dillon et. al 2003).

4.9 Semi-Confined Aquifers

The Woodburn Sand aquifer that is targeted in this study is a semi-confined aquifer. A semi-confined aquifer is one with a confining layer, or aquitard, that is not impermeable but has a hydraulic conductivity that is significantly less than the aquifer. Depending on the relative head levels of the unconfined surface aquifer and the semi-confined aquifer, there can either be flow upwards or downwards through the semi-confining Broadwater Sandrock Member. Since relatively large amounts of water will be injected into the Woodburn Sand Aquifer, I expect there to be a positive vertical pressure gradient in the aquifer, and the groundwater will flow upwards. Since the basic mathematical analysis of the aquifers assumed that the upper layer was impermeable, additional modeling will be needed to account for the flow through this semi-permeable layer.

4.10 Estimated Costs

Coffey (1997) provides cost estimates for *only* the injection scheme, including pretreatment, monitoring, effluent storage, delivery pipelines, pumping facilities, access roads, landscaping and fencing in Evans Head to be $90,000 in 1997 dollars. They project the operating costs, including the regular cleaning and redevelopment of bores to be $34,000 per year.

Dillon et. al (2003) provides general cost estimates for full ASR schemes in Australia to be between 8 and 18 cents/kL of volume recovered per well, which is less than the cost of 12 to 34 cents/kL for traditional groundwater extraction. This cost takes into account the capital and operation costs. The costs in Evans Head would be slightly different, as there could be schemes operation on both sides of the groundwater divide which would share some common infrastructure. For that reason I have not calculated full cost estimates in Evans Head. In Ballina, there is still considerable uncertainty as to the flow that the aquifer will accommodate, so a cost estimate calculated based on a flow rate at this point would not be practical.

Estimated costs for the recycled water treatment plants in Ballina and Lennox Head and the pipelines to transport the water are $30 million if the plants are combined and $32.5 million if the plants are separate. These costs are only for the plant upgrades, and not the injection or recovery systems (Hess & Balandin 2009).

5. CONCLUSIONS

I have concluded based on this study that an Aquifer Storage and Recovery scheme to augment the public drinking water supply would be feasible ~~in~~ for both Ballina and Evans Head. As sources of fresh water may become less reliable with climate change in Australia, recycling treated wastewater is a valuable resource that should be exploited. There are many advantages of Aquifer Storage and Recovery to accomplish this task, as it is an effective way to reuse reclaimed water *indirectly* to augment drinking water supply and it creates a large reservoir of water for times of elevated need.

Based on my research, there are semi-confined aquifers in both locations that are suitable for the flows of reclaimed water that are produced by the respective wastewater treatment plants. As the Ballina Council has already expressed a desire to reuse up to 80% of their treated wastewater by 2013, ASR would be a powerful tool to accomplish this goal. In Evans Head, there exists an aquifer of sufficient size and flow properties to accommodate this scheme, but more infrastructure to treat and transport the water is needed. In Ballina, I have calculated that the aquifer may be able to accommodate anywhere between 3% and 27% of its treated wastewater. More study is needed to determine whether or not this scheme would be feasible, based on the size and flow properties of the aquifer. It may be more feasible in Ballina though, as there already exists a plan to increase wastewater reuse and to build additional recycled water pipes. If further study finds this project feasible, Aquifer Storage and Recovery to recover potable water is a promising tool for meeting the water needs in the Northern New South Wales region of Australia.

6. REFERENCES

Australian Groundwater Technologies 2002, *Evans Head Wastewater Management Study*, AGT, Report 2002/2.

Bouwer, H. 1978, *Groundwater Hydrology*, McGraw Hill, Tokyo.

Central Mapping Authority of New South Wales 1987, *Woodburn 9539-1-N*, Second Edition, 1:25 000, Topographic Series.

Coffey 1997, *Evans Head – Woodburn Groundwater Recharge Investigation – Stage 1*. Coffey Partners Pty Ltd. Report G444/1-AC, December 1997.

Coffey 2002, *Additional Studies for Aquifer Injection of Reclaimed Water*, Coffey Partners Pty Ltd. Report G12019/4-AL, March 2002.

Dillon, P. 2002, *Evans Head Aquifer Injection of Reclaimed Waters – Review of Investigations*, CSIRO Land and Water, Glen Osmond, South Australia.

Dillon, P. et al. 2003, *Aquifer Storage and Recovery with Reclaimed Water at Bolivar, South Australia*, CSIRO Land and Water, Adelaide, South Australia.

Dillon, P. et. Al 2007, *Aquifer Storage Transfer and Recovery (ASTR)* – Drinking water from urban stormwater and a brackish aquifer, CSIRO Land and Water (online), Available: http://www.clw.csiro.au/research/urban/reuse/projects/astr-salisbury.html (1 December 2009)

Drury, L.W. 1982, *Hydrogeologic Report No. 1982 – 13, Richmond River Valley Groundwater Investigation*, Issn. 0727 – 968X, Water Resources Comission N.S.W., Sydney.

Hess, L. & Balandin, M. 2009, *Ballina – Lennox Head Recycled Water Master Plan: Environmental Impact Statement*, Ballina Shire Council, Report No. DC08174, September 2009.

Land and Property Information NSW 2002, *Ballina 9640-3N*, Third Edition, 1: 25 000, Topographic Series.

Metcalf & Eddy 2003, *Wastewater Engineering: Treatment and Reuse*, 4th edn., McGraw Hill, New York.

Natural Resource Management Ministerial Council 2000, Australian and New Zealand Guidelines for Fresh and Marine Water Quality (online), PIMC-NRMMC, Available:

Formatted: Indent: Left: 0 pt, Hanging: 28.35 pt, Line spacing: single

Formatted: Indent: Left: 0 pt, Hanging: 28.35 pt, Line spacing: single

http://www.mincos.gov.au/publications/australian_and_new_zealand_guidelines_for_fresh_and_marine_water_quality (20 November 2009).

National Resource Management Ministerial Council et. Al 2009, *Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 2): Managed Aquifer Recharge*, National Water Quality Management Strategy Document No 24, Canberra.

Parliament of Victoria 2004, *Aquifer Storage and Recovery (ASR)* (online), Available: http://www.parliament.vic.gov.au/osisdc/inquiries/sustainableurbandesign/finalreport/img/3-1-1-AquiferStorageAndRecovery_m.gif (1 December 2009)

Formatted: Indent: Left: 0 pt, Hanging: 28.35 pt, Line spacing: single

Pyne, David G., *Aquifer Storage Recovery* (online), Available: http://www.asrforum.com/What-is-Aquifer-Storage-Recovery.html (1 November 2009)

Formatted: Indent: Left: 0 pt, Hanging: 28.35 pt, Line spacing: single

Formatted: Indent: Left: 0 pt, Hanging: 28.35 pt, Line spacing: single

Richmond Valley Council 2009, *Assessment of Environmental Impact of STP Discharge to Evans River*, RVC Quotation 166.09.

Formatted: Indent: Left: 0 pt, Hanging: 28.35 pt, Line spacing: single

Rous Water, *Future Water Strategy* (online), Available: http://www.rouswater.nsw.gov.au/cmst/rw010/lp.asp?cat=135 (15 December 2009).

7. APPENDICES

7.1 Appendix A: Evans Head

Comment [d14]: Make flow chart of process also. Microfiltration with reverse osmosis prior to injection.

7.2 Appendix B: Ballina/Lennox Head

7.3 Appendix C: Water Quality Data

Source: AGT (2002); Hess & Balandin (2009); Richmond Valley Council (2009); Coffey (1997); Coffey (2002); Natural Resource Management Ministerial Council (2000)

Table 4. Effluent Water Quality

	Units	**Woodburn Sand Aquifer**	**Treated Sewage (Evans Head)**	**Treated Sewage (Ballina) with DAF system (2008)**	**Treated Sewage (Lennox)**	**Ballina Upgrade**
Temperature	*˚C*	25	25			
Redox Potential		7.03	6.5			
Eh	*mV (pe)*	-180 (-3)	700 (12)			
DO	*%*	< 0.1	115%			
Ca	$mg\ L^{-1}$	30	23			
Mg	$mg\ L^{-1}$	22	4.9			
Na	$mg\ L^{-1}$	110	66			
K	$mg\ L^{-1}$	8.5	11			
Fe (soluble)	$mg\ L^{-1}$	1.1	0.04			
HCO_3^-	$mg\ L^{-1}$	170	110			
SO_4^{2-}	$mg\ L^{-1}$	21	62			
Cl	$mg\ L^{-1}$	190	60			
P	$mg\ L^{-1}$	0.01	0.82	0.39	5.1	0.3
NH_3**-N /** NH_4**-N**	$mg\ L^{-1}$	0.9	4	2	0.04	1.2
NOx	$mg\ L^{-1}$	< 0.01	20	2	2.1	4.8
BOD	$mg\ L^{-1}$	< 2	9	4	7	6
TSS/NFR	$mg\ L^{-1}$		25	11	14	< 1
Total N	$mg\ L^{-1}$		12	6	4	6
Oil and Grease	$mg\ L^{-1}$		0	4	5	
Faecal Coliform	*cfu/100mL*		568	100	46	
Chlorophyll A	$mg\ L^{-1}$			74	80	< 1
TDS	$mg\ L^{-1}$	262		1834		

Table 5. End Use Quality Data

		Lowland River	**Estuaries**	**Marine**	**Irrigation**	**Livestock**	**Recreation**	**Target**	**Drinking**
Temperature	*˚C*							15 - 35	
Ph		6.5 - 8.0	7.0 - 8.5	8.0 - 8.4	> 6		6.5 - 8.5	7.0 - 8.5	6.5 - 8.5
Redox Potential	*mV (pe)*								
DO	*%*	85 - 110 %	80 - 110 %	90 - 110 %				90 - 100%	> 85 %
Ca	$mg\ L^{-1}$					1000		1000	
Mg	$mg\ L^{-1}$				2000			2000	
Na	$mg\ L^{-1}$				depending on crop, 230 avg		300	300	180
K	$mg\ L^{-1}$								
Fe (soluble)	$mg\ L^{-1}$						30	30	0.3
HCO_3^-	$mg\ L^{-1}$								
SO_4^{2-}	$mg\ L^{-1}$					1000	400	400	250
Cl	$mg\ L^{-1}$				depending on crop, 350 avg		400	400	250
P	$mg\ L^{-1}$	0.02	0.03	0.025	0.05			0.02	
NH_3-N / NH_4-N	$mg\ L^{-1}$	0.02	0.015	0.015			10	0.015	
NO_3^- / NO_2^-	$mg\ L^{-1}$	0.04	0.015	0.005				0.005	
NOx	$mg\ L^{-1}$					400 NO3, 30 NO2	10 NO 3, 1 NO2	10 NO3, 1 NO2	50 NO3
BOD	$mg\ L^{-1}$								
TSS/NFR	$mg\ L^{-1}$								
Total N	$mg\ L^{-1}$	0.5	0.3	0.12	5			0.12	
Oil and Grease	$mg\ L^{-1}$								
Faecal Coliform	*cfu/100mL*					100	150	100	0
Chlorophyll A	$mg\ L^{-1}$	0.005	0.004	0.001					
TDS	$mg\ L^{-1}$					4000 , 2000 poultry	1000	1000	500

7.4 Appendix D: Definition of Terms

Aquitard- A saturated layer with low hydraulic conductivity relative to adjoining layers.

Biological Oxygen Demand (BOD)- Empirical measurement that gives the relative oxygen requirement of a microbial population in the water sample.

Effluent- Treated wastewater leaving a wastewater treatment plant.

Groundwater- Water stored in rock and soil below the Earth's surface.

Head- The head is the height above a standard reference datum that a column of water can be supported by its static pressure against the atmospheric pressure.

Hydraulic Conductivity- A measure of the ease with which water can flow through rock or soil. Units of [length]/[time].

Hydrogeology- The study of groundwater.

Semi-confined Aquifer- Also known as a "leaky" aquifer, it is an aquifer where the confining layer has sufficient conductivity to allow some vertical water movement.

7.5 *Appendix E: ASR Schematic*