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Review of Relief Wells and Siphons to Reduce Groundwater Pressures and Water Levels in Discharge Areas to Manage Salinity

A Report to Water & Rivers Commission, WA

Ramsis Salama, Riasat Ali, Daniel Pollock,
Jasmine Rutherford and Viv Baker

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1. BACKGROUND

1.1 Causes of salinity

Salt in sea spray, mainly sodium chloride, is carried inland by the prevailing winds and deposited by rainfall on the land in small amounts. This ranges from about 200 kg/ha/year near the coast to 20 kg/ha/year on the eastern fringes of the agricultural areas, depending on the distance from the coast (Hingston & Gailitis, 1976). In its natural state, native vegetation used most of the rainfall leaving the salts behind in the soil. Over thousands of years this has resulted in salt accumulation ranging from a few hundred to a few thousand tonnes under each hectare of typical farmland. In the higher rainfall areas (generally with moderate relief and well drained soils), salt storage is lower due to leaching. In the low rainfall areas, having relatively flat and poorly drained soils with limited leaching, salt storage is high. Land and stream salinisation, in the wheatbelt of Western Australia, is the result of man-made changes in the delicate equilibrium which prevailed before European settlement. The replacement of native deep-rooted perennial plant species with shallow-rooted annual agricultural species altered the water balance in favour of increased groundwater recharge (Allison & Hughes, 1978; Allison *et al.*, 1990; Peck & Williamson, 1987; Williamson *et al.*, 1987; Salama *et al.*, 1993b-d). This led to a rise in groundwater levels and the rejuvenation of relict channels and increased underflow along drainage lines. Groundwater discharge increased along valley floors and upstream of geological structures and led to land and stream salinisation (Salama *et al*, 1993a). Salt stored in the soil profile has been mobilised by the rising groundwater and discharged to the surface causing land and stream salinisation (Williamson & Bettenay, 1979; Schofield *et al.*, 1988). The clearing of native vegetation resulted in large streamflow increases (~30% rainfall/yr) (Ruprecht & Schofield, 1989). Hydrographic separation techniques, using stable isotopes, indicated that storm runoff accounts for 40% of streamflow (Turner & Macpherson, 1990). It has also been shown from the long-term analysis of streamflow that groundwater flow component in streamflow can reach up to 30-40%. Of groundwater component about 30% is shallow groundwater and 70% deep groundwater (Salama *et al.*, 1993b).

1.2 Extent of the problem

Salinity is a major environmental threat facing Western Australia. In the south-west agricultural region, about 1.8 million hectares are already affected by salinity to some extent. Projections show that without rapid, large scale intervention, including significant changes to current land use practices, about 3 million hectares will be affected by 2020 and 6 million hectares (or 30% of the region) before a new groundwater equilibrium is reached (Ferdowsian *et al.*, 1996). Salt-affected land was defined as "...having excess salts in the root zone such that the potential yield of salt-sensitive crops and pastures reduced by more than 50%."

Stream salinisation is also a major problem in south-west Western Australia. Less than 50% of the divertible surface water resources remain fresh (Western Australian Water Resources Council, 1986).

1.3 Understanding of Need

The Western Australian State Government has an initiative aimed at evaluating engineering options for managing salinity, focussed primarily on the wheatbelt region. The widespread, *ad hoc* adoption of engineering schemes (pumps, relief wells, siphon wells and drains) in the absence of a sound understanding and guidelines for their placement, design and construction has proved costly to the farmers and the state.

To determine the effectiveness and efficiency of tools like groundwater pumping and drainage for reducing salinity, the Western Australian State Government established the Engineering Evaluation Initiative. This project is to be co-ordinated by the Department of Environment, Water & Catchment Protection (DEWCP) in partnership with the Department of Agriculture (DOA), Department of Conservation and Land Management (CALM), Commonwealth Scientific Industrial and Research Organisation (CSIRO) and NRM regional community groups. This four-year project will also consider the potential down-stream impacts of these engineering tools.

The WA State Government requires a review of the literature and collective experience with relief wells and siphons including design, impacts and opportunities. This review will draw upon the literature and experience arising from outside of WA as well as locally. A key component of the review will be the identification of key knowledge gaps and opportunities to improve the placement, design, construction and the optimum discharge rates in the different aquifers in Western Australia.

2. OBJECTIVES

This report provides an overview of the relief wells and siphons to reduce groundwater pressures and water levels in discharge areas to manage salinity. The review will also discuss relevant case studies from Western Australia, South Australia and New South Wales where relief wells and siphons are installed and have been monitored for a few years.

The report will specifically discuss and attempt to address the following:

- *Identify the impact of relief and siphon bores on lowering pressures and groundwater levels*
- *Appropriate design principles of relief and siphon wells*
- *Evaluated case studies*
- *Assessment of the economic, social and environmental aspects for the relief and siphon wells:*
    - *Effectiveness of siphons and relief wells to reduce hydrostatic pressures and water levels*
    - *Impact of siphons and relief wells on soil salinity*
    - *Impact of discharge water on stream salinity*
    - *Environmental impacts*
- *Assessment of knowledge gaps and recommendations*
- *Recommendations for the development of DSS or checklist for making decisions regarding which engineering options can be used*
- *Recommendations for appropriate monitoring schemes*

3. PRINCIPLES, HISTORY OF USE, OPERATION, AND MAINTENANCE OF RELIEF WELLS AND SIPHONS

All unconfined aquifers that receive more recharge than the capacity of the aquifer to discharge will develop high water levels; this will cause additional groundwater to discharge at the lower parts of the landscape. On the other hand, semi-confined and confined aquifers when they receive more recharge than the capacity of the aquifer to discharge will develop high pressures which will lead to discharge of groundwater in the lower parts of the landscape, or at break of slope or where the geological structures permit the pressure to be relieved.

Historically, relief wells are often installed to relieve subsurface hydrostatic pressures in pervious foundation strata overlain by more impervious top strata, conditions which often exist landward of levees and downstream of dams and various hydraulic structures.

In the wheatbelt of Western Australia, as well as in most other parts of the southern Australia agricultural zones, most stock water is provided by farm dams which seep into groundwater and create high pressure zones that cause seepage downstream at preferential sites. The same phenomenon is also created by interception, reverse and contour banks which cause increased recharge to the aquifer and create high pressure zones.

Relief wells can also be used to relieve hydrostatic pressures that may develop within semi-confined and confined aquifers due to rising water tables and pressures in these aquifers. These pressures might otherwise subject large areas of the landscape to act as discharge zones and cause land degradation. Relief wells, in essence, are nothing other than controlled artificial springs that reduce pressures and prevent the expansion of discharge areas and removal of soil via piping. The proper design, installation, and maintenance of relief wells are essential elements in assuring their effectiveness and are discussed in detail in Appendices A–I.

3.1 Relief Well

3.1.1 Description

Pressure relief wells refer to vertically installed wells consisting of a well screen surrounded by a filter material designed to prevent the aquifer materials entering the well. A typical relief well is shown in Figure 1. The wells, including screen and riser pipe, have internal diameters generally between 10 and 60 mm, sized to accommodate the maximum design flow without excessive head loss to maintain continuous discharge. Well screens generally consist of wire-wrapped steel or plastic pipe, slotted or perforated steel or PVC pipe (Appendices A-I).

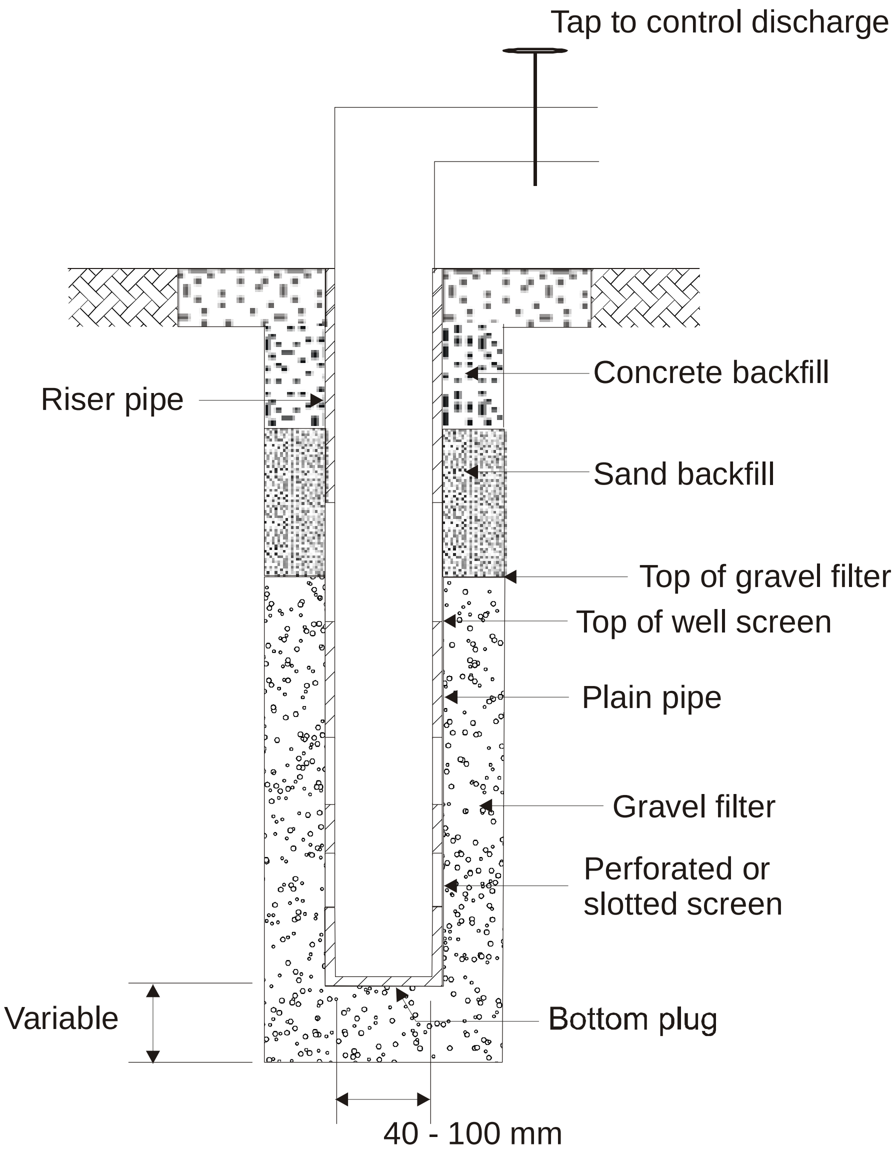

Figure 1 Construction details of a relief or siphon well

3.1.2 Use of Wells

a) Relief wells are used extensively to relieve excess hydrostatic pressures. Placing the well outlets in trenches or collector pipes below the soil surface serve to dry up seepage areas downstream of levees and dams. Relief wells are often used in combination with other under-seepage control measures, such as upstream blankets, downstream seepage berms, and grouting.

b) Relief wells provide a flexible control measure as the systems can be easily expanded if the initial system is not adequate. Also, the discharge of existing wells can be increased by pumping if the need arises. A relief well system requires a minimum of additional real estate as compared with other seepage control measures such as berms. However, wells require periodic maintenance and frequently suffer loss in efficiency with time for a variety of reasons such as clogging of well screens by intrusions of muddy surface waters, bacterial growth, or carbonate incrustation and iron deposition. Relief wells may increase the amount of under-seepage that must be handled at the ground surface, and means for collecting and disposing of their discharge must be provided. Adequate systems of piezometers and flow measuring devices must be installed to provide continuing information on the performance of relief well systems.

3.1.3 History of Use

a) The first use of relief wells to prevent excessive uplift pressures at a dam was by the US Army Engineer District, Omaha, when 21 wells were installed as remedial seepage control at Fort Peck Dam, Montana (Middlebrooks, 1948). The high pressure was first observed in piezometers installed in the pervious foundation. The excess head at the downstream toe was reduced from 15 m to 1.5 m, and the total flow from all wells averaged about 17,000 litres per minute (lpm). However, the steel screens corroded severely and were replaced by 17 permanent wells consisting of 200 mm (internal diameter) slotted redwood pipe at a spacing of 37.5 m in 1946.

b) The first use of relief wells in the original design of a dam was by the US Army Engineer District, Vicksburg, when wells were installed during construction of Arkabutla Dam, Mississippi, completed in June 1943. The relief wells were installed to provide an added measure of safety with respect to uplift and piping along the downstream toe of the embankment. The relief wells consisted of 5 m long (50 mm in diameter) brass well point screens attached to 50 mm galvanized wrought iron riser pipes spaced at 7.5 m intervals located along a line 30 m upstream of the downstream toe of the dam. Since these early installations, relief wells have been used at many levee locations to control excessive uplift pressures and piping through the foundation.

c) Relief wells can also be used to relieve hydrostatic pressures which may develop within semi-confined and confined aquifers due to rising water tables and pressures downstream of farm dams, banks and drains. Farm dams are very common in the wheatbelt of Western Australia. Seepage is reported and noticed downstream of nearly all dams. Two processes are known to cause groundwater discharge downstream of dams. The first process occurs when seepage from the dam creates a recharge mound below the dam. This will cause a rise in water level through the interconnection of the aquifer systems, and the concurrent development of a high pressure zone. The pressure causes a rise in groundwater levels downstream from the dam followed by groundwater discharge. The second process occurs when the elastic pressure generated by the weight of water increases during winter and causes the groundwater to discharge downstream of the dam (Salama *et al*., 1993).

d) Other Applications: Pressure relief wells have also been used extensively to control excess hydrostatic pressures in outlet channels including areas immediately downstream of navigation locks. Often wells incorporated in structures have been located so that they discharge through collector pipes and manholes which are not readily accessible to cleaning and maintenance unless the structures are dewatered.

3.2 Siphons

3.2.1 Description

A siphon is a closed conduit which passively (i.e. no power input) conveys liquid from a point of higher hydraulic head to one of lower head after raising it to a higher intermediate elevation which is at sub-atmospheric conditions (negative pressures). In other words, a siphon is essentially a passive vacuum pump. A siphon has a maximum theoretical lift of 10.2 m (equivalent to atmospheric pressure); however, it has a maximum practical lift of 8.3 m due to the vapor pressure of water and friction head loss.

3.2.2 Siphon Principles (Gibson, 1952)

In its simplest form this consists of an inverted U-tube (Figures I.1 and 2), both legs being full of water, and the flow is generally calculated by equating the total head producing flow, i.e. the head due to the unbalanced column of water $A_z - Z_c$, or the difference of heads in the two reservoirs, to the sum of the frictional and other losses in the pipe and of the velocity head produced (see Appendix I).

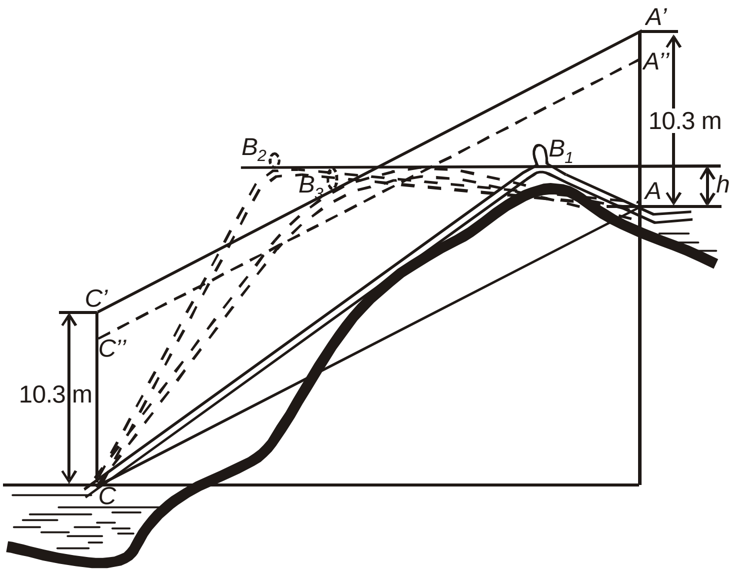

Figure 2 Siphon principles details

3.2.3 Siphon Performance (Edwards, 1984))

To analyse the performance of a siphon, it is assumed to be elementary in design and to flow full. These assumptions allow the application of the Bernoulli equation to flow from the upper reservoir to the exit end of the pipeline.

$$h = f\,\frac{L}{D}\frac{V^2}{2g} \text{ where}$$

h = the difference between the upper reservoir and the lower reservoir or exit end of conduit

f = friction constant for conduit material

L = length of conduit

D = diamater of conduit

V = velocity of fluid

g = gravitational constant

(Equation 1)

The velocity and thus quantity of flow can be calculated from Equation 1. As the summit (minimum) pressure decreases, dissolved gases present in natural water come out of solution and help form intermittent discontinuities as the pressure approaches a true vacuum. A break in the siphoning action occurs at a point less than the theoretical limit as the summit pressure continues to decrease. Writing the Bernoulli equation from the upper reservoir to the summit, we can determine the pressure at the summit using atmospheric pressure as datum.

$$O = \frac{V^2}{g}\frac{P_s}{Y} \quad h_s + f\,\frac{L_s}{D}\frac{V^2}{2g} \text{ where}$$

$\frac{P_s}{Y}$ = pressure at summit (Equation 2)

h_s = the difference between the upper reservoir and the summit

L_s = length of conduit from upper reservoir to summit

Trial application of these equations to a hypothetical system (Figure 2) pointed out several design considerations:

a) System flow would decrease as *h* decreased due to drawdown in the well. Equilibrium would occur at the drawdown yielding the system flow capacity.

b) Losses due to pipeline length and configuration could be minimised by over-sizing pipeline in relation to anticipated flow and selecting low friction pipeline materials. More the losses are minimised, the closer h_s approached P_s/y, resulting in increased siphoning efficiency.

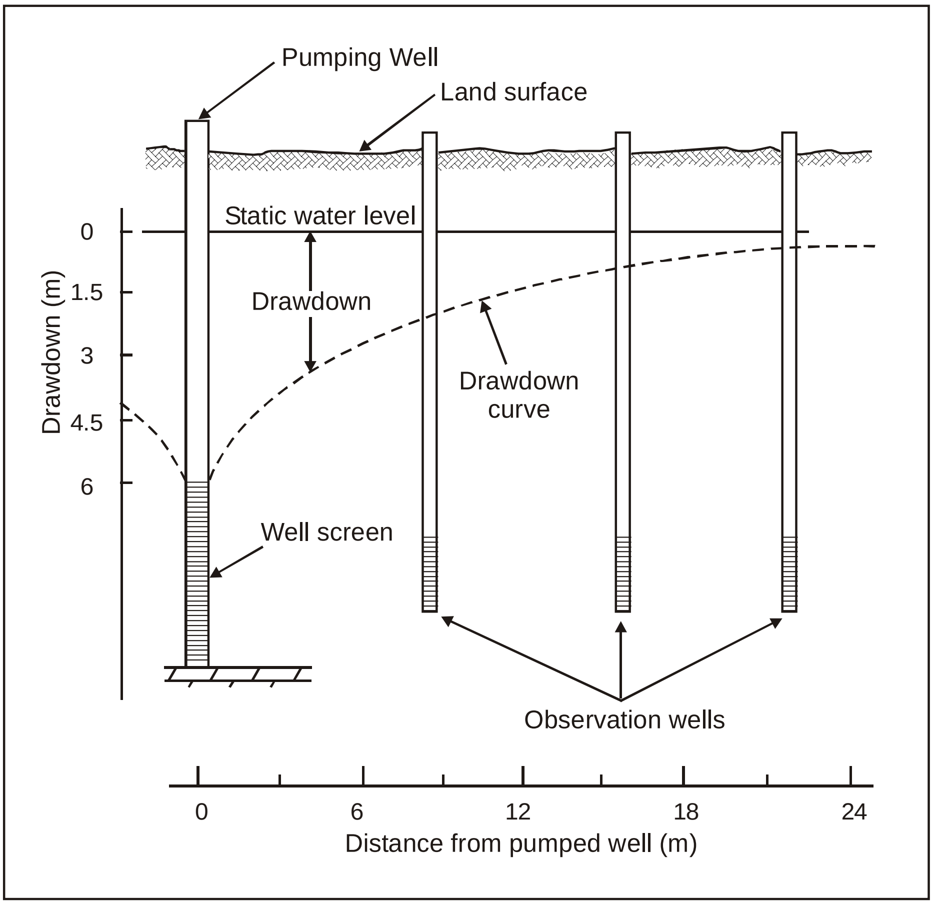

Figure 3 Extent of cone of depression as monitored in observation wells

3.2.4 Siphon operation

Siphons require priming (initial filling of line) to initiate flow. After priming, the siphon will passively convey liquid from the point of higher hydraulic head to the one of lower head indefinitely so long as the head differential is maintained and the prime is not lost.

Accumulation of air can break the siphon; however, this can be avoided by employing the following:

- Use of submerged inlets and outlets to prevent air from being drawn into the siphon line

- Maintenance of full flow in the siphon line through the removal of gases from the siphon line, which degas within the siphon line due to the sub-atmospheric pressures.

One or both of the following methods may be utilised to maintain full siphon flow:

- Maintenance of the minimum flushing velocity required to transport gases, which have degassed from the liquid, out the end of the siphon.

- Use of air chambers at the siphon crest to remove gases, which have degassed from the liquid, from the siphon. Use of air chambers renders the system less than entirely passive, since the chambers require periodic recharging.

Management of gas within the siphon line is considered to be of utmost importance in the maintenance of siphon flow. Siphon line gas management requires control of gas bubble transport, accumulation, and agglomeration and elimination of gas bubble entrapment. Gas bubble transport, accumulation, agglomeration, and entrapment are controlled by fluid flow velocity, gas buoyancy, siphon line grades and inside diameter discontinuities (i.e. fittings). Gas bubble transport in the upward leg of the siphon line is facilitated by higher fluid flow velocities, a continuous upward siphon line grade (no localised high points), and the minimisation or elimination of fittings which produce discontinuities in the inside diameter of the siphon line. The continuous upward grade and elimination of such fittings promotes buoyancy transport in the same direction as fluid flow and eliminates the accumulation, agglomeration and entrapment of gas bubbles in the upward leg of the siphon line. The fluid flow velocity in the upward leg is not as critical as it is in the downward leg of the siphon line, and the upward leg fluid flow velocity should be balanced against minimisation of head loss to maximize overall flow rates.

The direction of gas bubble transport, if any, in the siphon line downward leg is determined by whether transport due to fluid flow velocity or gas buoyancy is dominant. Fluid flow velocity tends to cause the gas bubbles to move downward in the downward leg of the siphon line towards the end of line. Gas buoyancy tends to cause the gas bubbles to move upward in the downward leg of the siphon line towards the siphon crest.

In order to utilise the minimum flushing velocity to maintain full flow in the siphon line downward leg, the fluid flow velocity must be dominant in the downward leg. That is, the fluid flow velocity must be greater than the required minimum. Additionally a continuous, downward, siphon line, grade (i.e. no localised high points) and the minimisation or elimination of fittings which produce discontinuities in the inside diameter of the siphon line, is necessary. The continuous downward grade and elimination of such fittings eliminates the accumulation, agglomeration and entrapment of gas bubbles in the downward leg of the siphon line.

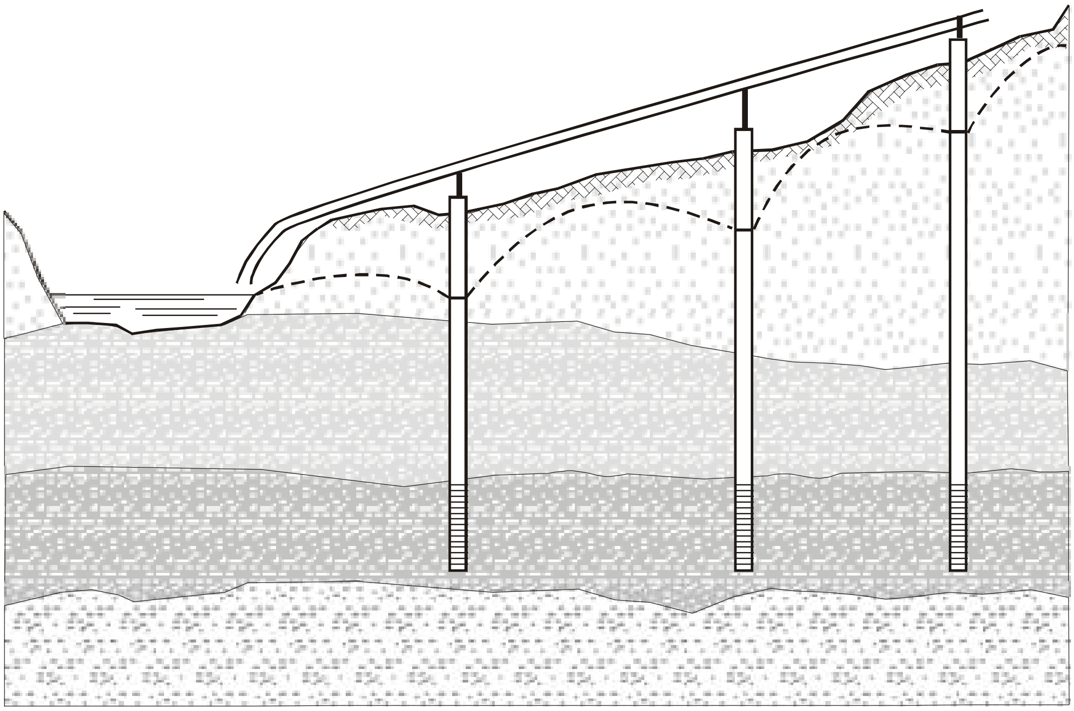

Figure 4 Several siphon wells can operate along a discharge area to reduce water levels and increase the area of maximum drawdown

4. APPROPRIATE DESIGN PRINCIPLES OF RELIEF AND SIPHON WELLS

4.1 Basic Considerations

4.1.1 Hydrogeological Investigations

The design of a relief or siphon well system should be preceded by thorough field and geologic studies. Sufficient data should be collated to define geomorphology, soils, the depth, thickness and physical characteristics of the prospectus aquifers, as well as the thickness and physical characteristics of the top soil layers upstream and downstream of the proposed site. Particular attention should be given to the presence of carriers like buried channels and barriers like dykes and veins. High exit gradients and concentrations of seepage which may occur adjacent to clay-filled swales or channels will often govern the location of individual relief wells.

4.1.2 Aquifer Permeability

Preliminary estimates of aquifer permeability can be made from a simple pumping test to be conducted at the site or in case of sedimentary formations from correlations with grain size. The pumping test well should fully penetrate the aquifer, and a well flow meter should be used to determine the variations in horizontal permeability with depth.

4.1.3 Anisotropic Conditions

Analytical methods for computing seepage through a permeable sedimentary deposit are based on the assumption that the permeability of the deposit is isotropic. However, natural soil deposits are stratified to some degree, and the average permeability parallel to the planes of stratification is greater than the permeability perpendicular to these planes. Thus, the soil deposit actually possesses anisotropic permeability. To make a mathematical analysis of the seepage through an anisotropic deposit, the dimensions of the deposit must be transformed so that the permeability is isotropic. Each permeable stratum of the deposit must be separately transformed into isotropic conditions. In general, the simplest procedure is to transform the vertical dimensions with the horizontal dimensions unchanged.

4.1.4 Chemical Composition of Groundwaters

Some groundwaters are highly corrosive with respect to elements of a pressure relief well or may contain dissolved minerals or carbonates that could in time cause clogging and reduce efficiency of the well. The chemical composition of the groundwater, including river or dam waters, should be determined as part of the design investigation. The chemical composition of groundwater is a major factor in the chemical and biological contamination of well screens and filter packs.

4.1.5 Indicators of Corrosive and Incrusting Waters

- Indicators of Corrosive Water

  i) A pH less than 7

  ii) Dissolved oxygen in excess of 2 ppmb

iii) Hydrogen sulfide (H_2S) in excess of 1 ppm detected by a rotten egg odor

iv) Total dissolved solids in excess of 1,000 ppm indicates an ability to conduct electric current great enough to cause serious electrolytic corrosion

v) Carbon dioxide (CO_2) in excess of 50 ppm

vi) Chlorides (Cl) in excess of 500 ppm

- Indicators of Incrusting Water

i) A pH greater than 7

ii) Total iron (Fe) in excess of 2 ppm

iii) Total manganese (MN) in excess of 1 ppm in conjunction with a high pH and the presence of oxygen

iv) Total carbonate hardness in excess of 300 ppm

5. AQUIFER TYPES AND LANDSCAPE CHARACTERSITICS

5.1 Hydrogeology

The success of dewatering bore will mainly depend on the hydrology and hydrogeological characteristics of each site. These in turn are also dependent on landscape characteristics of geomorphology, soils and geology. Beside this, long-term rainfall trends, streamflow regime, palaeochannel characteristics and the history of clearing and agricultural development need to be taken into consideration.

Hydrogeological characteristics, such as the lithology, types of aquifers and their areal distribution together with the hydraulic properties will exert the main control on the recharge and discharge patterns which need to be controlled (see 8.2.1 and 8.2.2).

5.1.1 Aquifer Types

There are three major aquifer categories; confined, unconfined and semi confined (Kruseman & deRidder, 1989). An aquifer is a geologic unit that can store and transmit water. Unconsolidated sands and gravel, sandstones, limestone, and fractured igneous and metamorphic rocks are an example of rock units known to be aquifers. Aquitards are water-bearing formations that transmit water in insignificant amounts.

- *Unconfined aquifers*: An unconfined aquifer is a permeable layer filled or partly filled with water and overlying a relatively impervious layer. Its upper boundary is formed by a water table under atmospheric pressure. Water in a bore penetrating an unconfined aquifer does not, in general, rise above the atmospheric pressure. In fine grained unconfined aquifers in some parts of the Western Australian wheatbelt, however, gravity drainage of pores is often not instantaneous; consequently the water is released only some time after a lowering of the water level. Unconfined aquifers showing this phenomenon are called unconfined aquifers with delayed yield. The surficial sediments and sand seeps in the wheatbelt are considered unconfined aquifers.

- *Confined aquifers*: A confined aquifer is a completely saturated aquifer with upper and lower impervious boundaries. In confined aquifers the pressure of the water (i.e. hydraulic head) is usually higher than that of the atmosphere and the water in bores stands above the top of the aquifer.

- *Semi-confined or leaky aquifer*: A completely saturated aquifer is bounded above by a semi-pervious layer and below by either an impervious or a semi-pervious layer. A semi-pervious layer is defined as a layer that has a low, though measurable, permeability. Lowering of the piezometric pressure in a leaky aquifer, by siphoning, will generate a vertical flow of water from the semi-pervious layer into the discharging aquifer. In the wheatbelt, a majority of the aquifers, particularly in the valley flats, is semi-confined.

5.1.2 Distribution of aquifers in Western Australian catchments

The distribution of the aquifer systems in weathered catchments is mainly controlled by the basin morphology (Salama *et al.*, 1993d; 1994c). Unconfined aquifers occur above the impermeable layers of duricrust and basement rock outcrops along the higher slopes and the catchment divide and above clay sediments in the main drainage line and the flanks of catchments. The water table is characterised by minimum diurnal fluctuations and sharp, rapid responses to the changing balance between recharge events (rainfall or stream fluctuations) and discharge events (evapotranspiration and natural discharge). Further down slope from the catchment divide, where the clay content is higher, the deeper aquifer is confined (Salama *et al*., 1996). The extent of confinement of the system depends on the areal extent of the clay layer. The gradation of aquifer types occurs mainly on mid-slopes where the confining layer is more prominent and fades out along the streams and towards the catchment divide. The semi-confined aquifer shows a moderate response to diurnal fluctuations and a lag time between the rainfall and the rise in water level. The typical configuration of a confined aquifer model does not exist as such because it is controlled by the presence of clay overlying the lower aquifer system. Its areal extent, thickness and lithology determine the degree of confinement of the aquifer. The confined aquifer system is characterised by the strong diurnal fluctuation and weak seasonal trends.

5.1.3 Hydraulic Properties of Aquifers

The water bearing formations generally contain voids that are filled with water. The voids are interconnected to some degree. The water contained in these voids is capable of moving from one void to another, thus circulating through water-bearing formations. The ability of water bearing formations to transmit water (rather than just their ability to hold water) is called hydraulic conductivity. This property constitutes an important factor in determining the impact of groundwater discharge in lowering the water table in unconfined aquifers, and the hydraulic head in confined and semi confined aquifers.

Some formations contain a considerable volume of voids that lack interconnectivity. These formations cannot convey water from one void to another and are characterised by low hydraulic conductivity (e.g. granite and dolerite rocks). These water bearing formations are called aquitards. The size of voids is also important in determining the efficiency of flow within these formations.

Sediments and weathered rocks with high clay content are characterised by very small voids through which the water flows with difficulty, resulting in low connectivity and low hydraulic conductivity. Generally well-sorted sands and gravel have high hydraulic conductivity ranging from 1–1000 m/day (Domenico & Shwartz, 1998). Hydraulic conductivity of silty and fine sand ranges from 0.001–1 m/day (Domenico & Shwartz, 1998). The hydraulic conductivity of the weathered granite profiles and sediments including palaeochannel sediments in Western Australia ranges from ~0.001 to ~10 m/day (Clarke *et al*., 2000). In the wheatbelt, the average hydraulic conductivities for the saprock and the overlying weathered clay material range from 0.5 to ~1 m/day and 0.05 to 0.1 m/day, respectively (Clarke *et al*., 2000). Surficial and palaeochannel sediments are characterised by higher hydraulic conductivity ranging from 1 to 100 m/day (Salama *et al*., 1997a).

These aquifers respond differently to groundwater discharge by siphon and relief wells. For confined aquifers, where groundwater is kept under pressure by overlying semi-pervious layers, the aim of groundwater discharge is to reduce the hydraulic head, this can be achieved either by a relief well which discharges naturally if the water level is above ground or by a siphon well if the water level is below the surface. The loss of hydraulic head caused by discharge propagates rapidly because the release of groundwater from storage is entirely *due to the compressibility of aquifer material and that of water. Therefore, the loss of head may still be measurable even a few hundred metres from a relief or siphon well. The abstraction of relatively small amounts of water may have a significant impact on the groundwater hydraulic head away from the siphon bore. The important characteristic of this type of aquifer is the relatively fast recovery of the hydraulic head once the groundwater discharge is stopped. The propagation of hydraulic head losses is rather slow in unconfined aquifers. Unlike confined aquifers, the release of water from groundwater storage in unconfined aquifers is mostly due to dewatering of the zone through which the water is moving. Therefore, the loss of hydraulic head caused by siphon discharge is only measurable within a relatively short distance of a siphon well. The recovery of the water table in unconfined aquifers is much slower than the recovery of the hydraulic head in confined aquifers. The response of semi-confined aquifers is variably intermediate to that of confined and unconfined aquifers. In the three types of aquifers, the extent of cone of depression of low pressures or water levels will depend mainly on the aquifer characteristics as highlighted in 5.1.3.*

5.2 Geomorphology

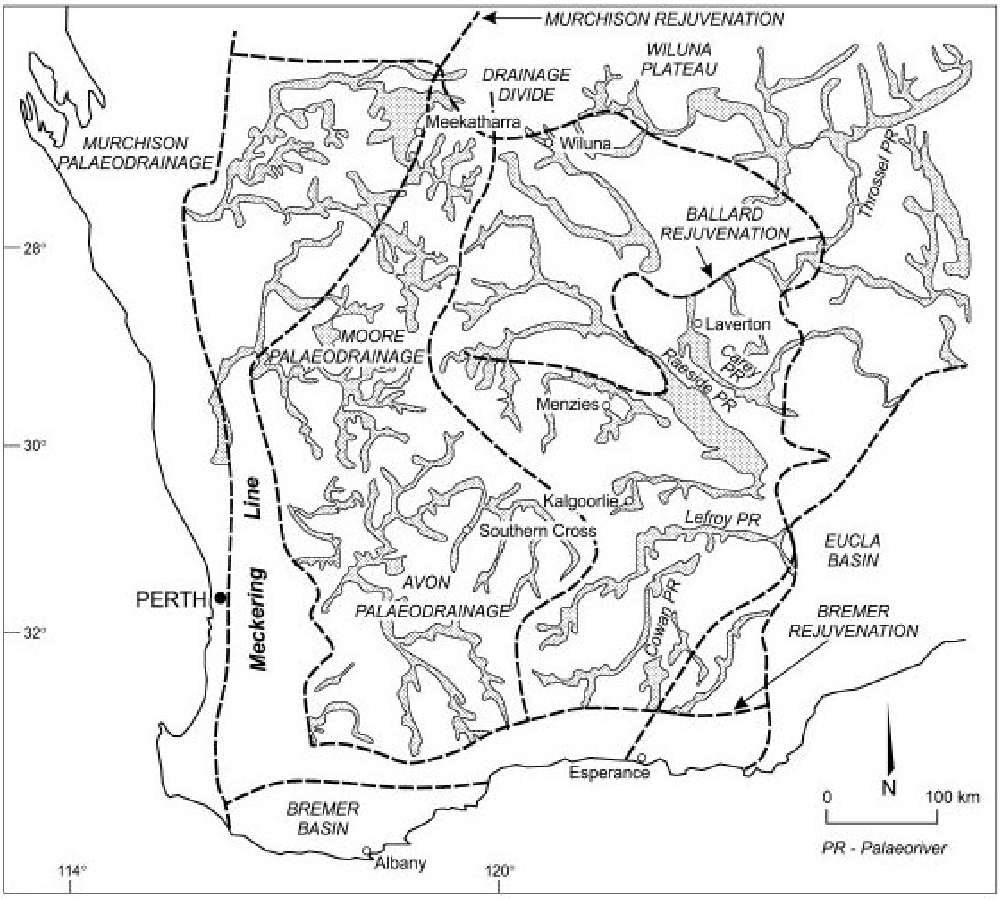

Figure 5 Palaeorivers and associated geomorphic features of the Yilgarn Craton (from Anand & Paine, 2002)

Basin geomorphology controls the mechanisms of recharge, transmission and discharge in the wheatbelt catchments. Classification of the catchments to different hydrogeomorphic units can be performed using GIS techniques (Salama *et al*., 1996; 1997b; 1999a). Most areas of the wheatbelt are now covered by a high-quality DEM produced by Land Monitor that can be used to create the hydrogeomorphic parameters required for the characterisation of the area and selection of the most suitable location to place the siphon or relief well. The methodology takes account of the important role of geology in forming topography through differential weathering, erosion and deposition. These in turn influence the formation of geomorphic and hydrogeomorphic characteristics of the catchments; the hydrogeomorphic units reflect most of the major geological features of the area (Figure 5) (Salama *et al*., 1994c, 1994f, 1997b*). In general, water levels are near the surface in the lower areas of the catchment and they increase in depth with increasing altitude. The exceptions are confined aquifers, which show an inverse relationship between water level and aquifer depth. In this case it is clear that relief wells will be more successful in the lower areas of the landscape which are natural discharge areas while siphon wells will operate successfully wherever the criteria for its operation is fulfilled (see Section 8).*

6. EVALUATED CASE STUDIES

As mentioned before, the original design and, as the name indicates, relief wells were first used for the relief of hydrostatic pressures in front of the dams and levees. Due to the rising water levels and pressures in the agricultural areas of southern Australia, monitoring wells drilled in the lower parts of the landscapes, especially near drainage lines, were found to have high artesian pressures and would be continuously flowing if the rising pipe was not raised above the water head. This led investigators to use the wells as relief wells. There are many wells of this kind discharging freely at different rates in several catchments in Western Australia: Yallanbee, Collie (Rutherford, 2000), Kent (Salama *et al*., 1995), Avon (Salama *et al*., 1997a), Blackwood and other areas of WA. The phenomena of saline seepage noticed in most of the saline rivers is caused by the rising water levels and pressures, which cause saline groundwater to discharge at the surface and cause land degradation and stream salinity. In this review we will report on five detailed studies conducted in the Western Australia in Wallatin Creek, Falls Farm, and Gordon River; Waitpinga Creek Catchment, Phil Hacket's siphon, South Australia; and in Springview, Young Catchment in New South Wales.

6.1 Wallatin Creek Pump and siphon experiment (George & Frantom, 1990)

One of the earliest experiments of using siphons was conducted in a saline hillside seep in Harvey sub-catchment in Wallatin Creek, Western Australia. Groundwater flow in the sub-catchment was taking place through semi-confined and confined aquifers. The seep was caused by the obstruction of the groundwater flow by a high basement and possible quartz veins and dyke. The experiment showed that the siphon was broken by gas build-up at the head of the pipe. This was partly solved by a gas-exchange tank which extended the operation of the siphon by up to seven days instead of two days without the tank. In conclusion, it was suggested that siphons are capable of maintaining flow rates of about 0.3 – 0.5 L/sec for periods of up to seven days before header tanks needed refilling. *Although the authors concluded that vaporisation of water in the siphon, low land-surface gradients (2.6%) and gas emanating from the borehole may make the use of siphons impractical in many cases for salinity control, it appears from the available information that the real cause of breakdown of the experiment was mainly due to the inconsistency in the design principles of the pipe line.*

6.2 Waitpinga Creek Catchment, Phil Hacket's siphon, South Australia (Henschke, 1999)

The trial site was located in a 1 ha seep, which was caused by a rock barrier. Anecdotal evidence suggests that the site became saline 20 – 30 years ago, typical of the Mt. Lofty Ranges. There were probably two phases of clearing – in the 1860 – 1870s and 1930 – 1940s. The seep was probably a response to the second clearing phase.

A production well was drilled to a depth of 12 m. The borehole was lined with 6 inch PVC casing including a 6 m screen. A 1 cm poly pipe was installed to 8 m depth in the borehole with a regulating tap at the top of the tube. The siphon commenced operation in January 1996 and had been flowing continuously for almost 4 years. The pipe discharged into the streamline 100 m down slope of the seep. Amazingly, the on-going function of the siphon was not troubled by iron oxidising bacteria.

Prior to 1996, the piezometric level was 0.5 - 0.7 m above the ground surface, in a piezometer located 20 m from the siphon bore. In November 1997, the water level was 0.3 m below ground level and in November 1999, the water level was more than 1 m below ground level. The wet seep had dried out considerably, but was still bare in the middle. A possibly acidic iron sulfide layer was present which most probably prevented germination of grasses.

There was still a small amount of baseflow into the creek, suggesting that a second siphon was required at the lower end of the seep to get better groundwater control. The baseflow had an EC of 17 dS/m (10,000 mg/L TDS).

The estimated discharge from the siphon was 83 L/min. The EC of water was 12 dS/m (7,700 mg/L TDS). Assuming a constant discharge rate and salinity, the siphon exported 40 ML of water and 300 tonnes of salt per year. Over 4 years this was equivalent to 170 ML of water and 1,300 tonnes of salt.

The analysis of the South Australian experiment indicates that in suitable hydrogeological conditions and with proper well design, siphons can be very effective in discharging large amounts of groundwater. This would reduce water levels around the well and would reduce the area of groundwater discharge, but if the accumulated salts and acidity cannot be leached, salinity will not be cured.

6.3 Relief wells in Springview, Young Catchment, New South Wales (Richardson, personal comm. 2002)

In the course of an investigation of a saline seep in Springview sub-catchment in 1990, 5 nested sites were drilled in the area to shallow (5 m), intermediate (10 m) and deep (15 m) depths. Sites P1, P2 and P3 (Figure 6) within and downstream of the seep were flowing, whereas sites P4 and P5 upstream of the seep were not flowing. The wells were monitored for a period of 10 years. The water level data in all wells showed a decline of 1 – 3 m during this period. The decline during the first 5 years was relatively slow. The rate of water level decline increased in the last 5 years and this was attributed mainly to lucerne and tree plantation in the upstream area of the catchment. *But the fact remains that although pressure heads and area of the seep decreased the wells are still flowing (although at a reduced rate (0.1 l/s)). The results of this experiment show that relief wells will not lower the water levels below the surface of the discharge area and might not be effective in managing salinity.*

6.4 Relief wells in Falls Farm, Cuballing Catchment, Western Australia. (Salama *et al*., 1993b)

Relief wells were installed in Falls Farm (Cuballing Catchment, Western Australia) in a seepage area downstream of a small farm dam. Four wells were drilled downstream of the dam to a depth of 5 m into the first saturated stratum just above the impermeable clay layer. The water levels of the wells had been related to the dam surface. Water levels in the deeper wells rose to above ground level, and fluctuations in the groundwater levels were found to be similar to changes in the surface water level in the dam. During winter, groundwater discharge occurred in the area surrounding the wells. Chemical analysis (D and ^{18}O) of the groundwater from the wells showed that the groundwater did not originate as seepage from the dam but from the main aquifer system. *Two processes are known to cause groundwater discharge downstream of dams. The first process occurs when seepage from the dam creates a recharge mound below the dam. This will cause a rise in water level through the* *interconnection of the aquifer systems, and the concurrent development of a high pressure zone. The pressure causes a rise in groundwater levels downstream from the dam followed by groundwater discharge. The second process occurs when the elastic pressure generated by the weight of the water increases during winter and causes the groundwater to discharge dowstream of the dam. In both cases, it seems that relief wells can successfully be used to relieve the pressure, but the wells will not reduce seepage from the dam, and in some cases they can even increase the seepage rates if a recharge boundary is created.*

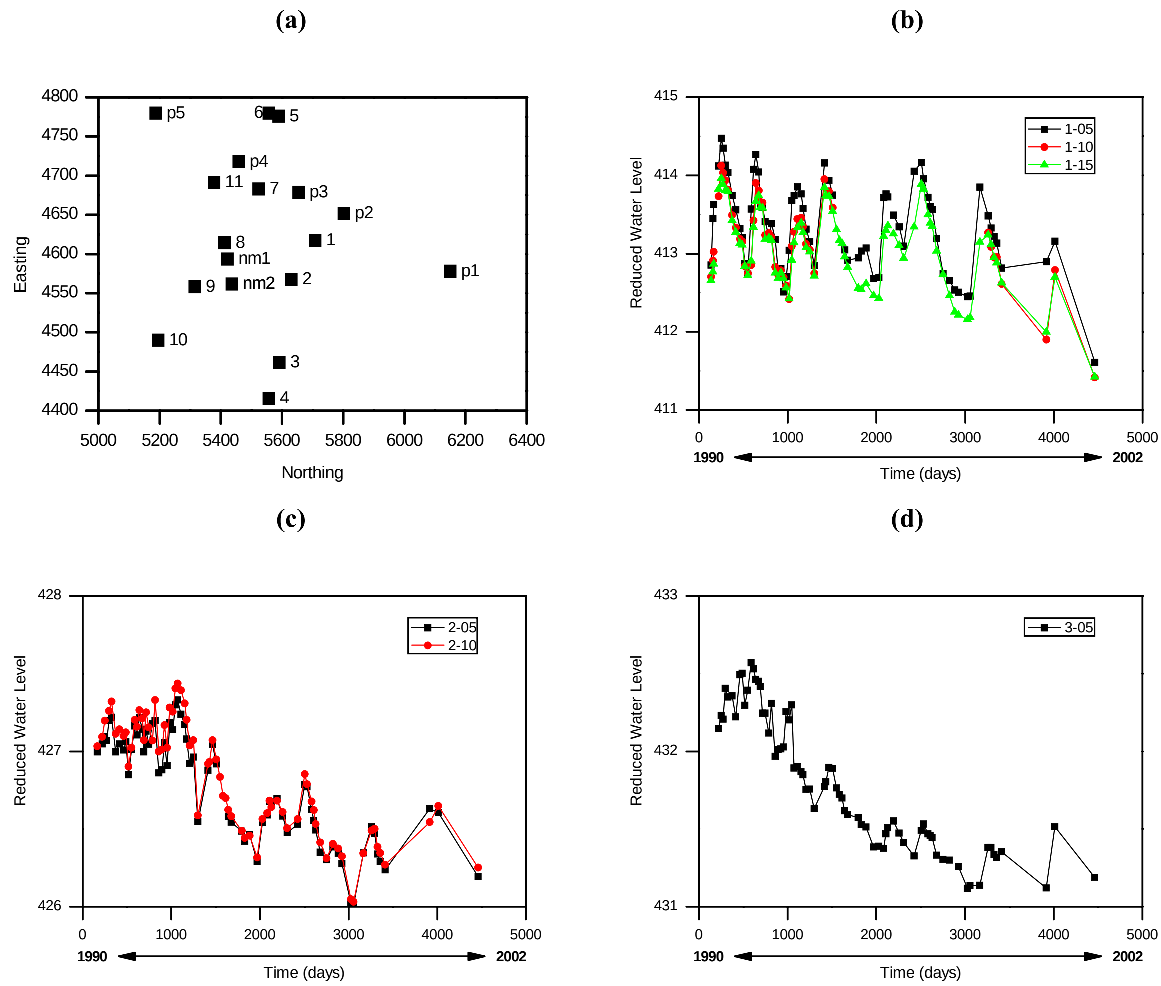

Figure 6 Location of relief wells (a) and water levels in the monitoring wells (b, c and d)

6.5 Groundwater Siphon trials, Gordon River, Western Australia (Seymour, 2002)

Two pre-feasibility groundwater (bore) siphons have been in operation since August 2000. More recently 7 groundwater siphon trial sites, and 7 other privately owned groundwater bore siphons have been in operation since September 2001. All 14 siphon sites have shown that groundwater siphoning can be made to flow at sustainable rates (Table 1).

Currently the Gordon River Catchment Group has raised sufficient funds, through NHT and private contributions, to drill a further 100 production bores. These bores will be used either as groundwater siphon bores (siphon discharge) or as relief wells (artesian discharge bores).

Table 1 Gordon Catchment siphon and relief wells

Site	Easting	Northing	Discharge L/sec	Maximum Drawdown in siphon well (m)	Total drawdown Area (ha)	% of area with drawdown < 0.5 m	% of area with drawdown ≥2m
Lockyer 1	555312	6229596	0.15		18	80	4
Lockyer 2	555302	6229604	0.1	~4			
Lockyer 3	555292	6229578	0.07				
Taylor 1	552036	6227000	0.15		67	66	14
Taylor 2	552058	6226993	0.16	~3			
Taylor 3	552084	6226978	0.17				
Thorn East 1	548477	6227309	0.15		6.2	47	17
Thorn East 2	548500	6227344	0.08	~7			
Thorn East 3	548501	6227318	0.1				
Thorn West 1	546629	6228041	0.3		16.7	58	42
Thorn West 2	546586	6228049	0.15				
Thorn West 3	546618	6228031	0.3				
Thorn West 4	546578	6227883	0.15				
Thorn West 5	546597	6227907	0.2	~7			
Thorn West 6	546613	6227877	0.15				
Diprose	547327	6229914	0.06	Dead site	-	-	Dyke, dam, flowing wells
Brown 1	548873	6224258	0.8	~4	-	-	Banks, dam
Brown 2	548881	6224188	0.7				
Arnold 1	554129	6224998	0.08	~1	21.7	55	8
Arnold 2	554112	6225022	0.1				
Arnold RW	553899	6224924	0.5	Relief well	-	-	Relief well
Thorn	546960	6225388	-	Bad site	-	-	Relief well
Moree Grazing	557664	6227619	-	flowing well	-	-	green algae

Detailed analysis of the siphon sites in the Gordon River showed the following:

- *All successful sites of constructed siphon and relief wells are located in lower parts of the landscape which are natural discharge areas (Figure 7).*
- *Relatively high productive sites are mainly due to relatively more transmissive aquifer and higher recharge caused by dams and banks upstream of salinity scorched area (Figure 8).*
- *There is adequate difference in elevation between the discharge and recharge site which allows the siphon to work continuously.*

Although the results of these experiments seem exciting from the first look, as the reported maximum drawdown near the pumping well was relatively high for the small discharge rates, yet the analysis of the results show that due to low hydraulic conductivity of the formations *the area with drawdown less than 0.5 m was found to range from 48 to 80 % of the total draw down area which reduce the effectiveness of siphon wells.*

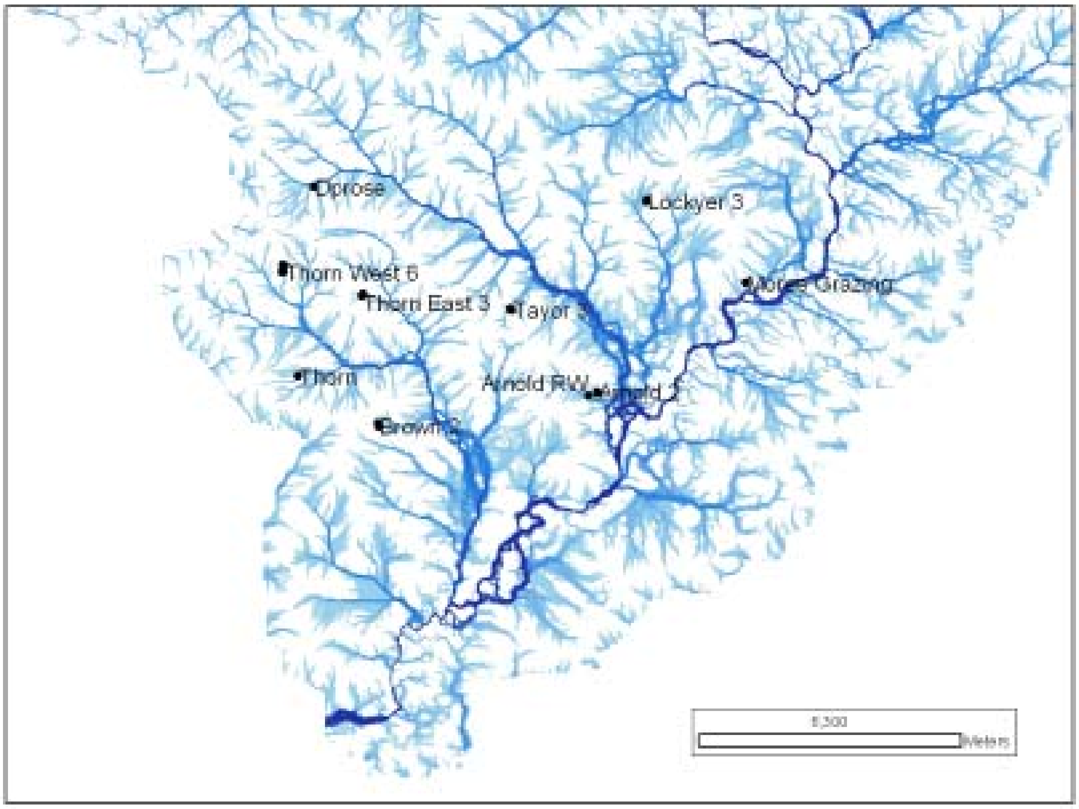

Figure 7 Location of siphon and relief wells in Gordon River Catchment

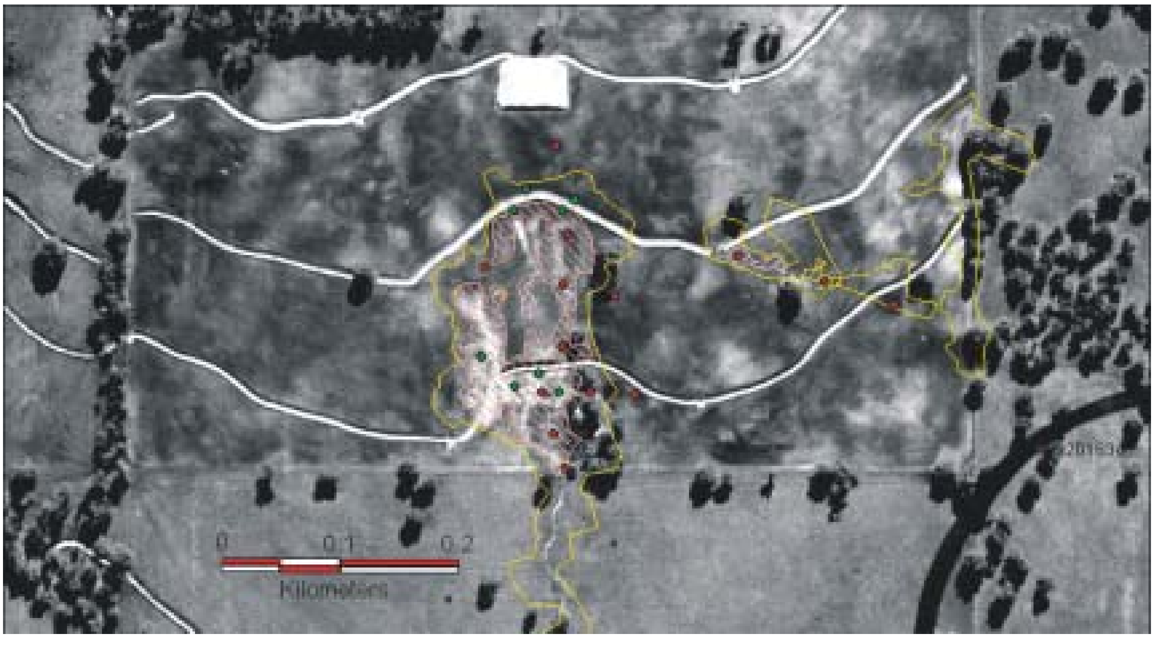

Figure 8 Siphon experiment site in Thorn west

7. ASSESSMENT OF ENVIRONMENTAL, SOCIAL AND ECONOMIC ASPECTS OF RELIEF AND SIPHON WELLS

7.1 Effectiveness of siphons and relief wells to reduce hydrostatic pressures and water levels

Relief wells: Groundwater flow in relief wells takes place under hydrostatic pressure. This pressure is created by the difference in elevation from the recharge to the discharge areas. Relief wells would generally be constructed in the lower parts of the landscape where there is enough head to cause the water to discharge freely. Due to the continuous recharge from the upper parts of the salinised area, it is not expected that the hydrostatic pressures will decrease below ground level. *From the results of the case studies as well as the theoretical analysis (Appendix I) it is unlikely that relief wells will cure salinity; the maximum they can do is to focus the areas of saline groundwater discharge to the level of the relief well outlet.*

Siphon wells: Siphon systems are installed in productive boreholes drilled in discharge areas. For a non-flowing borehole to produce, water pressures and water levels need to be reduced. Continuous abstraction will increase drawdown in the vicinity of well and also expand laterally. The extent of the cone of depression will depend on the amount of abstraction, the hydraulic properties of the aquifer and the abstraction period. The extension of the cone of depression will define the effectiveness of a particular siphon in reducing hydrostatic pressure and water levels. From the results of experiments in the Gordon River, drawdown varied from 1.0 m - 7.0 m at the siphon well and the cone of depression extended from an area of 3.5 ha to 67 ha (100 to 700 m radius from the discharge well). As the drawdown within the cone of depression surrounding the well will decrease in depth away from the well, it is expected that the water levels, in areas away from the siphon well, will only be reduced by less than 0.5 - 0.1 m. *The results from the Gordon River area show that these areas range from 50 to 80% of the total drawdown area. The minimum required water table depth (drawdown) for leaching of salts and reclaiming saline land is 2 m (Ali et al., 2000), therefore only one site (Thorn west) would be considered as partly successful in reducing the water levels to the optimum depth of 2 m and that is only for 42% of the total drawdown area. To expand the effective areas of the cone of depression (>2.0m), several siphon wells need to be constructed to extend the cone of depression to cover larger areas (Figure 4). In this case and due to the initial high cost, siphon wells might not be the panacea for salinity.*

7.2 Impact of siphons and relief wells on soil salinity

The problem of waterlogging and soil salinisation develops when the water levels rise relatively close to the soil surface. The salinity risk depends on quality of the water table. The presence of a saline shallow water table can be a major source of soil salinity if upward flux to the root zone area is sufficient. Salts are left in the root zone as a result of evapotranspiration and can adversely affect the soil structure and limit plant growth. Experiments conducted by Chaudhary *et al*. (1974), for quantification of crop response to depth and salinity of groundwater, indicated that the critical depth of water table which should be maintained for optimum crop production depends on its salinity level.

If salinity of the groundwater is relatively high and water level is at or within 2.0 m from the soil surface, soil salinity develops at a relatively fast rate because crops use that water to meet some of their ET requirements and salts get accumulated in the root zone area. Many experiments have been conducted in the past to examine crop water use from saline as well as nonsaline shallow water tables (Chaudhary *et al*., 1974; Saini & Childyal, 1977; Ayars & Schoneman, 1986; Kruse *et al*., 1993). The water table should be maintained at a depth of at least 2.0 m to minimise the saline shallow groundwater being taken up into the root zone (Ali *et al*., 2000). Salinity build-up in the root zone area also depends on the type of soil and the crops being grown. Torres & Hanks evaluated upward flow contributions to crop evapotranspiration. They concluded that, for the shallow water tables ($\leq$ 0.5 m), the contributions are similar irrespective of the soil type. At deeper water table depths when spring wheat crop was grown on the soil, the silty clay loam soil contributed more water towards ET requirements than the sandy loam.

Relief wells are used to enhance discharge at a given site and reduce the hydraulic head or upward pressure. Both relief wells and siphons can be used to reduce the hydrostatic pressures and water levels, but their impact on water logging and soil salinity will vary depending upon the quality of groundwater, soil type, the magnitude and extent of the cone of depression, the quality and quantity of the leaching water (rainfall). In relatively permeable areas, where the accumulated salts can be leached down, soil fertility can be restored. But in most cases these areas of saline seeps are characterised by low permeability soils and due to the continuous accumulation of salts by the seeping water, and the slow process of leaching of salts renders soil recovery in these cases a fruitless exercise. In areas with permeable soils, the leaching process will depend on the available drawdown, the recharge rate and the quality of the recharge water.

Relief wells can reduce the upward pressure to their outlet level at the point of their discharge. Their outlet level is kept at or above the soil surface. Because upward pressure, at the location of their discharge, remains at or near the ground level, therefore the soil salinity is not expected to decrease at the location of a relief well. Provided the yield of the relief well(s) is significant, it will however lower upward pressure below the soil surface level in uphill areas. In this case, if the water levels are below 2 m, this will enable leaching down of salts and possibly reducing the soil salinity. However, the relief wells may only economically be used at locations where significant upward pressures exist. They are not expected to be used to effectively recover prime saline land, but they are likely to have best impacts in areas having secondary or low level salinity. However, relief wells can be the safety valve of the catchment by continuously discharging an equivalent amount to the recharge in the upper parts of the catchment. This will ensure that the water levels in other parts of the catchment will not rise and salinity will not spread in the other areas.

Siphons are usually constructed where soil salinity has developed within a local area. The yield of the wells, extent of soil degradation and rainfall are some of the factors that determine the rate and degree of soil reclamation. If the problem of soil salinity was developed recently, and groundwater salinity is not very high, the area is likely to be reclaimed relatively quickly provided the rainfall is adequate to leach down the salts and yield of the wells is significant to reduce pressures below 2.0 m from the soil surface. A badly degraded area (under salinisation for a relatively long period) may take more time for reclamation. Leaching of the salts from the soil profile due to heavy rainfall events, may however give rise to soil sodicity and other several complex interactions (precipitation, adsorption, exchange processes). The chemistry of the soil is much more complex than can even be described by these interactions. There are several factors which contribute to this complexity including the time scales of chemical reactions, the extent and distribution of pores and mobility of soil water, the distribution of native and reprecipitated soil constituents by percolating water, the formation of soluble complex molecules, etc (Ali *et al.*, 2000). In the Gordon River Catchment, multiple siphons were used at 7 sites to reduce soil salinity and waterlogging. In a period of about 1 year after their installation, waterlogging was reduced at those sites where enough gradients were available and the yield of the wells was significant. The reduction in the salinity was observed by the presence of vegetation on the soil which was bare before the installation of siphons. Their relative impact on soil salinity and waterlogging was minimal where the wells collapsed due to low yield and/or gradients and geochemical reactions (increased resistance and reduction of flow area in the pipe due to precipitation of iron). The spatial extent of the impact varied among sites. Therefore the siphons are likely to be very effective in reducing soil salinity and waterlogging within localised areas provided the yield of the wells is enough to reduce water levels and rainfall is adequate to cause leaching down of salts below critical levels.

7.3 Impact of groundwater discharge from relief and siphon wells on stream salinity

Recent investigations suggest that the likelihood of reversing or even containing salinity and recovering saline rivers is low over much of the south west of West Australia (Hatton & Salama, 1999). This is mainly due to the fact that saline groundwater discharge is increasing as the groundwater levels are continuously rising and dissolving more salts from the unsaturated zones. The impact of groundwater discharge on stream salinity depends on the chemical composition of groundwater, the groundwater component of streamflow, evaporation and accumulation of salt, leakage rates and the process of salt export. We will discuss the impact of groundwater discharge based on detailed review of each one of these components:

Chemical composition of groundwater:

Meteoric water infiltrates through the unsaturated zone to the water table aquifer and through the aquifer outcrop in the case of a confined aquifer. The groundwater composition changes in space and time, becoming more saline with depth and distance away from the recharge zone. The concentration of salt in the system can be explained by four main mechanisms: withdrawal of water through uptake by plant roots for transpiration; loss of water during the weathering process and the formation of new minerals; leakage between aquifers; and evaporation upstream of geological structures and near discharge zones (Salama *et al.*, 1993c, 1994a). The groundwater is mainly Na-Cl type and at saturation with respect to most of the carbonate minerals, chalcedony, talc and tremolite. The water changes in its chemical composition as rock-water interaction takes place. The weathering products are gibbsite and kaolinite, with the release of Na^+, K^+, Mg^{++}, Ca^{++}, HCO_3^- and H_4SiO_4. The preclearing weathering products are produced in a system open to CO_2 (through the plant roots), with groundwater under this system having excess Na^+. Following clearing, the system becomes depleted in CO_2 and the groundwater becomes depleted in Na^+ through exchange with Mg^{++} from the rock surface. Geochemical modelling showed that most of the constituents in groundwater can be accounted for by taking into consideration the constituents of rainfall with minor additions from the weathering process. *Based on this analysis it is expected that salt in groundwater will increase with distance from the recharge to the discharge point and that salt will be stored behind geological structures, in stagnant areas of palaeochannels and* *in terminal discharge points and that relief and siphon wells sited in these locations will contain more salts than in any other areas of the catchment.*

Groundwater component in streamflow:

It is well established that clearing would lead to increase in streamflow (Ruprecht & Schofield, 1989). In many catchments in the wheatbelt, the drainage line would be a depression in the landscape covered by trees. The increase in streamflow and the high velocity of the surface runoff eroded the clay surface and exposed the sandy layers of the relict channel. The increase in gradient during the last twenty years alone would be about several metres, which would increase the discharge rate to five fold. The unconfined aquifer transmissivity would increase by the additional thickness added to the aquifer. Recharge rates increased ten to twenty fold after clearing: this in turn would have caused a similar increase in groundwater discharge. Previous studies have shown that the major part of streamflow volumes are generated as throughflow from perched, shallow groundwater systems, and that overland flow and groundwater flow only makes minor contribution (Turner *et al*., 1987). It has been shown from the long-term analysis of streamflow that groundwater flow component in streamflow can reach up to 30-40% with shallow groundwater forms 30% of the groundwater component, while deep groundwater forms about 70% (Salama *et al*., 1993; Salama & Bartle, 1998). *Although it is expected that it may have taken several years for the groundwater discharge to reach the surface, groundwater discharge would have been taking place as throughflow to the streambeds and palaeochannels which is the main process of salt accumulation in these areas.*

Evaporation and accumulation of salt:

Salinity develops as the discharge groundwater evaporates and salt accumulates in the top layers of the soil. Evaporation rates depend on the difference between vapour pressures in the atmosphere and the surface of the ponds. Evaporation from the open surface of a pond was found to range from 1 to 10 mm/day depending on the time of the year (Otto & Salama, 1994). On the other hand, evaporation from saline water decrease by increase of salinity as the presence of dissolved salts lower vapour pressure of the water body and therefore the vapour pressure gradient. These depend on relative humidity of the atmosphere and chemical activity of the saline water. Evaporation from bare soils depends on the reflectivity of the soils and decreases with increase of accumulated salt. Evaporation from stream-beds is much higher than bare soils due to the rapid rate of leakage of water in relatively more permeable stream bed. *Salt accumulation and spread of salinity will depend on the rate of groundwater discharge and evaporation rate.*

Leakage and fingering process:

Leakage will depend on permeability of the stream-bed on which the water is flowing. In a pumping test experiment conducted for more than 12 months in the Salt River System (Salama *et al*., 1997a), water was discharging from a pumping well at a continuous rate ranging from 840–1200 m^3/day. Groundwater from the pumping well was discharged about 500 m downstream of the pumping well. The running water from the discharge did not flow more than 300 m away from the point of discharge.

In another detailed study of leakage from evaporation ponds in Useless Loop (Townley *et al*., 1990), it was found that leakage mainly occurs by a fingering mechanism, due to the instability created by dense brines which overlie seawater of lower salinity (Wooding, 1989). The downward movement of a single finger must be balanced by the upwards movement of an equal volume of old sea water. In laboratory experiments to study the fingering process, it was found that fingers were formed at locations where there were depressions in the sand surface. This observation is consistent with expectations, because any unstable process needs some kind of perturbation to initiate. This type of leakage is most probably similar to what happens during leakage of discharge water along stream where the flow runs only for a few hundred metres and in most cases stands in small pools if the gradients and the water levels in the stream are near the surface. The salinity will increase by evaporation and the water in the surface will be more saline than the water underneath which will start a downward fingering process (Salama *et al*., 1993a). High salinity in two flat areas in Wallatin Creek stream was also attributed to a similar process. As water is ponded in flat areas behind a geological structure, water evaporates leaving behind a dense saline layer. *Leakage and fingering are the main processes through which salt accumulates in palaeochannels and other similar structures. Leakage occurs by gravity along a saline "finger" created by the instability of the denser saline layer overlying the less dense saline layer. The downward movement of the saline finger will be balanced by an upward movement of the same volume of less dense water. As this process continues, salinity accumulates in the aquifer. It is therefore not expected that salinity of the upper layers in the stream will increase by the groundwater discharge from a relief well or a siphon.*

Salt export:

Salinity of streams in the catchments increases as annual rainfall decreases and the salt storage increases (Schofield & Ruprecht, 1989; Johnston *et al*., 1980; Peck & Williamson, 1987). Stream salinity and salt export in the wheatbelt catchments is higher than in the Darling Range catchments due to the fact that groundwater salinities and salt storage are higher because the rainfall is lower and there are different hydrogeological patterns controlling the distribution, storage and mobilisation of salt (Salama *et al*., 1994c).

Export of salt is controlled mainly by groundwater discharge. In the uncleared sub-catchment (Durrokoppin) in Wallatin Creek (Salama *et al*., 1993), no salt is exported despite the presence of highly saline groundwater aquifer because the water level is still 7 m below ground surface and there is no groundwater discharge. The small salt export recorded comes from leaching of salt into surface runoff during heavy rainfall. By comparison, salt export from a small, cleared sub-catchment (Wimmera), which accounts for almost 20% of the total export from the Wallatin Creek catchment, comes from groundwater discharge into the stream. In the cleared catchments, groundwater levels are at the surface in most of the low-lying areas, and groundwater discharge is taking place along the channels. In order to account for the salt load in the stream in the Wimmera sub-catchment, groundwater discharge has to take place along a 4 km stretch of the stream channel. The minimum amount of groundwater discharge that can cause this amount of salt load is approximately 80-120 m^3/day, for a groundwater salinity of 0.03 tonnes/m^3.

The increase in groundwater discharge will increase the areas affected by salinity in the valley floor of the catchments in two ways. As the streamflow increases due to increased discharge, more of the low lying areas will be flooded by saline water. As the water gets evaporated, the area will become more saline. Concurrently the groundwater will continue to rise with the result that there will be more diffusive discharge of saline groundwater in the valley floor. The extent of the area affected by salinity will depend on the hydraulic *characteristics of the top soil layer, the volume of groundwater discharge and the type of salt crust which develops (Salama et al., 1993d and e).*

In all cases of groundwater discharge through any of the engineering options, the regional environmental aspects will depend on the amount and quality of groundwater discharge. Groundwater discharge through seepage from large areas is mainly controlled by the hydraulic conductivity of the top soil layers, the area of discharge will increase proportionally to the hydraulic conductivity. The discharge through relief wells will bring the same or larger amount of water that is discharging naturally but through a smaller outlet. It is therefore expected that at a regional scale there would be no difference in the amount of salt discharged to the surface. The only difference would be that the salt discharge through diffusion will take a long time to come to the surface and in most cases will be deposited in the soil surface by evaporation of the seepage water. The accumulated salt will be washed to the stream at the beginning of the rainy season. On the other hand, the discharge from relief wells will be continuous through a smaller outlet, and the water could form a rivulet if a series of discharge wells are operating at the same time. The effect of this needs to be further investigated.

7.4 Other environmental aspects

There are many other unknown environmental impacts as well. A project is currently under way by an Honours student (Annabelle Bushell) at Murdoch University to assess the impact of siphon discharge on streamflow, water quality, aquatic macro-invertebrate communities and groundwater, as well as economic feasibility of siphons in the agricultural industry.

Although it is highly recommended that the community should play a strong role in setting the objectives of salinity policy and salinity management (Pannell, 2001b), the construction of these siphon systems was not based on economic evaluation or environmental criteria. The farmers were keen to see the white salty areas in their landscape disappear. In the lower parts of the landscape this is usually the most difficult target to achieve. The environmental aspects of the discharge water on the streams were not of any major concern.

7.5 Social and Economic aspects

In Western Australia, the story of salinity is largely the story of wheatbelt valley floors. Today, they are the locations of the most severe dryland salinity problem, but historically, they were where agriculture was established first in the region, and they often produced the best crop yields. They are home to a host of unique biology, and are the sites of creeks, rivers and lakes. Because of their flatness, valley floors often determined the routes for railway lines, and consequently the locations of many towns now suffering salinity damage (Pannell, 2001b). Economics is only one facet but clearly it is an important one. Economic development was one of the key objectives in opening up and clearing the wheatbelt in the first place. These days, many see the harnessing of economic incentives as providing the best prospect for dealing successfully with the salinity that resulted from such clearing (Pannell, 2001b). Losses of productive land to salinity will contribute to declines in farm numbers and farm incomes, with flow-on social effects on rural towns and the provision of services. Overall, salinity is just one of a number of factors contributing to economic pressures on farmers. For most farmers, salinity is not the most important of these factors. The rate of adjustment of some farmers out of agriculture is not likely to be greatly influenced by land salinisation, although it will no doubt be the decisive factor for some individuals. Other economic pressures will continue to be the main influence on farm numbers and farm incomes (Pannell, 2001b).

In this context, the question need to be answered is: What is the cost effectiveness of relief and siphon wells? No detailed systematic analysis of cost and benefits for relief and siphon wells has been carried out anywhere in Australia, but there are several studies associated with groundwater pumping for mitigation of salinity (Dogramaci, 2002). The main conclusions of the analysis indicate that groundwater pumping is expensive and difficult to justify except in very rare cases. The cost of groundwater pumping is related to the initial cost of constructing the borehole, price of the pump and running expenses. Relief wells on the other hand do not require a pump or running expenses, siphon systems are the same except that they require a discharge line. It is therefore possible that both relief and siphon wells can be cost effective if the reduction in pressure and levels can be translated to reduction in salinity and recovery of scorched land.

8. RECOMMENDATIONS FOR THE DEVELOPMENT OF DSS OR CHECKLIST FOR SELECTING APPROPRIATE ENGINEERING OPTIONS

8.1 Treatment options

There are great expectations among the farming community, the public and some officials that a range of treatments are available and could be adopted for the reclamation and /or prevention of salinity. In reality, viable treatments for salinity prevention are only available for a small proportion of the agricultural land where they can be applied successfully (Salama *et al*., 1994b; Pannell, 2000). Necessary treatments for salinity prevention in the agricultural land include extensive areas of perennial plants (including shrubs, perennial pastures and trees), integrated with engineering works such as pumping, drainage, relief and siphon wells. For farmers at least, the benefits from salinity prevention are usually not enough to outweigh the high up-front costs that farmers have to bear to establish large areas of perennials, not to mention the ongoing income sacrifice from the land on which they have been established (Pannell, 2000). The rate of groundwater rise and the spread of salinity can only be slowed or reduced by either limiting the recharge to groundwater or increasing groundwater discharge by finding ways to remove groundwater in an environmentally sound and practical way. Available options include:

- reducing recharge through surface water management;
- reducing recharge by increasing the area of the catchment planted to perennial vegetation; and
- increasing discharge with drains or pumps

No single salinity management option is likely to be successful on its own. In most cases a combination of reducing recharge and enhancing discharge are required to manage salinity in an effective way.

8.1.1 Surface water management

Water on the surface, or perched above a clay layer within 50 cm of the surface, is the easiest water in the catchment to manage. If not controlled, this water causes erosion, waterlogging and ponding. Earthworks such as grade banks, W-drains, spoon drains and reverse interceptor banks can be used to direct this water to on-farm storage or into a watercourse. Generally surface water is relatively fresh and unlikely to cause downstream salinity problems. However, due care must be taken to ensure that diverting the water does not cause erosion or further waterlogging or flooding problems for neighbours. *Care must also be taken in the design and construction of these structures as in most cases these structures could increase recharge to the groundwater, as gradients change due to silting, water would be retained for a longer time behind the structures and thus enhance recharge.*

8.1.2 Recharge reduction

This will include surface water management to reduce the residence time of water in the catchment, and introducing more water using crops in winter. In most catchments recharge occurs to some extent though at different rates over all the areas that are not salty (these are the discharge areas). Generally recharge reduction options need to be applied to large areas.

Options include incorporating perennial pastures in a phase farming system and farming between alleys of trees or shrubs such as oil mallees and tagasaste. Scope is limited to increase the water use of annual crops and pastures, but profitable annuals may allow land managers to undertake some other less profitable salinity management strategies. Many land managers are also protecting and enhancing remnant native vegetation, and revegetating land for biodiversity, conservation and commercial returns.

8.1.3 Discharge enhancement

The first step of discharge enhancement should be planting of trees in selected areas of the catchment including dams, banks and drains if existing in the catchment as these structures are the major areas which cause further recharge beside the normal recharge in the catchment. The second step is the selection of an engineering solution if required; in most cases these solutions are going to be on a provisional basis to be replaced by the recharge control strategies when fully operational. The selection, of which engineering options works best in a particular part of the landscape, will depend upon several parameters which in most cases are spatially variable and require expert advice before rushing into such an endeavour:

Three options are available for increasing groundwater discharge:

- Strategic placement of bands of trees at the break of slope will intercept water before it moves to deeper layers (Farrington & Salama, 1996).

- Engineering options such as deep drains, aquifer pumps, relief wells and siphons which actively remove groundwater from the system. These can be very effective in containment, and if applied intensively, can result in an area being reclaimed. Because of the cost of installation, operation and maintenance, these options may be most suited to protecting valuable assets such as farm buildings, dams, towns, roads and threatened ecosystems.

- The best management options for catchment rehabilitation is to combine recharge control with discharge enhancement (Farrington & Salama, 1996)

The criteria for the selection of the most suitable management options as well as the role of soils, geology and geomorphology in positioning relief wells and siphons in south-western Australia are detailed in Appendix J. It must be emphasised that this can be used as a preliminary guide only. One of the important criteria for the selection of the management option is to estimate the amount of ground discharge which need to be disposed to solve the salinity problem, a simple calculator was designed which can be used for this estimation (Appendix J). For siphons another simple calculator was constructed to help design a continuously operating siphon

9. RECOMMENDATIONS FOR APPROPRIATE MONITORING OF THE DISCHARGE ENHANCEMET SCHEMES

The environmental impacts of all engineering discharge enhancement schemes for salinity mitigation are either vaguely known or in most cases unknown. At the same time salinity development in the catchment as well as the catchment health requires some type of monitoring before and after the construction of such projects to be able to assess the effects of constructed relief and or siphon wells on the catchment health.

To be able to conduct such studies, certain catchment indicators for land, water and biota need to be selected for monitoring and evaluation (Section 9.1 and Table 2) of the overall catchment health. On the other hand, for monitoring the effects of groundwater discharge from relief well or siphon on water levels in the area surrounding the constructed wells, these need to be measured at regular basis. The water quality of the stream upstream and downstream of the area of discharge must also be monitored.

9.1 Catchment indicators

The indicator approach (National Land and Water Resources Audit) for assessing catchment condition selects indicators either as specific or aggregated measures. The approach recognises that broad-scale data sets are often more readily available and better depict regional pattern than fine-scale data. Broad-scale coverages are usually generalised from detailed data and so tend to highlight the predominant biophysical processes and characteristics that determine catchment condition. The major benefit of broad-scale data in decision-support systems is a clearer identification of key and dominant patterns than can be provided through aggregating a collection of discontinuous and inconsistent fine-scale data sets. http://audit.ea.gov.au/ANRA/coasts/docs/estuary_assessment/Catchments_Assessing.cfm

9.2 Monitoring and evaluation

Satellite imagery is being used under the Land Monitor program to provide maps of saline land and vegetation in agricultural areas. Satellite images are combined with digital elevation modelling (DEM) based on aerial photographs. This is proving to be a very valuable tool for planners and engineers as it provides contour maps of much greater accuracy than previously available.

A long-term groundwater monitoring network has been extended and information stored through the AgBores and ComBores databases. A comprehensive analysis of groundwater status and trends in the agricultural region has been undertaken as part of the National Land and Water Resources Audit.

Table 2 Indicators used to define the water, land and biota sub indices and the catchment condition index

Indicators	Related catchment management issue
Water	
Suspended sediment load	Modelled post-settlement change in suspended sediment loads
Pesticide hazard	Pesticide use is a surrogate for pesticide pollution risk
Industrial point source hazard	Industrial pollution contamination risk
Nutrient point source hazard	Nutrient point source loading of waterways
Impoundment density	Ecosystem changes associated with altered flows
Land	
2050 high dryland salinity risk/hazard	Modelled risk assessment of salinity impacts
Soil degradation hazard	Soil and land use assessment of soil degradation risk
Hill slope erosion ratio	Modelled assessment of changes in hill slope erosion potential from natural conditions
Biota	
Native vegetation fragmentation	Deterioration in native habitat
Native vegetation extent	Habitat quantity and distribution
Protected areas	How much habitat is protected
Road density	Human population and land use intensity pressures
Feral animal density	Extent feral animals have impacted on native biota
Weed density	Extent of disturbance to native vegetation

Table 3 River condition assessment indices and sub-indices

<table>
<tr><td>Macro invertebrates</td><td></td><td>Aquatic Biota Index</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td>Landuse</td><td rowspan="3">Catchment disturbance</td><td rowspan="13">Environment Index</td></tr>
<tr><td>Infrastructure</td></tr>
<tr><td>Landcover change</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td>Bedload condition</td><td rowspan="3">Habitat</td></tr>
<tr><td>Riparian vegetation</td></tr>
<tr><td>Connectivity</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td>Flow duration</td><td rowspan="4">Hydrological disturbance</td></tr>
<tr><td>Seasonal periodicity</td></tr>
<tr><td>Seasonal amplitude</td></tr>
<tr><td>Mean annual flow</td></tr>
</table>

9.3 Water level monitoring

Monitoring groundwater is the only way to determine the depth, quality and rate of change of levels. This information is essential in determining the likely risk of salinity and whether or not the treatments are effective. One or two shallow piezometers should be constructed upstream and sideways from the discharging well to monitor water level changes.

9.4 Stream and soil salinity

Monitoring to follow long term trends in stream salinity, and spread of areas affected by salinity can help determine effective treatments and whether or not the treatments are working. Monitoring stream salinity is usually very difficult as it changes with variability in seasonal rains and runoff groundwater seepage into the stream and quality of the groundwater discharge from the relief or siphon well. Nevertheless keeping long time records of electrical conductivity might shed some light on possible changes.

9.5 Sustainability Indicators

The focus on monitoring by some of its advocates is probably not sufficiently grounded in an understanding of farm management. It would probably be more productive in many cases to focus on management practices first, and allow monitoring to follow if that is appropriate (Pannell, 2001a). Even if management changes are made to avert a problem of land or water degradation, it does not necessarily follow that monitoring of indicators will form part of the management package. This depends on factors such as how useful the indicators are to subsequent management decisions, and how accurate they are. It should be accepted that most farmers will not choose to monitor a wide range of sustainability indicators unless it is beneficial to do so, and that economic motivations will play an important role in that decision. Some of the benefits from monitoring indicators accrue to the broader community, particularly where farmer data is used by agencies in assessing resource management issues. Some reviewer have highlighted the importance of these data, and decried the lack of farmer monitoring. However, a more pragmatic position is to accept that if the data are important enough to the agencies, they need to take steps to ensure that they are collected, rather than relying on voluntary cooperation from public-spirited farmers (Pannell, 2001a).

One of the most succinct comments by Pannell (2001a) on the common practice of including standard socio-economic variables in lists of suggested sustainability indicators (e.g. farm profit, farm debt), such variables are already routinely collected by a range of statistical and economic agencies. While they are, no doubt, related in various ways to the resource management issues of interest, including them in indicator programs appears to be mainly a needless distraction from the core issues. A better role in the process for the economics discipline would be to evaluate the economic viability of available resource management practices, and to assist in assessing the economic benefits of monitoring.

10. CONCLUSIONS AND RECOMMENDATIONS

The main aim of this review is to evaluate siphons and relief wells as an option for managing salinity, focussed primarily on the wheatbelt region. Based on the arguments presented in this review we will now try to answer the basic questions of the project objectives:

10.1 Appropriate design principles of relief and siphon wells

The technology and expertise for the construction of groundwater wells which can be used as relief or siphon wells are well known and applied by farmers in all parts of the wheatbelt. We provide in Appendices A-I detailed and systematic instructions for the design and construction of relief and siphon wells modified from U.S.A.C.E. (1992) and Driscoll (1995).

No more work is required in this area.

10.2 Evaluated Case Studies

Five cases studies from different parts of the country were presented in this review, the main conclusions are:

- *Relief and siphon wells are constructed by farmers and researchers in many parts of the country, but very few of them are regularly monitored or reported.*
- *All successful sites of constructed siphon and relief wells are located in lower parts of the landscape which are natural discharge areas. Relatively high productive sites are mainly due to relatively more transmissive aquifer and in some cases in higher recharge caused by dams and banks upstream of salinity scorched area*
- *The analysis of the South Australian experiment indicates that in suitable hydrogeological conditions and with proper well design, siphons can be very effective in discharging large amounts of groundwater. This would reduce water levels around the well and would reduce the area of groundwater discharge, but if the accumulated salts and acidity cannot be leached, salinity will not be cured.*
- *Although relief well can reduce pressure heads in discharge areas, the results show that relief wells will not lower the water levels below the surface of the discharge area and as such might not be effective in managing salinity.*
- *Relief wells can successfully be used to relieve hydrostatic pressure, but the wells will not reduce seepage from the dam, and in some cases they can even increase the seepage rates if a recharge boundary is created.*
- *There is adequate difference in elevation between the discharge and recharge site which allows the siphon to work continuously. Failure in siphon operation is mainly caused by inconsistency in the design principles of the pipeline.*
- *Although the results of siphon experiments in the Gordon River seem exciting from the first look, as the reported maximum drawdown near the pumping well was relatively high for the small discharge rates, yet the analysis of the results show that due to low hydraulic conductivity of the formations the area with drawdown less than*

0.5 m was found to range from 48 to 80 % of the total draw down area which reduce the effectiveness of siphon wells.

10.3 Assessment of the environmental, economic and social aspects for the relief and siphon wells:

10.3.1 A review and assessment of the role of relief and siphon wells in reducing pressure and lower water tables

There is more than enough evidence to show that relief wells can reduce pressures and siphons can reduce pressures and water levels (Appendices A – I). Due to the fact that relief and siphon wells are always constructed in the lower areas of the landscape which are always a natural groundwater discharge zone or potential discharge zone, all the presented evidence indicates that salt export to these sites will continue until all the mobile salt in the catchment is depleted, which can vary between a few hundred to a few thousand years (Hatton *et al*., 2002).

Due to their position in the landscape, being in the lower part of catchments in the vicinity of discharge areas, relief wells are usually shallow in depth and if no recharge management is conducted in the upstream parts of the catchment, the recharge areas from which the relief well will get its supply will remain the same; therefore it is expected that the discharge of relief wells will also be continuous (though decreasing for the first few months until equilibrium is reached between the recharge and discharge rates), unless the recharge pattern is changed. As such, relief wells have the following advantages over pumped wells, drains or siphons:

1. Shallow depth to the water bearing formations

2. Low cost of installation and maintenance

3. Minimal running cost

4. Socially more acceptable as relief wells will limit the area of groundwater discharge (seepage) to the well point and does not need extensive work to improve the area

5. Environmentally more acceptable at the local scale

On the other hand relief wells can have the following disadvantages:

1) Although relief wells will limit the areas of discharge, they will not reduce water levels in the discharge area; therefore the area might not be reclaimed. Hypothetically, on the assumption that aquifers are continuous throughout the catchment; it is possible that if enough relief wells are constructed to balance the overall catchment recharge, the overall rising trend of groundwater levels might be controlled and the catchment will not suffer additional salinity problems.

2) Relief wells will, in most cases, be more productive at the lowest part of the landscape, adjacent to valleys and palaeochannels which is a natural discharge area.

3) In most cases relief wells need to be operated with other engineering solution(s) which causes water levels to drop (i.e. siphon wells).

No more work is required in this area.

10.3.2 A review of the literature and discussion on the role of relief and siphon wells in managing salinity

As relief wells cannot reduce water levels below ground surface, it is not possible that they will be effective in solving salinity problem at the discharge point. On the other hand if relief wells are designed in the best hydrogeological plan to take care of all the additional recharge in the catchment, that salinity spread in the catchment will be stopped and possibly reverse the trends of rising water levels in the upper parts of the catchment.

In case of siphons, if the water levels are reduced below levels (>2.0 m) where the accumulated salts can be leached out, it might be possible to manage the saline areas. The yield of the wells, extent of soil degradation and rainfall are some of the factors that determine the rate and degree of soil reclamation. If the problem of soil salinity was developed recently, and groundwater salinity is not very high, the area is likely to be reclaimed relatively quickly provided the rainfall is adequate to leach down the salts and yield of the wells is significant to reduce pressures below 2.0 m from the soil surface. A badly degraded area (under salinisation for a relatively long period) may take more time for reclamation. Leaching of the salts from the soil profile due to heavy rainfall events, may however give rise to soil sodicity and other several complex interactions (precipitation, adsorption, exchange processes). ***As the case in all discharge enhancement engineering solutions, this area needs further investigation through more rigorous groundwater modelling and field experiments.***

10.3.3 Environmental impacts of engineering solutions

This is the biggest unknown in all salinity mitigation endeavours. Although the knowledge, techniques and expertise for the construction of any of the engineering solutions are readily available and there are some reviews on the potential downstream impacts of the discharge water, yet it is not based on any substantial evidence.

In all cases of groundwater discharge through any of the engineering options, the regional environmental aspects will depend on the amount and quality of groundwater discharge. Groundwater discharge through seepage from large areas is mainly controlled by the hydraulic conductivity of the top soil layers, the area of discharge will increase proportionally to the hydraulic conductivity. The discharge through relief wells will bring the same or larger amount of water that is discharging naturally but through a smaller outlet. It is therefore expected that at a regional scale there would be no difference in the amount of salt discharged to the surface. The only difference would be that the salt discharge through diffusion will take a long time to come to the surface and in most cases will be deposited in the soil surface by evaporation of the seepage water. The accumulated salt will be washed to the stream at the beginning of the rainy season. On the other hand, the discharge from relief and siphon wells will be continuous through a smaller outlet, and the water could form a *rivulet if a series of discharge wells are operating at the same time.* ***More rigorous detailed work is required in this area.***

10.3.4 A review and assessment of the cost effectiveness

No detailed systematic analysis of cost and benefits for relief and siphon wells has been carried out anywhere in Australia, but there are several studies associated with groundwater pumping for mitigation of salinity (Dogramaci, 2002). The main conclusions of the analysis indicate that groundwater pumping is expensive and difficult to justify except in very rare cases. The cost of groundwater pumping is related to the initial cost of constructing the borehole, the price of the pump and the running expenses. *Relief wells on the other hand do not require a pump or running expenses, siphon systems are the same except that they require a discharge line. It is therefore possible that both relief and siphon wells can be cost effective if the reduction in pressure and levels can be translated to reduction in salinity and recovery of scorched land. That is without taking into consideration the possible environmental side effects of saline water discharge into streams which might have adverse effects and as such would be counter productive.*

10.4 Assessment of knowledge gaps and recommendations

10.4.1 A review of the placement of wells in different hydrogeological environments.

The literature review did not reveal adequate information regarding selecting the optimum location of relief and siphon wells; however we were able to design two tables which can be used for providing information to assist in the selection of the most suitable engineering option at a specific site (Appendix J). Although there are regional maps of soils, geology, geomorphology and in some areas detailed hydrogeology, the spatial variability makes it difficult to use the available information on the local scale. Guidelines produced in Appendix J based on geological and geomorphological provinces provide an approximate framework. A better understanding of the spatial variability within each province with respect to aquifer materials and landform and slope, would assist more accurate selection to be made.

Site specific studies are required for each case with detailed photo interpretation, site inspection and analysis of available records and data for selecting the most suitable engineering solution as well as the best location of the production well. Additional national and regional projects to characterise the different hydrogeological provinces will not substitute for the detailed site specific studies and will only be waste of resources.

In summary:

1. Due to spatial variability, the extent of the cone of depression will depend on aquifer characteristics which will depend on local hydrogeology and aquifer types.
2. Lowering water levels in confined aquifers at low rates as expected from relief and siphon wells will not affect the unconfined aquifers and as a consequence will not reduce water levels and will not have noticeable impact on salinity management.

3. If siphon operation is interrupted for some time the effect of lowering the water table will be negated.

It is therefore recommended that siphon sites be selected for small saline areas which are caused by local recharge areas. In this case it might be possible to control the discharge rates which can cause effective drawdown.

(Effective drawdown is defined as the drawdown which is appropriate for leaching down of salts and will depend on permeability of the soil in the drawdown horizon, the amount of leaching water and the quality of the leaching water).

Do relief and siphon wells work in broad valley flats of the ancient and rejuvenated landscape zones which are highly saline?

Most of the groundwater in the aquifers that occur in the broad valley flats of the ancient and rejuvenated landscape zones is under pressure. Relief wells can be very productive in some of these areas but the continuous discharge which will take place through the relief well will, in most cases, be almost the same as the diffuse discharge which is taking place through the streambeds as most of these aquifers are interconnected. The utmost it can achieve is the localisation of the area of discharge. On the other hand although siphons can reduce water levels but due to the relatively high transmissivity of sediments in palaeochannels and to the continuous flow of water from the upstream parts, areas of effective drawdown will be very small which render them ineffective.

10.4.2 A review of design and construction of siphon lines

We designed a simple calculator for estimating the discharge area which can be caused by different rates of recharge in a catchment using Darcy's Law. This calculator can be used for estimating the amount of excess groundwater which needs to be discharged by any of the engineering solutions: siphon, relief well, pumping well or drain. It can also be used to estimate the number of trees to be planted to reduce the recharge in the upper parts of the catchment.

We also designed another calculator for the design of siphon lines; the calculator will estimate the optimum velocity and carrying capacity of the line using Bernoulli's equation.

No more work is required in this area.

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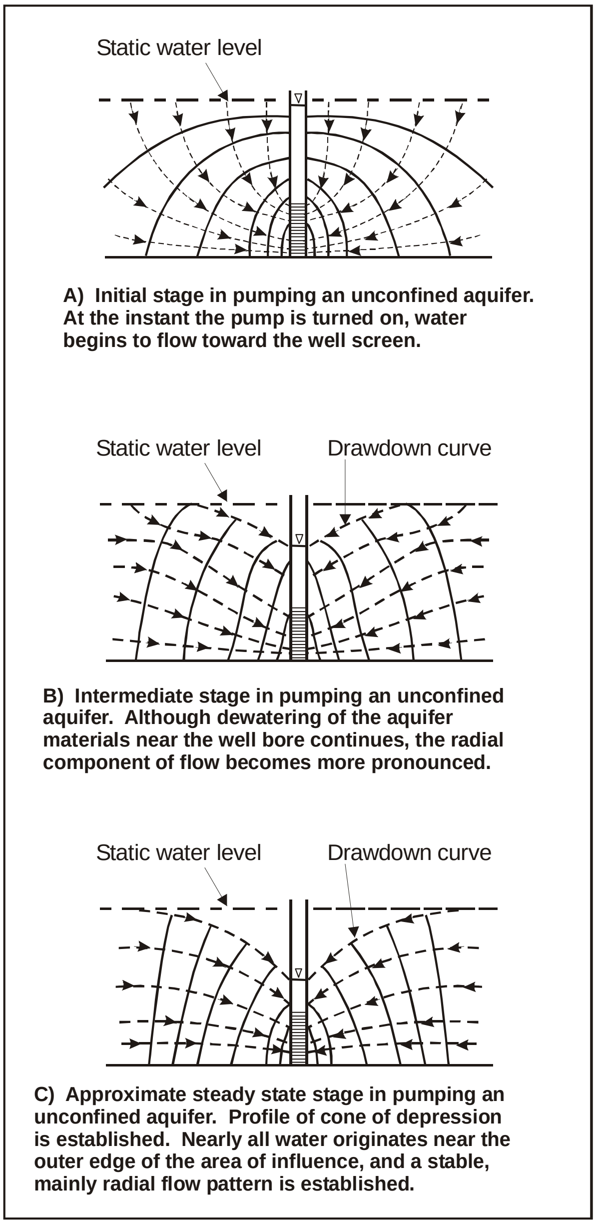
APPENDICES

APPENDICES

APPENDIX A: THEORETICAL ANALYSIS OF FLOW AND DRAWDOWN IN AND AROUND RELIEF AND SIPHON WELLS (after Driscoll, 1986)

Analysis of Single Well - Assumptions

Analytical procedures for determining well flows and head distributions adjacent to single artesian relief wells are presented below. By definition, relief wells signify artesian conditions, and equations for artesian flow are applicable. It is assumed in the following analyses that all seepage flow is laminar or viscous, i.e., Darcy's Law is applicable. It is also assumed that steady state conditions prevail; the rate of seepage and rate of head reduction have reached equilibrium and are not time dependent. Unless otherwise indicated, the well is assumed to penetrate the full thickness of the aquifer (Figure A.1).



A) Initial stage in pumping an unconfined aquifer. At the instant the pump is turned on, water begins to flow toward the well screen.

B) Intermediate stage in pumping an unconfined aquifer. Although dewatering of the aquifer materials near the well bore continues, the radial component of flow becomes more pronounced.

C) Approximate steady state stage in pumping an unconfined aquifer. Profile of cone of depression is established. Nearly all water originates near the outer edge of the area of influence, and a stable, mainly radial flow pattern is established.

Figure A.1

Equilibrium Well Equations

Well discharge equations for equilibrium conditions were derived by various investigators (Slichter, 1899; Turneaure & Russell, 1901; Thiem, 1906). These equations relating well discharge to drawdown assumed two-dimensional radial flow toward a well (the vertical component of flow is ignored). There are two basic equations; one for unconfined conditions and the other for confined conditions. For both equations, all dynamic conditions in the well and ground are assumed to be in equilibrium; that is, the discharge is constant, the drawdown and radius of influence have stabilised, and water enters the well in equal volumes from all directions. Both assume horizontal flow everywhere in the aquifer with recharge occurring at the periphery of the cone of depression. Figure A.2 shows a vertical section of a well constructed in an *unconfined* aquifer.

The equation for the well yield of an unconfined aquifer is:

$$Q = \frac{1.366K(H^2 - h^2)}{\log R/r} \qquad \text{(A.1)}$$

where

Q = well yield or pumping rate, in m^3/day

K = hydraulic conductivity of the water-bearing formation, in $m^3/day/m^2$(m/day)

H = static head measured from bottom of aquifer, in m

h = depth of water in the well while pumping, in m

R = radius of the cone of depression, in m

r = radius of the well, in m

Equation A.1 is often called the equilibrium, or Thiem, equation.

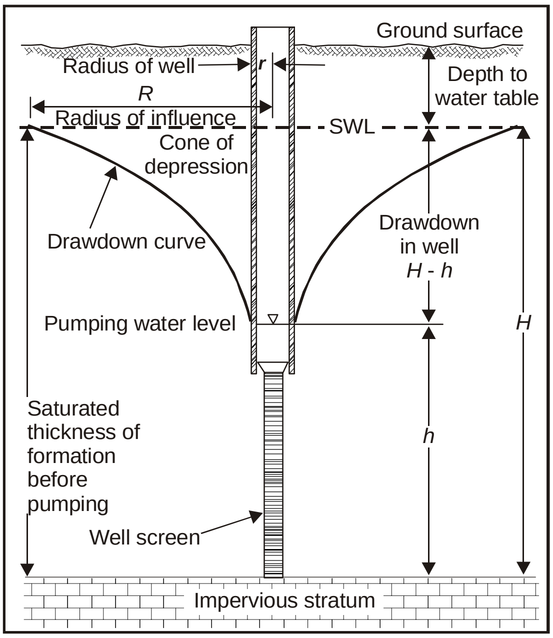


Figure A.2 Well in an unconfined aquifer showing the meaning of the various terms used in the equilibrium equation

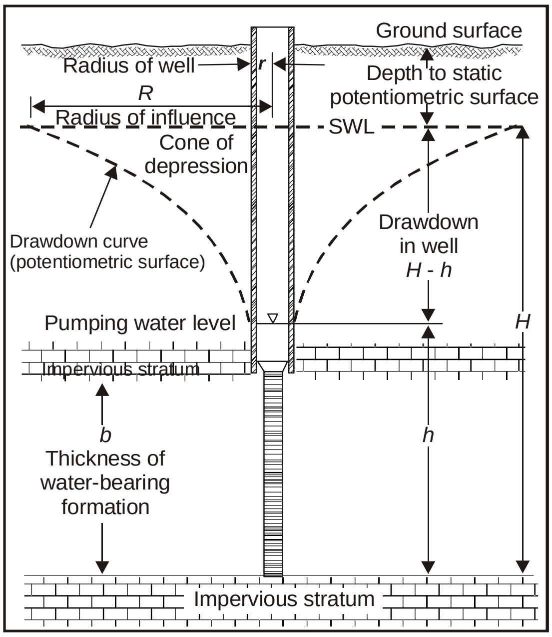


Figure A.3 Well in a confined aquifer showing the meaning of the various terms used in the equilibrium equation

Figure A.3 is a vertical section of a well pumping from a *confined* aquifer.

The equation for a well operating under confined conditions is:

$$Q = \frac{2.73Kb(H-h)}{\log R/r} \qquad \text{(A.2)}$$

where

h = thickness of aquifer, in m

(All other terms are as defined for Equation A.1)

Derivations of the foregoing equations are based on the following simplifying assumptions:

1. The water-bearing materials have a uniform hydraulic conductivity within the radius of influence of the well.
2. The aquifer is not stratified.
3. For an unconfined aquifer, the saturated thickness is constant before pumping starts; for a confined aquifer, the aquifer thickness is constant.
4. The pumping well is 100% efficient, that is, the drawdown levels inside and just outside the well bore are at the same elevation. Head losses in the vicinity of the well are minimal.
5. The intake portion of the well penetrates the entire aquifer.
6. The water table or potentiometric surface has no slope.

7. Laminar flow exists throughout the aquifer and within the radius of influence of the well.

8. The cone of depression has reached equilibrium so that both drawdown and radius of influence of the well do not change with continued pumping at a given rate.

These assumptions appear to limit severely the use of the two equations. In reality, however, they do not. For example, uniform hydraulic conductivity is rarely found in a real aquifer, but the average hydraulic conductivity as determined from pumping tests has proved to be reliable for predicting well performance. In confined aquifers where the well is fully penetrating and open to the formation, the assumption of no stratification is not an important limitation.

Assumption of constant thickness is not a serious limitation because variation in aquifer thickness within the cone of depression in most situations is relatively small, especially in sedimentary rocks. Where changes in thickness do occur, as in glacial sediments, for example, they can be taken into account. The assumption that a well is 100% efficient can cause the calculated well yield to be seriously in error if the real well is inefficient because of improper design or construction.

The assumption that the water table or potentiometric surface is horizontal before pumping begins is not correct. The slope or hydraulic gradient, however, is usually almost flat and the effect on calculation of well yield is negligible in most cases. Slope of the water table or potentiometric surface does cause distortion of the cone of depression, making it more elliptical than circular.

Flow in all regions of an aquifer is considered to be laminar. Some investigators have theorised that turbulent flow near a well could result in relatively high head losses. Laboratory and field tests show, however, that some departure from laminar flow near a well causes only small additional head losses (Mogg, 1959).

Determining aquifer hydraulic conductivity

Equations A.1 and A.2 can be modified to calculate hydraulic conductivity if *Q*, *H* and *R* are determined from a pumping test, and *b* is known from the driller's log. For an unconfined aquifer, the equation for calculating *K* is:

$$K = \frac{Q \log r_2 / r_1}{1.366\left(h_2^2 - h_1^2\right)} \qquad \text{(A.3)}$$

where

r_1 = distance to the nearest observation well, in m

r_2 = distance to the farthest observation well, in m

h_2 = saturated thickness, in m. at the farthest observation well

h_1 = saturated thickness, in m. at the nearest observation well

All other terms are as defined in Equation A.1

All the parameters on the right-hand side of Equation A.3 can be determined from a pumping test. Two observation wells, located at distances r_1 and r_2 from the pumped well, are required to determine h_1 and h_2.

Figure A.4 shows a sectional view of a pumping test layout in an unconfined formation for determining the hydraulic conductivity of the formation. All pertinent factors are easily measured in this kind of test, and the hydraulic conductivity of the aquifer can be determined accurately.

For confined conditions, the equation for determining the hydraulic conductivity from a test installation similar to Figure A.4 is:

$$K = \frac{Q \log r_2 / r_1}{2.73b(h_2 - h_1)} \qquad \text{(A.4)}$$

where

all terms except the following are the same as for Equation A.3

b = thickness of the aquifer, in m

h_2 = head, in m. at the farthest observation well, measured from the bottom of the aquifer

h_1 = head, in m. at the nearest observation well, measured from the bottom of the aquifer

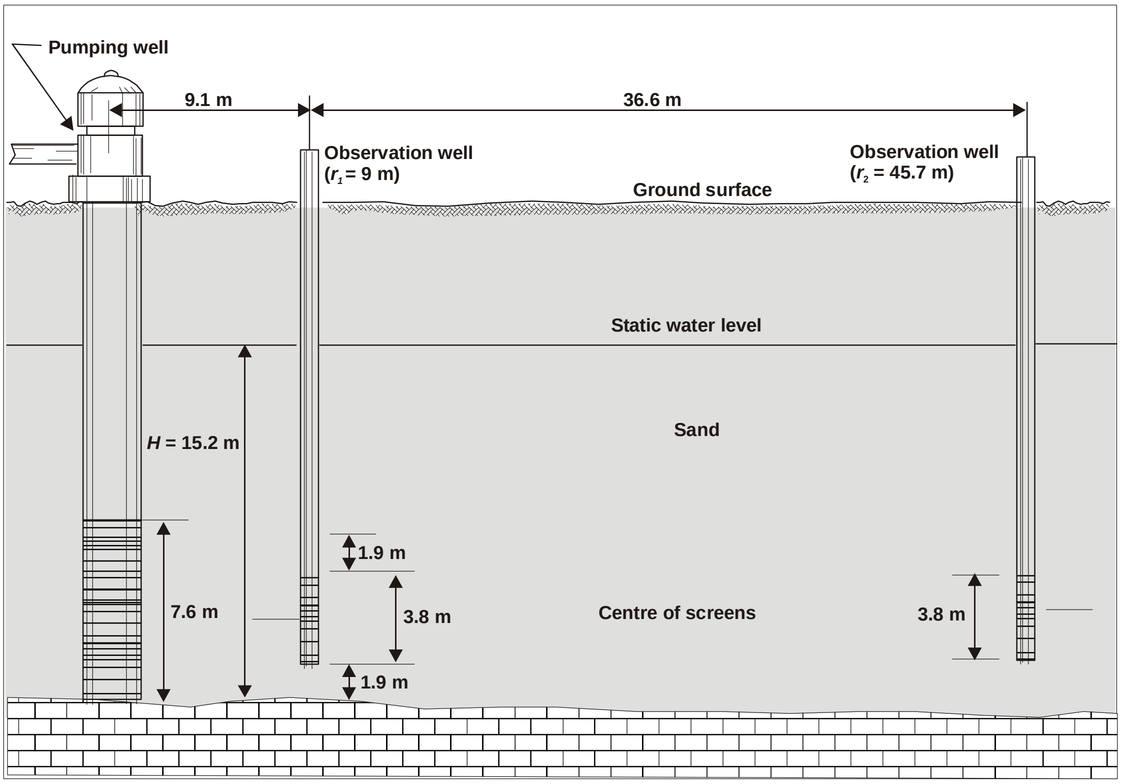


Figure A.4 Typical arrangement of a pumped well and observation wells for obtaining field data required to calculate hydraulic conductivity from well-discharge equations. Observation wells can be placed further away from a production well in confined conditions and still provide reliable data

In addition to providing accurate means for calculating the average hydraulic conductivity of an aquifer, the equilibrium equations are useful for studying the relationship of various factors to each other and to well yield. They show, for example, that if all other parameters are equal, well yield is directly proportional to hydraulic conductivity. A formation with twice the hydraulic conductivity of another should provide twice the yield. For a confined aquifer, Equation A.2 indicates that the yield is directly proportional to the formation thickness when all other parameters are equal.

Relationship of Drawdown to Yield

Equation A.2 for a well operating under confined conditions shows that yield is directly proportional to drawdown, $H - h$, as long as the drawdown does not exceed the distance from the static potentiometric surface to the top of the aquifer. If the drawdown exceeds this amount, b will then be reduced and the proportionality no longer holds true. Theoretically, this means that if the drawdown is doubled, the yield is doubled. Stated another way, the specific capacity of a well is constant at any pumping rate as long as the aquifer is not dewatered.

For a well in an unconfined aquifer, the part of the formation within the cone of depression is actually dewatered during the pumping. This affects the ratio of drawdown to yield. When the drawdown is doubled, the well yield is less than doubled because the saturated thickness is reduced. The specific capacity decreases with increased drawdown; in fact it decreases directly in proportion to the drawdown.

Figure A.5 shows the relationship between drawdown and yield for an unconfined aquifer. Maximum drawdown means lowering of the water level to the bottom of the well; 50% drawdown means lowering of the water level to a point halfway between the static water level and the bottom of the well. Maximum yield is the quantity a well will produce at maximum of 100% drawdown. For example, suppose that a well 12.2 m deep has a static water level of 1.5 m and the saturated thickness of the formation is 10.7 m. During a test, the water was pumped at 87 m^3/day and the pumping level stabilised at 4.6 m below the ground surface, or at a drawdown of 3m. How much will the yield be with 6.1 m of drawdown and the pumping level at 7.6m?

In this case, 100% drawdown is 10.7m. The 3 m drawdown during the test is thus 29% of the total possible drawdown. The curve in Figure A.5 shows that at 29% drawdown, the yield is 50% of the obtainable maximum; thus 87 m^3/day is 50% of the maximum yield of the well. A drawdown of 6.1 m is 57% of the total possible. The curve shows that this drawdown would give 82% of the maximum yield. If 87 m^3/day is 50% of the maximum, then 82% of the maximum would be 82/50 x 87 = 142 m^3/day. The well can be expected to yield 142 m^3/day at 6.1 m of drawdown.

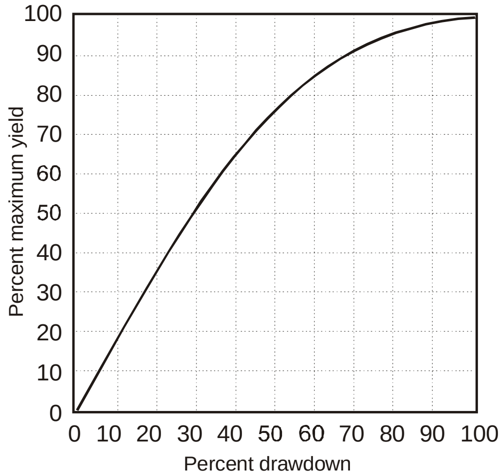


Figure A.5 Comparison of yield with drawdown in an ideal unconfined aquifer that is fully penetrated and open to the well

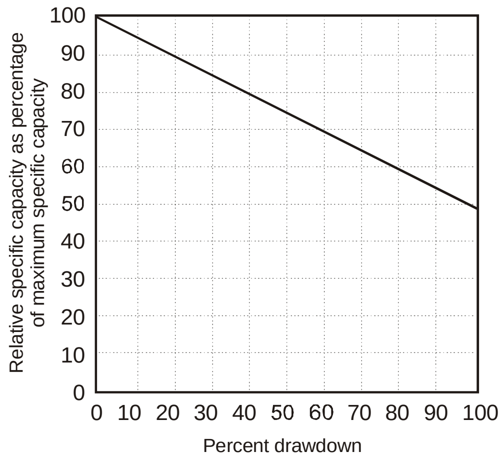


Figure A.6 Relationship between specific capacity and drawdown in an unconfined aquifer that is fully penetrated and open to the formation

Figure A.6 indicates how specific capacity varies with drawdown. Theoretically, maximum specific capacity corresponds to zero drawdown because there is no reduction in the saturated thickness; the minimum occurs when drawdown and yield are at the maximum. Note that the minimum specific capacity is 50% of the maximum. In the previous example, 85% of the maximum specific capacity would be obtained with 3 m of drawdown and 71% with 6.1 m of drawdown.

Figure A.5 shows why it is uneconomical to operate a well with a drawdown greater than 67% of the maximum. At 67% of maximum drawdown, 90% of the maximum yield is obtained. To obtain the remaining 10% requires an additional 33% drawdown. Obviously the extra pumping costs would be out of proportion to the increase in yield.

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APPENDIX B: WELL DESIGN (after USACE, 1992)

Description of Well

While the specific materials used in the construction vary and the dimensions and methods of installations differ, relief and siphon wells are basically very similar. They consist of a drilled hole to facilitate the installation; a screen or slotted pipe section to allow entrance of ground water; a bottom plate; a filter to prevent entrance and ultimate loss of aquifer material; a riser to conduct the water to the ground surface; a check valve to allow escape of water and prevent back flooding and entrance of foreign material; backfill to prevent recharge of the formation by surface water; and a cover and some type of barricade protection to prevent vandalism and damage to the top of the well by maintenance crews, livestock, etc. Figure B.1 shows a typical well installation. The hole is drilled large enough to provide a minimum thickness of 20-50 mm depending on the gradation of the filter material as subsequently described. The hole is also over drilled in depth to provide for the fact that initial placements of filter material may be segregated. The amount of over drilling required is variable depending upon the size of tremie pipe used for filter placement, the total depth of the well, and most importantly on the tendency of the selected filter material to segregate. The backfill indicated as sand in Figure B.1 normally consist of concrete sand or otherwise excess filter material. Its only function is to fill the annular space around the riser pipe to prevent collapse of the boring; these granular materials are easily placed and require a minimum of compaction. The backfill indicated as concrete in Figure B.1 forms a seal to prevent inflow of surface water from rains and flooding.

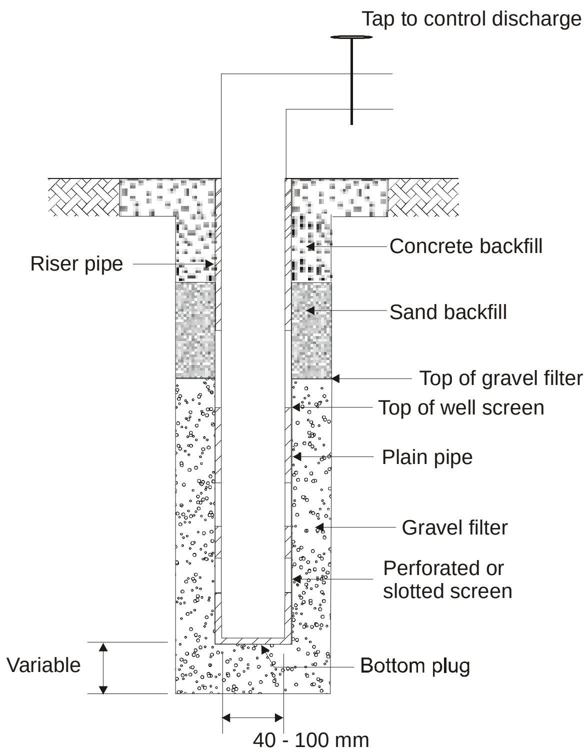

Figure B.1 Typical well installation

Materials for Wells

Commercially available well screens and riser pipes are fabricated from a variety of materials such as black iron, galvanised iron, stainless steel, brass, bronze, fiberglass, polyvinyl chloride (PVC), and other materials. How well a material performs with time depends upon its strength, resistance to damage by servicing operations, and resistance to attack by the chemical constituents of the ground water. Type 304 stainless steel has excellent corrosion resistance; whereas Type 403 stainless steel has moderate corrosion resistance. Low-carbon or other-type steel wire-wrapped screen may be more economical in many instances; however it has no corrosion resistance. Brass and bronze are extremely expensive and are not completely stable in some acid environments. Fiberglass is a promising material; however its performance history is relatively short. PVC appears to be completely stable, and it is easy to handle and install; however it is a relatively weak material and easily damaged. The life of iron screens is extended by galvanising, which may not provide permanent protection. Ferrous and nonferrous metals should never be placed in direct contact with each other, such as the case of a brass screen and a steel riser; the direct contact of these dissimilar metals may induce electrolysis and a resultant deterioration of the material.

Selection of Materials

Generally, the choice of well screen material will depend on three factors: (a) water quality, (b) potential presence of iron bacteria, and (c) strength requirements. A water quality analysis will determine the chemical nature of the ground water and indicate whether it is corrosive and/or incrusting. Enlargement of screen openings due to corrosion can cause progressive movement of fines into the well, therefore it is essential that the well screen be fabricated from corrosion-resistant material where corrosive waters are expected. Similarly, if incrusting ground water is expected, future maintenance which may require acid treatments necessitates the use of material that can withstand the corrosive effect of the treatments. When the presence of iron bacteria is anticipated, the well screen should be selected which can withstand the damaging effects of the repeated chemical treatments. The strength of the well screen is usually not a major factor when commercial well screens designed for deeper well installations are employed. The screen sections should be able to withstand maximum compression and tensile forces during installation operations as well as horizontal forces which may develop during installation and possibly later because of lateral earth movements.

Well Screen

a. Slot type. A variety of slot types are available in most types of well screens. PVC screens with open slots of varying dimensions consisting of a series of saw cuts are typically available. Metal and fiberglass screens are available with open slots, louvered or otherwise shielded slots, or "continuous slots." The "continuous slot" screens consist of a skeleton of vertical rods wrapped with a continuous spiral of wire. The wire can be a variety of cross-sectional shapes. The trapezoidal-shape wire provides a slot that is progressively larger toward the inside of the screen. This shape allows any filter gravel that enters the slot to fall into the well rather than clog the screen. The open-type slots are advantageous in developing the filter. They allow the successful use of water jets; whereas shielded slots deflect the water jet and reduce or destroy its effectiveness in the filter. Machine cut slots typically have jagged edges which facilitate the attachment of iron bacteria making screens difficult to treat later. Continuous slot screens are commercially fabricated of Type 304 and 316 stainless steel, monel, galvanised or ungalvanised low-carbon steel, and thermoplastic materials, mainly PVC and ABS or alloys of these materials. Couplings and the bottom plate for the well screen may be either glued, threaded, or welded and should be constructed of the same material as the well screen.

b. Dimensions. The size of the individual openings in a well screen is dictated by the grain size of the filter. The openings should be as wide as possible, yet sufficiently small to minimise entrance of filter materials. Criteria for selection of screen opening size are presented subsequently. The anticipated maximum flow of the well dictates both the minimum total open slot area of the screen (the spacing and length of slots) and the minimum diameter of the well. The open area of a well screen should be sufficiently large to maintain a low entrance velocity of less than 3 cm per second at the design flow. The well diameter must be large enough to conduct the maximum anticipated flow to the ground surface and facilitate testing and servicing of the well after installation. Head loss in the well should also be taken into consideration in selecting a well diameter.

Filter

a. In order to prevent infiltration of foundation sands into the filter, the filter gradation must meet the stability requirement that the 15% size of the filter should be not greater than five times the 85% size of the aquifer materials. The design should be based on the finest gradation of the foundation materials, excluding zones of unusually fine materials where blank screen sections should be provided. If the aquifer consists of strata with different grain size bands, different filter gradations should be designed for each band. Each filter gradation must also meet the permeability criterion that the 15% size of the filter should be more than three to five times the 15% size of aquifer sands. Either well graded or uniform filter materials may be used. A uniform filter material has a coefficient of uniformity, C_u, of less than 2.5 where C_u is defined as:

$$C_u = \frac{D_{60}}{D_{10}} \tag{B.1}$$

where

D_{60} = grain size at which 60% by weight is finer

D_{10} = grain size at which 10% by weight is finer

The C_u of well-graded filter materials should be greater than 2.5 and less than 6 to minimise segregation. The grain sizes should be reasonably well distributed over the specified range with no sizes missing. Well-graded filter materials used with proper well development procedures increase efficiency and permit the use of large screen openings; however they are subject to segregation during handling and placement.

b. The filter should consist of natural material made up of hard durable particles.

Selection of Screen Opening Size

In general, the slot width (or hole diameter) of the screen should be equal to or less than the 50% size of the finest gradation of filter. Use of the 50% size criterion for the selection of screen slot size appears to provide reasonable assurance against in wash of filter materials during well development and surging and furthermore results in suitably large openings to minimise the effects of incrustations and blockages which may develop during the life of the well.

Well Losses

a. Head losses within the system consist of entrance head loss in the screen and filter (H_e) plus friction head losses arising from flow in the screen, riser, and connections (H_f) plus velocity head loss (H_v). The total hydraulic head loss in a well (Hw) is given by

$$H_w = H_e + H_f + H_v \qquad \text{(B.2)}$$

b. The entrance losses in the screen and filter for a properly designed and developed screen and filter will generally be relatively small at the time of well installation. Installation techniques resulting in smear or undue disturbance of the drill hole walls, however, can result in relatively large initial entrance losses. Entrance losses can be expected to increase with time for a variety of reasons. The initial entrance losses for wire wrapped screens should be even less. Both field and laboratory tests indicate that the average entrance velocity of water moving into the screen should not exceed 3 cm/s. At this velocity, friction losses in the screen openings will be negligible and the rates of incrustation and corrosion will be minimal. The average entrance velocity is calculated by dividing estimated well yield by the total area of the screen openings. If the velocity is greater than 3 cm/s, the screen length and/or diameter should be increased accordingly.

c. Friction losses in the screen and riser sections could also be estimated if using other material than PVC.

d. Velocity head losses, Hv, should be computed by means of the equation:

$$H_v = \frac{v^2}{2g} \qquad \text{(B.3)}$$

where

v = the velocity of the water in the riser pipe

g = acceleration due to gravity = 9.66 m/sec^2

Losses due to elbow connections should be included where applicable.

Effective Well Radius

The effective well radius to be used in design computations is calculated as the outside radius of the well screen plus one-half the thickness of the filter.

Well Costs

The design of well systems will normally produce various combinations of well spacing and penetration which satisfy the design criteria. The optimum design should be based on initial cost as well as overall costs including maintenance and possible replacement costs over the life of the structure. Elements included in the estimate of initial costs are the cost of drilling or other installation technique, as well as the cost of well screen, riser pipe, and filter, all of which are on a foot basis. Additional fixed costs include backfilling, well development and testing, plus the costs of well guards, check valves, and horizontal outlet pipes if used. Well spacing and screen penetration should be selected that will result in the minimum well cost per station over the life of the structure.

APPENDIX C: WELL INSTALLATION (after USACE, 1992)

General Requirements

Proper installation of wells is essential to the successful completion. Before installation is begun, all materials required for completion of the installation should be on hand at the worksite. The well screen and riser should be checked for proper material, length, diameter, and slot openings. The filter material should be inspected and checked against gradation specifications. Successful completion of a well installation is often dependent upon time, and many installations have been aborted because of delays. An open boring of sufficient size and depth is necessary to facilitate the installation of a well. The hole should be vertical so that the screen and riser may be installed straight and plumb. As previously discussed, the hole is drilled large enough to provide a minimum thickness of 10 – 15 cm, depending on the gradation, of the filter material. The methods of providing an open boring in the ground are numerous; however not all are acceptable for the installation of permanent relief wells, and those considered acceptable are discussed in the following paragraph.

Standard Rotary Method

One method of drilling for well installation which has gained popularity in the well drilling industry is standard rotary drilling using a biodegradable, organic drilling fluid additive. No bentonitic clays are used in the drilling fluid. Standard rotary drilling consists of rotating a cutter bit against the bottom of a boring, while a fluid is pumped down through the drill pipe to cool and lubricate the bit and return the cuttings up the open hole to the ground surface. The required size of bit is governed by the screen diameter and the thickness of filter. The ability of the fluid to carry the cuttings is dependent on its velocity and viscosity. The velocity of the returning fluid is reduced with increased boring diameter, and the reduction is compensated by increased viscosity of the drilling fluid.

a. Equipment. A rotary-type drill rig of sufficient hoisting and torque capacity is required. The cutter or drill bit can be of either drag or roller design. The drill pipe should be as large as practicable to increase the volume of fluid at the drill bit and, consequently, the velocity of the fluid returning up the open hole.

Reverse-Rotary Method

This method is generally considered to provide the most acceptable drill hole and should be used whenever possible for the installation of permanent wells. In the reverse-rotary method, the hole for the well is made by rotary drilling, using a similar cutting process as employed in standard rotary drilling except the drilling fluid is pulled up through the drill pipe by vacuum and the drilling fluid reenters the top of the open boring by gravity. Soil from the drilling is removed from the hole by the flow of drilling fluid circulating from the ground surface down the hole and back up the hollow drill stem from the bit. Since the cross-sectional area of the boring is many times larger than that of the drill pipe, the slow downward velocity of the fluid acting against the open boring does not erode the walls. The drilling fluid consists of water and, unavoidably, a small amount of the finer fraction of the natural material being drilled. A high velocity is attained with the fluid returning up through the drill pipe, thus eliminating the need for a high viscosity. The drill water is circulated by a centrifugal or jet-eductor pump that pumps the flow from the drill stem into a sump pit. As the hole is advanced, the soil particles settle out in the sump pit, and the muddy water flows back into the drill hole through a ditch cut from the sump to the hole. The sides of the drill hole are stabilised by seepage forces acting against a thin film of fine-grained soil that forms on the wall of the hole. A sufficient seepage force to stabilise the hole is produced by maintaining the water level in the hole at least 2.134 m above the natural water table.

a. Equipment. Reverse-circulation rotary drilling requires somewhat specialised equipment, most of which is commercially available or easily fabricated. Any rotary-type drill rig large enough to handle the load and having sufficient torque capability can be adapted to circulate water through an eductor to create a vacuum on the drill pipe. Drill pipe and hoses should be of a constant inside diameter throughout the system to assure that material entering the system can be circulated completely through it. In alluvial deposits, a drag-type bit similar to the cutter head for a dredge is sufficient. Roller-type bits are commercially available for use in consolidated deposits. The eductor consists of a pipe Y with a nozzle fitted into one end of the Y.

b. Problems. It is necessary to maintain an excess hydrostatic pressure on the drill hole to stabilise the walls. In most materials, a minimum excess head of 2.134 m is required and greater is desirable. When the static water level is very near the ground surface or artesian conditions prevail, it may be necessary to elevate the drilling rig on temporary berms. Some success has been experienced by lowering the water level with well points, but if the pressure is derived from a deeper, artesian source, it is necessary to lower the pressure in the aquifer with deep wells. A large sump is required to supply adequate water. During the drilling, all cuttings from the boring are deposited in the sump and must be provided for. A sump three times the anticipated volume of the completed boring is adequate, if it can be kept filled with water from another source. Consideration should be given to the required thickness of the natural impervious clay blanket when constructing a sump. An instantaneous loss of water resulting in loss of excess head can cause failure of the boring walls. Often, if the rotation of the drill bit is stopped, the water loss is greatly reduced. The boring must be kept full of water until the well screen, riser, and filter are installed.

Bailing and Casing

In cases where standard or reverse-rotary drilling is not successful, especially in caving alluvial sands and unconsolidated palaeochannel deposits, an equally acceptable method of drilling consists of bailing while driving a steel casing into the hole to stabilise the boring walls. This method is economical in some materials, and it does not inject deleterious materials into the formation. Loose to medium dense, clean, granular materials can be bailed economically. Often the granular materials are overlain with a cohesive overburden which does not yield easily to bailing, and it is more economical to auger through this overburden.

a. Equipment. A drill rig with a wire line hoist and driving capability is adaptable to this method of well installation. It should be remembered that large casing, heavy enough to sustain driving, presents a sizable load to be handled by the drill rig. The use of a vibratory pile driver can greatly facilitate the driving and subsequent removal of the casing. The casing should be flush-joint, or welded-joint steel pipe. Two types of bailers are commonly used for this purpose. The bailer is operated on a wire line by lowering to the bottom of the boring and quickly pulling, or snatching, up a short distance a number of times to fill the bailer.

b. Problems. This method of drilling produces good results but often presents problems in operations. Thin layers of cohesive materials, or cemented materials within the formation, can preclude the advance by bailing and may also produce smear along the sides of the drill hole which could impair free flow into the well. Penetration of the casing can be retarded by friction of the granular formation against the outside of the casing unless vibratory hammers are used. After the casing is set, the boring completed, and the well installed, the casing is removed. The casing should be pulled, as the filter material is placed, to prevent disturbing the well installation by the friction of the filter material inside the casing. Using a vibratory pile hammer to drive and extract casing can densify loose foundation materials and filter materials. Generally, when material is densified, the hydraulic conductivity is reduced. The vibratory hammer cannot be used in wells that have more than one filter pack. As densification in the filter pack occurs, the material settles. This settlement, combined with settlement which occurs as the filter fills the void left by removal of the casing, results in uncertainties regarding the final position of the top of the filter. There are many uncertainties associated with this method of installation which makes it very difficult to estimate time and costs.

Bucket Augers

Under certain conditions drill holes for relief wells can be made with a bucket auger. The method has been successfully employed where cobbles up to 254 mm. have been encountered. A bucket with side cutters is employed, and only water is used as the drilling fluid. The rate at which the bucket is inserted or withdrawn must be carefully controlled; thus close inspection is obligatory. A steel casing is installed through the top stratum to prevent smearing of fine-grained materials on the walls of the drill hole.

Disinfection

Before drilling begins, all tools, rods, bits, and pumps should be thoroughly washed with a chlorine solution to kill any bacteria remaining from previous well installations. Water used in the drilling process and filter materials should also be treated with a chlorine solution. The strength of the chlorine solution should not be less than 100 ppm.

Installation of Well Screen and Riser Pipes

Once the boring is completed and the tools withdrawn, the boring should be sounded to assure an open hole to the proper depth. The well screen and riser pipe can be constructed at the site in varying lengths. The contractor will determine these lengths based on the capacity of his equipment. The bottom joint of the well screen should be fitted with a cap or plug to seal the bottom of the screen. The lengths of screen are connected together as they are lowered into the hole. Each length must be measured to determine its total made-up length, and the bottom of the screen should be set at the designed depth, or as field conditions require. The method of connecting the lengths of screen and riser vary: metal screen and riser have threaded or welded joints; plastic and fiberglass screens usually have either mechanical or glued joints. Each joint should be made up securely to prevent separation of the well during installation and servicing activities. Each joint should be kept as straight as possible to facilitate ease of servicing and testing. The riser and screen sections of the well should be centered in the drill hole by means of appropriate centering devices to facilitate a continuous filter around the well screen. If materials appreciably finer than anticipated in design are encountered, design personnel should be notified. In such cases, it may be necessary to replace the screen by a solid pipe or blank screen to prevent piping of foundation materials into the well. Immediately after installation of the well screen and riser, the total inside depth should be sounded. The exact inside depth of the well must be known to determine whether damage occurs during development and servicing of the well.

Filter Placement

Caution in proper design, control of manufacture, and handling of filter materials to the jobsite can be completely negated by improper placement in the well. Acceptable construction of permanent relief wells demands that the filter be placed without segregation because widely graded filters when placed in increments tend to segregate as they pass through water, with coarse particles falling faster than fine particles. A tremie should be used to maintain a continuous flow of material and thus minimise segregation during placement. A properly designed, uniform (D_{90}/D_{10} 3 to 4) filter sand may be placed without tremieing if it is poured in around the screen in a heavy continuous stream to minimise segregation. The tremie pipe should be at least 50 mm in diameter, be perforated with slots 1.6 – 2.38 mm wide and about 150 mm. long, and have flush screw joints. The slots allow the filter material to become saturated, thereby breaking the surface tension and preventing "bulking" of the filter in the tremie. One or two slots per linear foot of tremie is generally sufficient. To avoid contamination by iron bacteria, the filter should be washed through the tremie pipe using a 100-ppm chlorine solution. The tremie pipe is lowered to the bottom of the open drill hole, outside the well screen and riser pipe. The presence of centering devices will interfere with the proper use of the tremie by preventing uniform filling to some extent. The use of dual diametrically opposed tremie pipes will ensure more uniform placement. After the tremie pipe or pipes have been lowered to the bottom of the hole, they should be filled with filter material and then slowly raised to keep them full of filter material at all times. Extending the filter material at least 60 cm above the top of the screen will depend on the depth of the well to compensate for settlement during well development. The top of the filter should also terminate below the bottom of the overlying top stratum if present. The level of drilling fluid or water in a reverse-rotary drilled hole must be maintained at least 2 m above the natural ground-water level until all the filter material is placed. If a casing is used, it should be pulled as the filter material is placed, and the bottom of the casing kept 60 - 300 mm below the top of the filter material.

APPENDIX D: WELL DEVELOPMENT (after USACE, 1992)

Development

A well is at best inefficient until properly developed. Development procedures include both chemical and mechanical processes. Development of a well should be accomplished as soon after the hole has been drilled as practicable. Delay in doing this procedure may prevent a well being developed to the efficiency assumed in design.

Chemical Development

Chemical development is applied usually in the case where special drilling fluids are utilised and chemicals are injected into the well to aid in the dissolution of the residual drilling fluid in the filter. The chemicals should be of a type and concentration recommended by the manufacturer of the drilling fluid. They should be placed starting at the bottom of the well and dispersed throughout the entire screen length by slowly raising and lowering the injection pipe. After the chemicals have been dispersed, the well should be pumped and the effluent checked to ensure that the drilling fluid has completely broken down.

Mechanical Development

The purpose of mechanical development is to remove any film of silt from the walls of the drilled hole and to develop the filter immediately adjacent to the screen to permit an easy flow of water into the well. The result of proper development is the grading of the filter from coarsest to finest extending from the well. The effect of proper development is an increase in the effective size of the well, a reduction of entrance losses into the well, and an increase in the efficiency of the well. Many factors, including but not limited to development methods, well design, and filter installation, affect the time it takes to fully develop a well. Basically there are three methods used in development as discussed below.

a. Water Jetting. A water jet, consisting of a series of small nozzles at the end of a pipe, lowered into the well screen, is very effective in developing the continuous slot-type, wire-wrapped screens. Water is pumped down and out through the nozzles at a high velocity. Nozzles are directed toward the screen slots in small concentrated areas. The water jet equipment can be fabricated in local welding shops. The size and number of nozzles must be consistent with the size and length of the pipe through which the water is pumped to ensure a high-pressure and high-velocity jetting action. This method requires a high-pressure, relatively high-volume water pump. Normally, development with a water jet is started at the bottom of the screen. Jetting is accomplished at one depth with the jet rotated for a fixed period of time. The jet is raised approximately 15 cm; rotation and jetting is continued for another fixed period of time. For the most effective jetting, the wells should be pumped or airlifted during jetting to remove the fines as they are dislodged by the jetting. This process is continued until the entire well screen has been jetted. The jetting tool should be continuously in motion since a small amount of sand is disturbed and may cause localised erosion of the screen. Jetting must be repeated a number of times to ensure optimum development of the well.

b. Surging. A surging block is a plunger consisting of one or more stiff rubber or leather discs attached to a heavy shaft. These discs should be about 2.5 cm smaller in diameter than the screen ID. Surging consists of moving water in and out of the screen using the up and down motion of the surge block through short sections of the well screen. The well should always be pumped or bailed to ensure a relatively free inflow of water prior to surging. Surging should begin with a slow and gentle motion above the well screen and continue with more vigor from the top of screen downward. This method is less effective than the water jet described above in continuous slot screens and more effective in screens with widely separated slots and louvered or shielded slots. The surging block should be pulled at approximately 60 cm/s for effective surging. For record keeping purposes, it is convenient to use 15 round trips as one cycle. The amount of material deposited in the bottom of the well should be determined after each cycle (about 15 trips per cycle). Surging should continue until the accumulation of material pulled through the well screen in any one cycle becomes less than about 6 cm deep. The well screen should be bailed clean if the accumulation of material in the bottom of the screen becomes more than 30-60 cm at any time during surging, then recleaned after surging is completed. Material bailed from a well should be inspected to see if any foundation sand is being removed. If the well is oversurged, the filter maybe breached with resulting infiltration of foundation sand when the well is pumped.

c. Pumping. One of the least effective and slowest methods of developing a well is simply pumping from the well. Pumping should be accomplished at a sufficient rate to effect maximum drawdown in the well.

The water passing from the formation through the filter into the well removes part of the finer fraction of the filter material. The pumping equipment required depends on the size, yield, and anticipated drawdown in the well. Surging produced by repeatedly starting and stopping a pump is only effective where the static water level is well below the ground surface. Pumping, continued over a long period of time, is a reasonably effective method of well development. Pumping of the well is normally accomplished by inserting a pipe in the well and forcing compressed air to the bottom of the well. If the depth of submergence of the pipe is at least 50% of its length, air bubbles reduce the weight of the water column and will cause a flow to the ground surface. If 50% submergence is not possible, the water column which must be physically blown out of the well as it accumulates will require a large supply of air. Pumping can be accomplished using a mechanical pump, but granular material in the water can cause damage.

Sand Infiltration

During the development process, sand and silt will be brought into the well. When the depth of sand collected in the bottom of the screen reaches 30 cm, it should be removed by bailing. The accumulation of sand in the screen prevents development of that portion of the screen. A properly developed well will not produce an appreciable amount of sand, and entrance losses through the filter will be reduced to a minimum. In each of the methods discussed above, the actual amount of development must be recorded: the length, diameter, speed, and number of cycles of a surging block; the volume, pressure, and diameter of water jets; and the rate and method of pumping and length of time pumped. In addition, the amount of filter and foundation materials brought into the well and bailed out should be recorded. Upon completion of the development of the well, all material infiltrated into the well should be bailed out. If the well produces sand during pumping in excess at approximately 2 pints per hour (as determined from sounding and from collection of well flow in a 10-gal container) the well should be resurged or developed further and repumped. Wells continuing to produce excessive amounts of sand after 4 to 8 hours or surging or pumping should be abandoned and properly plugged.

Testing of Relief Walls

Performance of relief wells properly installed and developed is determined by pumping tests. The pumping test is used primarily to determine the specific capacity of the well and the amount of sand infiltration experienced during pumping. The information from this test is required to determine the acceptability of the well and will be used to evaluate its performance and loss of efficiency with time. The results of this pumping test must be made a part of the permanent record concerning the well.

a. Equipment. The equipment required for a pumping test consists of a pump of adequate size to effect a substantial drawdown. If the water level in the well is near enough to the ground surface, and the specific capacity of the well is high enough to produce a substantial flow with a small drawdown, a centrifugal pump may be used for this purpose. If the water level in the well is lower than about 5.5 - 6.0 m, a deep-well pump will be required to effect substantial drawdown. A flow meter is required to measure the flow rate. A flat-bottom sounding device and a steel tape are required to determine the amount of sand infiltration deposited in the bottom of the well. A suitable baffled stilling basin is used to determine the amount of sand in the effluent. A sounding device suitable for determining the depth to the top of the water is needed to find the exact drawdown in the well. A well flow meter is desirable to measure the amount of flow at various depths within the well to define flow from various zones.

b. Pumping. The well must be pumped to obtain a specified drawdown or flow rate. Drawdown measurements in the well should be made to the nearest 3 cm and recorded with the flow rate at 15-minute (min) intervals throughout the duration of the tests. Sufficient sand infiltration determinations are necessary to establish an infiltration rate for each hour of the pumping test. The rate of sand infiltration may be determined from sounding and measurements of sand in the effluent. For most properly developed wells, the amount of sand deposited in the well will be negligible and sand inflitration in the effluent can be recorded in terms of parts per million (Note: sand infiltration in parts per million is approximately equal to pints per hour times 3,000 divided by the pumping rate in gallons per minute) as measured with a centrifugal sand tester or other approved sediment concentration test (Driscoll 1986). The length of time that the pumping test must be continued is normally specified for the particular project. If the rate of sand infiltration during the last 15 min of the pumping test is more than 5 ppm, the well should be resurged by manipulation of the test pump for 15 min; then the test pumping should be resumed until the sand infiltration rate is reduced to less than 5 ppm. If after 6 hours (hr) of pumping the sand infiltration rate is more than 5 ppm, the well should be abandoned.

Backfilling of Well

After completion of the well testing, the annular space above the top of the filter gravel should be filled with filter gravel if necessary to achieve design grade. The remainder of the hole should be filled with either a cement-bentonite mixture tremied into place or concrete where the height of drop does not exceed 2.4 m. In both cases, a 30 cm layer of concrete sand or excess filter material should be placed on top of the filter before placement of grout or concrete. A tremie equipped with a side deflector will prevent jetting of a hole through the sand and into the filter.

Sterilisation

Upon completion of the pumping tests and before installation of the well cover, each well should be sterilised by adding a chlorine solution with a minimum strength of 500 ppm. Sufficient solution should be added to the bottom of the well to provide a volume equal to three times the volume of the well based on the outer diameter of the filter. Before the solution is introduced into the well, all flow from the well should be stopped with inflatable packers or riser extensions. The solution should be injected into the well through a jetting tool by slowly raising and lowering the tool through the screened portion of the well. The well should be gently agitated at 10-min intervals every 2 hr for the first 8 hr and then at 8-hr intervals for at least 24 hr. As the chlorine will dilute with time, the concentration should be periodically checked; if it falls below 500 ppm, additional chlorine compound should be added. It should be noted that calcium hypochlorite may combine with naturally occurring calcium in the ground water to form a precipitate of calcium hydroxide which can plug the pores of the foundation soils. Therefore, chlorine in the form of calcium hypochlorite should not be used in waters containing high calcium content.

Records

Permanent records of the installation, development, testing, and sterilisation of a permanent relief well must be kept for evaluation of future testing. To monitor the efficiency and performance of the installation, the record must include identification of the well, method of drilling, type, length and size of well screen, and slot size. The filter should be defined as to grain-size characteristics, depth, and thickness. Elevation of the top of the well and the ground surface should be recorded. An abbreviated log of the boring should be included to define the depth to granular material, the thickness of that material, and the% penetration of the well. Development data should include the method of development, the amount of effort expended in development, and the amount of materials pulled into the well during development. The record should show the final sounded depth of the well in case some fines remain at the bottom. The pumping test data should include the rate of pumping, the amount of drawdown, the length of time the pumping test was conducted, and the amount of sand infiltration during pumping. Installation and pumping test data should be recorded on special forms. Forms should be filled in completely at the time each operation is completed and any additional observations should be recorded in a "remarks" section.

Abandoned Wells

Wells that produce excessive amounts of materials during pumping tests or that do not conform to specifications and can not be rehabilitated should be abandoned. Abandoned wells should be sealed to eliminate physical hazards, prevent contamination of ground water, conserve hydrostatic heads in aquifers, and prevent intermingling of desirable and undesirable waters. Primary sealing materials consist of cement or cement-bentonite grout placed from the bottom upward. In general, abandoned wells should be sealed following procedures established by local, state, or Federal regulatory agencies.

References

Driscoll, F.G. (1986). Groundwater and Wells. Johnson Division, SES, Inc., St Paul, MN.

APPENDIX E: RELIEF WELL OUTLETS (after USACE, 1992)

General Requirements

Relief wells should always be located where they are accessible by a drill rig for pump testing and cleaning and provided with outlets for this purpose. The outlets should be designed to minimise maintenance and to provide protection against contamination from back flooding, damage from floating debris, and vandalism. When wells are to discharge into a collector ditch or backwater which may contain organic matter, debris, and fine-grained sediment in suspension, or where high velocities may be expected while the wells are flowing, they should be installed off to the side and should discharge into the ditch or area through a tee connection and horizontal outlet pipe protected against corrosion. A flat-type check valve should be installed on the well riser with a flap gate on the end of the horizontal pipe.

Check Valves

Control of backflooding, which greatly impairs well efficiency, is best implemented by flat-type check valves. The check valve is supported by a soft rubber gasket which fits snugly over the top of the riser or cast iron tenon set in the concrete backfill. Other types of check valves may be used but should be thoroughly tested under controlled conditions before application in the field.

Outlet Protection

For wells discharging at ground surface, the tops of the wells should be provided with a metal screen to safeguard against vandalism, accidental damage, and the entrance of debris. A suitable alternative consists of a section of stainless steel wire wound screen. In the case of a T-type well where the top of the riser pipe is more than 1.5 m below ground, the well guard should be 110 cm in diameter to permit safe access by a ladder. A guard screen consisting of a wire mesh with 2.5 cm-square openings may be installed at the end of the outlet pipe to prevent animals and debris from entering the outlet pipe in the event the flap gates do not close properly.

Plastic Sleeves

Where relief wells are provided for under seepage control at levees, the well flows at relatively low river stages will be somewhat in excess of natural seepage. In cases where the additional seepage is considered objectionable, each well can be provided with a plastic sleeve, 30 or 45 cm in length, which will raise the discharge elevation of the well accordingly. The sleeves prevent well flow at low river stages when no pressure relief is necessary. At higher river stages or as soon as substratum pressures develop to the extent that water begins to spill over the top of the sleeves, they should be removed so that the well can function as intended.

APPENDIX F: INSPECTION MAINTENANCE AND EVALUATION (after USACE, 1992)

General Maintenance

Relief wells require a certain amount of nominal maintenance to ensure their continued and proper functioning. Any trash or obstruction in the well or well guard should be removed immediately. Sand or other material that may have accumulated in and around flap gates to obstruct the flow or prevent functioning of the gates should be removed. Outfall ditches, bank slopes, or berms should be properly maintained in the vicinity of horizontal outlet pipes. The area in the immediate vicinity of the wells should be kept free from weeds, trash, and debris. Mowing and weed spraying should be extended at least 1.5 m beyond the well, and the ground shaped and maintained for inspection and servicing of the wells.

Periodic Inspections

a. Periodic inspections of relief well systems should be carried out. Observation should be made for evidence of wet spots on the dam or on the ground around the wells and structures, for evidence of sloughing or piping, for indications of discharge of sand or other materials from the wells, and for surficial signs of damage. The inspection should detect whether vandalism, theft, abuse by carelessness, unauthorised use of the wells or associated piezometers, or other irregularities have occurred. The inspection should include an examination of check valves, gaskets, well guards, cover plates, flap gates on tee outlets, and other appurtenances. Malfunctioning or damaged items should be repaired or replaced. At yearly intervals, piezometric levels and flow quantities should be measured, and wells should be sounded for evidence of deposition of sand or other material in the wells. Where relief wells penetrate two or more aquifers, the well flows at various depths should be checked at yearly intervals to determine whether flows between aquifers are occurring. Piezometric levels and flow quantities should also be measured approximately one week after the attainment of an unusually high reservoir level. Wells in relatively inaccessible locations, as beneath stilling basins, should be inspected whenever the structure is unwatered for a general maintenance inspection, or when there is evidence of significantly decreased effectiveness, as shown by changes in flow quantities or piezometric levels for a constant combination of reservoir level and tailwater level.

b. Flowing wells located in areas in which failure would not constitute a hazard to life or property, as on excavated slopes of canals, should be visually inspected at monthly intervals. Measurements of piezometric levels and flow quantities should be made annually.

c. Relief wells located along the toe of levees and at locations where they flow infrequently should be inspected annually, preferably immediately prior to normal high-water seasons and more often during major high waters. Flow quantities and piezometric levels should be measured approximately a week after a peak in the reservoir level or in the river level at a levee. Pumping tests should be performed at five-year intervals on wells that flow infrequently. The tests should be performed to determine the specific capacities and the efficiencies of the wells. The amount of sediment in the wells should be measured before and after performance of the pumping tests.

Records

A record should be kept of all inspections and maintenance performed on each well. The record should include all pumping test data, descriptions of rehabilitation efforts, and summaries of well flows and piezometric data during periods of high river stages or pool levels.

Evaluation

a. It should be noted that a reduction in well discharge accompanied by a fall in piezometric levels in downstream areas probably indicates a decrease in seepage due to reduction in seepage, which is a favorable condition. It is possible, however, that such a reduction was caused by erosion or excavation of an impervious top stratum at a point downstream of the line of wells, thus permitting exit of seepage to tail water much closer to the wells. This condition would be unfavorable, because it would indicate a higher value of the seepage gradient and an increased potential for piping immediately downstream from the well line. A reduction in well discharge accompanied by an increase in piezometric levels indicates clogging or obstruction of the relief wells, and requires immediate remedial action. Observation of changes in flow and piezometric levels must be related to changes or lack of changes in both reservoir level and tail water level. Often, variation in tail water level at a dam has greater influence on well performance than variation in reservoir level, because the point at which the tail water has access to the aquifer is considerably closer to the well than the point at which the reservoir pressure can enter the aquifer.

b. The values obtained from measurement or piezometric levels and flow quantities should be extrapolated to predict the values that would be produced by a maximum design reservoir or river elevation. If these values are greater than those for which the structure was designed, or if the specific capacities or the efficiencies of the wells are less than 80% of the values that were obtained at the time of installation of the wells, additional investigations should be performed to determine the cause of the inadequacies. Investigations may include the examination of the well screen by means of a borehole camera, sounding the well with a caliper, and the performance of chemical tests on the water and on any deposits or incrustations found in the well. If there are any inclinometer tubes installed in the foundation in the vicinity of the wells, they should be read to determine if there has been any horizontal movement of the foundation that would cause disruption of well screens or risers.

APPENDIX G: MALFUNCTIONING OF WELLS AND REDUCTION IN EFFICIENCY (after USACE, 1992)

General

Relief wells may not function as intended and may also be subject to reduced efficiency with time. Failure of relief wells to function as intended can be attributed to a number of causes. Deficiencies in design can usually be assessed during initial operation of the well system. Based on piezometric and well flow data, an assessment of the effectiveness of the well system can be made and if considered inadequate, additional relief wells may be installed. Relief wells may malfunction for a variety of reasons including vandalism, breakage, or excessive deformation of the well screens due to ground movements, corrosion or erosion of the well screen, and a gradual loss in efficiency with time. The reduced efficiency generally determined as a percentage loss in specific capacity based on the specific capacity determined from pumping tests at the time of installation is a measure of increased well losses, which in turn result in higher landside heads. Thus, reduced well efficiency will result in hydrostatic heads larger than those anticipated in the design. The major causes of reduced specific capacity with time are (a) mechanical, (b) chemical, and (c) biological.

Mechanical

Most relief wells undergo some loss in specific capacity probably due to the accumulation of fines into the filter pack with a corresponding reduction in permeability. The process occurs more commonly in cases of poorly designed filter packs, improper screen and filter pack placement, or insufficient well development. Generally, the major cause of reduced efficiency by mechanical processes is the introduction of fines into the well by backflooding of muddy surface waters. Normally, backflooding can be prevented by the use of check valves at the well outlet; however if not properly designed and maintained, the valves may not function as intended. The introduction of fines into the well and surrounding filter pack under backflow conditions can result in serious clogging which will result in reduced specific capacities.

Chemical

Chemical incrustation of the well screen, filter pack, and surrounding formation soils can be a major factor in specific capacity reduction with time. Chemical deposits forming within the screen openings reduce their effective open area and cause increased head losses. Deposits in the filter pack and surrounding soils reduce their permeability and also increase head losses. The occurrence of chemical incrustation is determined chiefly by water quality. The type and amount of dissolved minerals and gases in the water entering the well determine the tendency to deposit mineral matter as incrustations. The major forms of chemical incrustation include: (a) incrustation from precipitation of calcium and magnesium carbonates or their sulfates, and (b) incrustation from precipitation of iron and manganese compounds, primarily their hydroxides or hydrated oxides.

a. Causes of carbonate incrustations. Chemical incrustation usually results from the precipitation of calcium carbonates from the ground water of the well. Calcium carbonate can be carried in solution in proportion to the amount of dissolved carbon dioxide in the ground water. For a well discharging from a confined aquifer, the hydrostatic pressure adjacent to the well is reduced to provide the gradient necessary for the well to flow. The reduction in pressure causes a release of carbon dioxide which in turn results in precipitation of some of the calcium carbonate. The precipitation tends to be concentrated at the well screen and surrounding filter pack where the maximum pressure reduction occurs. Magnesium bicarbonate may change to magnesium carbonate in the same manner; however incrustation from this source is seldom a problem as precipitation occurs only at very high levels of carbonate concentration.

b. Causes of iron and manganese incrustation. Many ground waters contain iron and manganese ions if the pH is about 5 or less. Reduction of pressure due to well flow can disturb the chemical equilibrium of the ground water and result in the deposition of insoluble iron and manganese hydroxides. The hydroxides initially have the consistency of a gel but eventually harden into scale deposits. Further oxidation of the hydroxides results in the formation of ferrous, ferric, or manganese oxides. Ferric oxide is a reddish brown deposit similar to rust, whereas the ferrous oxide has the consistency of a black sludge. Manganese oxide is usually black or dark brown in color. The iron and manganese deposits are usually found with calcium carbonate and magnesium carbonate scale.

Biological Incrustation

a. Iron bacteria are a major source of well screen and gravel pack contamination. They consist of organisms that have the ability to assimilate dissolved iron which they oxidise or reduce to ferrous or ferric ions for energy. The ions are precipitated as hydrated ferric hydroxide on or in their mucilaginous sheaths. The precipitation of the iron and rapid growth of the bacteria can quickly reduce well efficiency. Iron bacteria problems in ground water and wells are recognised throughout the world and are responsible for costly well maintenance and rehabilitation.

b. Despite the widespread familiarity with iron bacteria problems in wells, relatively little is known about their growth requirements. One reason for the lack of research on iron bacteria is that these organisms are difficult to culture for experimental study and that cultures of many of these organisms have never been obtained. Available information on the nature and occurrence of iron-precipitating bacteria in ground water is summarised by Hackett & Lehr in Leach & Taylor (1989).

c. In order to determine which genus of iron bacteria is contained in a particular water sample, a system of classification based on the physical form of these organisms has been employed by the water well industry (Driscoll 1986). The three general forms recognised are:

(1) *Siderocapsa*. This organism consists of numerous short rods surrounded by a mucoid capsule. The deposit surrounding the capsule is hydrous ferric oxide, a rust-brown precipitate.

(2) *Gallionella*. This organism is composed of twisted stalks or bands resembling a ribbon or chain. A bean-shaped bacterial cell, which is the only living part of the organism, is found at the end of the stalk.

(3) *Filamentous Group.* This filamentous group consists of four genera: Chrenothrix, Sphaerotilus, Clonothrix, and Leptothrix. The organisms are structurally characterised by filaments which are composed of series of cells enclosed in a sheath. The sheaths are commonly covered with a slime layer. Both the sheath and slime

layers or these organisms typically become encrusted with ferric hydrate resulting in large masses of filamentous growth and iron deposits.

d. Identification. The presence of iron bacteria is usually indicated by brownish red stains in well collector pipes or ditches. Television and photographic surveys can pinpoint the locations of screen incrustation, and samples of the incrustations can be obtained by a small bucket-shaped container. Samples can be sent to the USAE Waterways Experiment Station, or a private firm familiar with iron bacteria for identification. Identification is best accomplished by scanning electron or transmission electron microscopy and phase contrast techniques. Correct identification is necessary for selection of an appropriate treatment method.

e. Prevention. It is not clear whether iron bacteria exist in ground water before well construction takes place, or whether they are introduced into the aquifer from the foundation soils or in mix water during well construction. Evidence exists that iron bacteria may be carried from well to well on drill rods and other equipment and therefore every effort should be made to avoid introducing iron bacteria into a well during installation, maintenance, or rehabilitation operations. After completion of operations on a well, all drilling equipment, tools, bits and pumps, should be thoroughly disinfected by washing with a chlorine solution (100 ppm) before initiating work on another well.

References

Leach, R.E. & Taylor, H.M. Jr (1989). Proceedings of REMR Workshop on Research Priorities for Drainage System and Relief Well Probelsm. Final Report, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Driscoll, F.G. (1986). Groundwater and Wells. Johnson Division, SES, Inc., St Paul, MN.

APPENDIX H: WELL REHABILITATION (after USACE, 1992)

General

The analysis of well discharge records and accompanying piezometric data will often indicate whether the relief wells are functioning as intended. A decrease in well discharges with time for similar pool or river stages with rising piezometric levels between wells is usually indicative of decreasing well efficiency. A quantitative measure of the loss in efficiency is only determined by carefully conducted pumping tests as previously described. Should the pumping tests indicate a reduction in specific capacity of more than 20% compared to that measured at installation, a detailed study should be made of the consequences of the reduction and what remedial measures should be employed. Generally, it may be possible to restore the wells to about their original efficiency by means of rehabilitation techniques. Rapidly developing technology in the fields of chemistry and microbiology, as they are related to wells and aquifers, could negate portions of the following rehabilitation techniques but the items covered are at least broadly covered and represent present practice. Environmental concerns (past and present chemical usage) also require that certain Federal, State, and local laws be followed and rehabilitation techniques may have to be modified to comply with these laws.

Mechanical Contamination

Plugging of relief wells by silts, clays, or other particulate media entering the filter pack either from the formation or through the top of the well is usually difficult to determine except as indicated by periodic pumping tests. If significant reductions in specific yield are noted, rehabilitation of the well is in order. Mechanical redevelopment of the well similar to that used to develop a new well should be the first step. Over pumping or pumping the well at the highest rate attainable is generally advantageous. Surging and the use of horizontal jetting devices also may produce beneficial results.

Chemical Treatment with Polyphosphates

Mechanical plugging of relief wells is corrected most often by chemical treatment with polyphosphates. These chemicals act as dispersing agents which causes silt and clay particles to repel one another and calcium, magnesium, and iron ions adhering to the particles to remain in a soluble state. The most widely used chemicals for this purpose are the glassy sodium phosphates which are inexpensive and readily available. The chemicals are usually applied in concentrations of 15 to 25 lb per 100 gal of water in combination with at least 50 ppm of chlorine (about one-half gal of 3% household bleach or chlorox in 100 gal of water). Phosphate solutions are mixed in a barrel or tank adjacent to the well. The material is best dissolved in small amounts in a wire basket or perforated container in agitated or swirling water. If the material is dropped directly into the tank or well, it will sink to the bottom and form a large gelatinous mass that could remain undissolved for some time. One of the most effective means of introducing the phosphate and chlorine solution into the well is by means of a horizontal jetting device. The well should then be surged vigorously prior to pumping. Three or more repetitions of injecting, surging, and pumping over a 2 to 4-hr cycle will be much more effective than a single treatment with a longer detention time.

Chemical Incrustations

If the cause of reduced well efficiency is determined to be chemical incrustation, more frequent cleaning and maintenance should be initiated. If the efficiency remains low, consideration should be given to treating the well with a strong acid solution which can chemically dissolve the incrusting materials so that they can be pumped from the well. Acids most commonly used in well rehabilitation are hydrochloric acid, sulfamic acid, and hydroxyacetic (glycolic) acid. Acid treatment should be used with caution on wooden screen wells as the acid may tend to attack the lignin in the wood and cause severe damage. Methods for acid treatment of wells are described in detail by Driscoll (1986). The methods require great care and only experienced personnel with specialised equipment should be employed. Specialised firms with experience in this field should be utilised for this purpose.

Bacterial Incrustation

Incrustation of wells by iron bacteria is best controlled by a combination of chemical and physical treatments. Many chemical treatments have been suggested and applied in practice but their success has been variable as evidenced in many cases by recolonisation or regrowth in the treated wells. A strong oxidising agent such as chlorine is widely used to limit the growth of iron bacteria. Chlorine, in the form of a gas, is used in the restoration of commercial wells; however safety and experience requirements limit its general application. A more convenient alternative is the use of hyperchlorite or other chlorine products. A discussion of procedures for the use of the various products is given by Driscoll (1986). Physical methods for control of iron bacteria are available, however sufficient research has not been accomplished to justify their use in relief wells. A survey of new techniques is presented by Hackett and Lehr in Leach & Taylor (1989).

Recommended Treatment

As clogging of well screens and filter materials is caused not only by the organic material produced by the bacteria but also by oxides and hydroxides of iron and manganese, better results are usually obtained by treating the well alternately with a chlorine compound to attack the organic material and a strong acid to dissolve the mineral deposits. Between each treatment the well is pumped to waste to ensure that chlorine and acid are not in the well at the same time. A recommended procedure using the two procedures is:

a. Inject a mixture of acid, inhibitor, and wetting agent. The addition of a chelating agent such as hydroxyactic acid may sometimes be beneficial. An inhibitor is needed only if the well screen is metal. The amount of acid should be typically one and a half to two times the volume of the well screen. If a chelating agent is not used, iron will precipitate out if the pH rises above 3. The precipitate can result in clogging; therefore the pH should be monitored throughout the acid treatment and not be allowed to rise above 3 regardless of whether a chelating agent is used.

b. Gently agitate the solution with a jetting tool at 10-min intervals for a period of 1 to 2 hrs.

c. Pump out a volume of solution equal to the volume of the well.

d. Determine the pH of solution removed from the well. If the pH is more than 3, repeat steps (a) to (c).

e. Allow the acid to remain in the well for a minimum of 12 hrs and then pump to waste.

f. Inject a mixture of chlorine and one or more chloric-stable surfactants (detergents and wetting agents, for example). The concentration of the chlorine should exceed 1,000 ppm.

Specialised Treatment

The USAE Waterways Experiment Station personnel, funded under a repair evaluation maintenance and restoration (REMR) work unit, developed a field procedure (Kissane & Leach 1991) for cleaning water wells that provides initial kill of the active bacteria in the well, dissolves the biomass in the screen, in the gravel pack, and some distance into the aquifer, and provides some inhibition of future growth. The procedure was developed using a patented process known as the Alford Rodgers Cullimore Concept (ARCC). The procedures in general include an initial well diagnosis performed with a prepackaged field microbiological test kit which is designed to give a qualitative indication of the types of bacterial and chemical agents at work in the wells, and a very general indication of the bacterial concentrations. The initial water chemistry is also measured prior to treatment. A treatment is then designed with the information from the tests, targeting the problematic agents with an appropriate set of chemicals. Redevelopment of the wells using the ARCC method is based on the use of blended chemicals and high temperature (BCHT) and is divided into three principle elements of treatment:

a. Shock. This phase is achieved by adding high temperature chlorinated water to the well and surrounding aquifer to "shock" kill or reduce the impact of deleterious algae and bacteria. The water is chlorinated to >700 ppm with gaseous chlorine to avoid binders found in powdered chlorine and is applied to the well as steam until the well temperature is brought above 120 deg F for massive bacteria kill. The chlorine treatment remains in the well for a specified period of time; mechanical surging is used; and pumping follows for removal of the initial loosened biomass.

b. Disrupt. This phase is achieved by the addition of chemical agents, acids and surfactants, and steam to the well and surrounding aquifer while the well is pressurised. Mechanical surging to break up organic and mineral clogging in the system is also used. The mechanical surging and chemical set time are important during this phase to achieve dissolution of the remaining biomass.

c. Disperse. This phase of treatment consists of removal of the material that has been clogging the well and aquifer. Acceptance criteria for the well are checked and further cycles are considered or a final cold chlorination treatment is applied for inhibition of any remaining bacterial colonies.

References

Driscoll, F.G. (1986). Groundwater and Wells. Johnson Division, SES, Inc., St Paul, MN.

Leach, R.E. & Taylor, H.M. Jr (1989). Proceedings of REMR Workshop on Research Priorities for Drainage System and Relief Well Probelsm. Final Report, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Kissane, J. & Leach, R. (1991). Redevelopment of Relief Wells, Upper Wood River Drainage and Levee District, Madison County, Illinois. Technical Report REMR GT-16, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

APPENDIX I: SIPHON PRINCIPLES (after GIBSON, 1952)

In its simplest form this consists of an inverted U-tube (Figure I.1), both legs being full of water, and the flow is generally calculated by equating the total head producing flow, i.e., the head due to the unbalanced column of water $A_z - Z_c$, or the difference of heads in the two reservoirs, to the sum of the frictional and other losses in the pipe and of the velocity head produced.

Thus $Z_A - Z_C$ = loss at entrance and exit

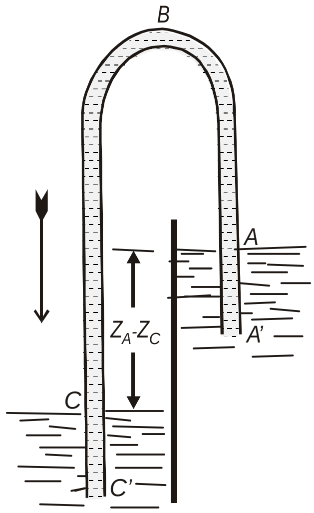

Figure I.1

This may be seen by considering the flow along each leg of the siphon separately.

Along *A′ B*, we have

$$Z_A - Z_C = \frac{v^2}{2g}\left\{1 + \frac{fl}{m} + K\right\} = \text{loss at exit + friction loss + loss at entrance.}$$

l being the total length of the siphon *A′B′C′*

EXAMPLE

$$\text{If} \left\{ \begin{aligned} Z_A - Z_C &= 15\text{m} \\ l &= 300\text{m} \\ Z_B - Z_A &= 3\text{m} \end{aligned} \right.$$

$$l_1 > \frac{300 \times 7.2}{15} = 144\text{m}$$

or the outlet leg will not run full if the inlet leg is more than 144 m in length.

With a longer inlet and shorter outlet the flow up the inlet will not be able to keep pace with that down the outlet and this will then run only partly full. Also the velocity up the inlet will not now be so great as with a shorter inlet, so that the discharge will be less. Evidently, then, the position of the apex of the siphon has a great influence on the discharge.

With a shorter inlet and a longer outlet, the total length being the same, the discharge will be unaltered, but the siphon will have the advantage of working under a greater absolute pressure at the apex, and is therefore less likely to be affected by air leakage at the joints.

In practice it is necessary to place an air chamber at the highest point of the siphon, into which air gradually accumulates during its working. This air is then removed at frequent intervals, either by some form of air pump, or by means of a steam ejector.

Where the siphon discharges into the atmosphere, any failure of the outlet leg to run full, by admitting air to the apex at once breaks the vacuum and stops the flow.

Figure I.2 shows the hydraulic gradient for a siphon, the straight line *A C* being the gradient line. In drawing this, the only losses taken into account have been those due to friction. If a second line *A*' *C*' be drawn parallel to and at a vertical distance from *A C* equal to the barometric height, the distance of the siphon below *A*' *C*' will give the absolute pressure at any point. In the sketch, siphons $A\ B_1\ C$, $A\ B_3\ C$, and $A\ B_2\ C$ are shown connecting *A* and *C*, all rising to the same height *h*, above the surface at *A*. Here, although B_2 is not nearly 10.2 m above *A*, an absolute vacuum would be attained before reaching B_2 and the siphon will consequently not work. A comparison of 1 and 3 shows that there is a greater pressure in the air vessel at B_1 than at B_3, and the siphon 1 will thus run longer without removal of air from this chamber than will 3. Leakage at joints is not likely to have so serious an effect as with 3. Where a regulating valve is to be used on a siphon, this should always be placed on the outlet leg.

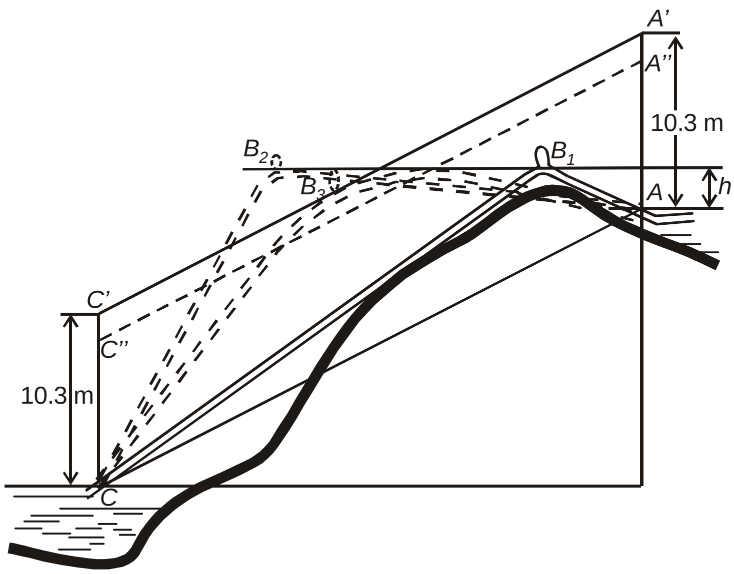

Figure I.2

APPENDIX J: RECOMMENDATIONS FOR THE DEVELOPMENT OF DSS OR CHECKLIST FOR SELECTING APPROPRIATE ENGINEERING OPTIONS

Criteria for the selection of management options

There are several factors that need to be considered before making a decision to apply certain management schemes for the control of saline areas or saline seeps:

- Distribution of soils, geology and structures in the catchment
- Catchment shape, slope, break of slope and curvature
- Rainfall patterns and evaporation
- Hydraulic properties of the aquifers at the site or catchment
- History of the catchment clearing and cropping regimes
- Location and dates of construction of dams, banks, drains and windmills
- History of the development of salinity at the site and salinity of discharge and possible origin of the groundwater discharge
- Order and type of stream
- Signs of noticeable seeps in the stream
- Stream groundwater quality

After careful analysis of all the above data, a decision has to be made if it is required to proceed further and put together a catchment management plan based on the answers to the following questions:

- The rate of expansion of the seep area and the development of salinity, in relation to the catchment clearing and cropping history:
- Did the catchment reach its maximum discharge capability?
- Are there other potential areas in the catchment that can become saline (depressions, break of slope where seeps can develop)?

In all cleared catchments of the wheatbelt, the recharge potential of the catchments is now several folds more than preclearing and due to the low hydraulic properties of the geological formations which form the aquifers in these catchments, the discharge potential is low. Similarly in catchments with a developing salinity problem, the discharge capacity of the catchment is much smaller than the recharge; it is therefore recommended that the catchment management plan should include reducing recharge and enhancing discharge strategies.

The role of soils, geology and regolith in positioning relief wells and siphons in southwestern Australia (Tables J.2 and J.3)

Archean granitoids, crosscut by suites of Archaean and Proterozoic mafic dykes and veins, are the dominant lithologies in the Yilgarn Craton of south-western Australia (Myers & Hocking, 1998). The physical and chemical composition of these rocks has influenced the development of this landscape and aquifer systems, and although they are often deeply weathered this is not always the case, and the presence (or absence) of deeply weathered profiles, along with landform information is used to describe three main Geomorphological Provinces, from west to east as follows (Tille & Percy, 1995):

> ***Darling Range***: where the variation in relief produces higher interpreted hydraulic gradients. Valleys tend to be incised and percentage of the area described as broad

flat-floored valleys is low, and restricted to the eastern part of the province. Permian sediments are preserved in geological basins, and thick sequences of Tertiary sediments are mapped in some river channels, and in the broad flats to the east. Deep weathering of the crystalline basement rocks is commonplace, particularly in the upper to mid landscape areas, and sands, ferruginous gravels and duricrust tend to overlie mottled zones and saprolites (Anand & Paine, 2002).

Zone of Rejuvenated Drainage: is marked by a decrease in the variation in relief with low hills and undulating rises being the dominant landforms. Broad valley flats become more prevalent in this province and tend to coincide with areas containing thicker sequences of Tertiary sediments, and in some localities Palaeochannel sediments. In this province the weathered profile of the crystalline basement rock is often 'stripped' or poorly developed across landscape position, with 'thin' soils directly overlying saprolite, saprock or even fresh rock.

Zone of Ancient Drainage*:* located east of the Meckering Line is typified by low topographic, and hence hydraulic gradients, to the extent that the majority of surface waters drain internally in this province. Undulating rises and broad flat-floored valleys predominate, and contain sandplain, Tertiary palaeochannel sediments and salt lake systems. Beneath the sediments ferruginous duricrust, saprolite or bedrock may be present.

The weathered crystalline basement forms the major aquifer in this region; therefore these geomorphological provinces also represent relevant hydrogeomorphological zones where they coincide with gross changes in aquifer character.

For example, in the Zone of Rejuvenated Drainage where the regolith may be stripped or poorly developed, the aquifer becomes 'thinner' and therefore more likely unconfined. Also, transmissivities may be relatively higher in these immature regolith materials, which complicates predictions of water levels and hydraulic head pressures across the landscape. This should be an important consideration when positioning relief and siphon wells in this province. Conversely, in the remaining two provinces the regolith is more commonly thicker, which means deeper wells must be constructed to access zones of high transmissivity in the aquifer (Clarke *et al*., 2000).

Similarly, for surficial and sedimentary aquifers, the presence and thickness of these materials is constrained by the geomorphological provinces to some extent. The usefulness of these aquifers is further constrained by their hydraulic properties, along with aquifer geometry and connectivity with deep groundwater. No geomorphic discrimination is required for mafic dykes and veins or faults, the main criteria being the orientation of the structures (Tables J.2 and J.3).

Guidelines produced from this broad geomorphological provinces framework are approximate. A better understanding of the spatial variability within each province with respect to aquifer materials and landform and slope, would assist more accurate predictions to be made. As previously mentioned, detailed photo interpretation, site inspection and analysis of available records and data is required for successful siting of a relief or a siphon well.

Table J.2 Potential Engineering solutions for selected geormoplogical provinces, landforms and geology.

Aquifer	Geomorphological Province	Landform	Geology	Potential Engineering Solutions
Surficial aquifer	Darling Range	valley floors (<1ºslopes—<20% of eastern geomorphological province only)		Relief wells if under pressure
		valley slopes	Duricrust	
			alluvium, colluvium, aeolian sandplain sediments and sheetwash	Siphon in lower parts of the catchment with essential slope and break of slope or windmill
	Rejuvenated Drainage	broad flats and valleys (<1ºslopes—20–30% of geomorphological province)		Relief wells if under pressure
		undulating rises and low hills	duricrust	
			alluvium, colluvium, aeolian sandplain sediments and sheetwash	Siphon in lower parts of the catchment with essential slope and break of slope or windmill
	Ancient Drainage	broad flats and valleys (<1ºslopes—30–50% of geomorphological province)		
		undulating rises	duricrust	
			alluvium, colluvium, aeolian sandplain sediments and sheetwash	Siphon in lower parts of the catchment with essential slope and break of slope or windmill
Sedimentary aquifer	Darling Range	valley floors (<1ºslopes—<20% of eastern geomorphological province only)		
		valley slopes	sandstones, shale and coal (Permian Basins)	
	Rejuvenated Drainage	broad flats and valleys (<1ºslopes—20–30% of geomorphological province)		
		undulating rises and low hills	lacustrine sediment	
			fluvial sediments	Siphon in lower parts of the catchment with essential slope and break of slope or relief well if under pressure
	Ancient Drainage	broad flats and valleys (<1ºslopes—30–50% of geomorphological province)		
		undulating rises	lacustrine sediment	
			fluvial sediments	Siphon in lower parts of the catchment with essential slope and break of slope or relief well if under pressure

Table J.2 (continued)

Aquifer	Geomorphological Province	Landform	Geology	Potential Engineering Solutions
Weathered rock aquifer	Darling Range	valley floors (<1ºslopes—<20% of eastern geomorphological province only)		
		valley slopes	granitoid and granitoid gneiss; mottled and/or pallid clay saprolite	
			granitoid and granitoid gneiss; saprock–saprolite	Position relief or siphon bores in mid to lower-mid landscape positions where catchment shape and local slope will focus groundwater movement
			dolerite and gabbro (dykes and sills); saprolite	Position relief or siphon bores up gradient where dykes are perpendicular to groundwater movement
	Rejuvenated Drainage	broad flats and valleys (<1ºslopes—20–30% of geomorphological province)		
		undulating rises and low hills	granitoid and granitoid gneiss; mottled and/or pallid clay saprolite	
			granitoid and granitoid gneiss; saprock–saprolite	Position relief or siphon bores in mid to lower-mid landscape positions where catchment shape and local slope will focus groundwater movement
			dolerite and gabbro (dykes and sills); saprolite	Position relief or siphon bores up gradient where dykes are perpendicular to groundwater movement
	Ancient Drainage	broad flats and valleys (<1ºslopes—30–50% of geomorphological province)		
		undulating rises	granitoid and granitoid gneiss; mottled and/or pallid clay saprolite	
			granitoid and granitoid gneiss; saprock–saprolite	Position relief or siphon bores in mid to lower-mid landscape positions where catchment shape and local slope will focus groundwater movement
			dolerite and gabbro (dykes and sills); saprolite	Position relief or siphon bores up gradient where dykes are perpendicular to groundwater movement
Fractured rock aquifer	Darling Range	valley floors (<1ºslopes—<20% of eastern geomorphological province only)		
		valley slopes	granitoid, granitoid gneiss, migmatite, schist and quartzite	Siphon in lower parts of the catchment with essential slope and break of slope or windmill
	Rejuvenated Drainage	broad flats and valleys (<1ºslopes—20–30% of geomorphological province)		
		undulating rises and low hills	granitoid, granitoid gneiss, migmatite, schist and quartzite	Siphon in lower parts of the catchment with essential slope and break of slope or windmill
	Ancient Drainage	broad flats and valleys (<1ºslopes—30–50% of geomorphological province)		
		undulating rises	granitoid, granitoid gneiss, migmatite, schist and quartzite	Siphon in lower parts of the catchment with essential slope and break of slope or windmill

Table J.3 Types of aquifers in different geology and potential engineering solutions

Geology	**Aquifer type,Transmissivity and Connectivity**	**Potential Engineering Solutions**
Surficial and sedimentary material		
Alluvium; sand, silt and clay	Minor local aquifer; low to moderate transmissivity; unconfined	Siphon in lower parts of the catchment with essential slope and break of slope or windmill
Colluvium and sheetwash; sand, silt, clay and gravel	Minor local aquifer; moderate to high transmissivity; unconfined	Siphon in lower parts of the catchment with essential slope and break of slope or windmill
Duricrust; ferruginous, siliceous and calcareous	Aquiclude	
Aeolian sandplain sediments; sands	Minor local aquifer; high transmissivity; unconfined	Siphon in lower parts of the catchment with essential slope and break of slope or windmill
Lacustrine sediment; clay	Aquitard; low transmissivity, partially confines the lower palaeochannel sand aquifer	
Fluvial sediments; sands and clays	Minor aquifer; low to moderate transmissivity; partially confines the lower palaeochannel sand aquifer	Siphon in lower parts of the catchment with essential slope and break of slope or relief well if under pressure
Fluvial sediments; sand	Minor to major aquifer; moderate to high transmissivity; semi-confined to confined	
Weathered crystalline basement rocks		
Granitoid and granitoid gneiss; saprolite/saprock	Very minor local aquifer; low to moderate transmissivity (dependent on degree of weathering); semi-confined to confined	Position relief or siphon bores in mid to lower-mid landscape positions where catchment shape and local slope will focus groundwater movement
Dolerite and gabbro (dykes and sills); saprolite	Aquiclude	Position relief or siphon bores up gradient where dykes are perpendicular to groundwater movement
Fractured crystalline basement rocks		
Granitoid, granitoid gneiss, migmatite, schist and quartzite	Minor local aquifer; moderate transmissivity (higher in elevated areas); unconfined	Siphon in lower parts of the catchment with essential slope and break of slope or windmill

Soils

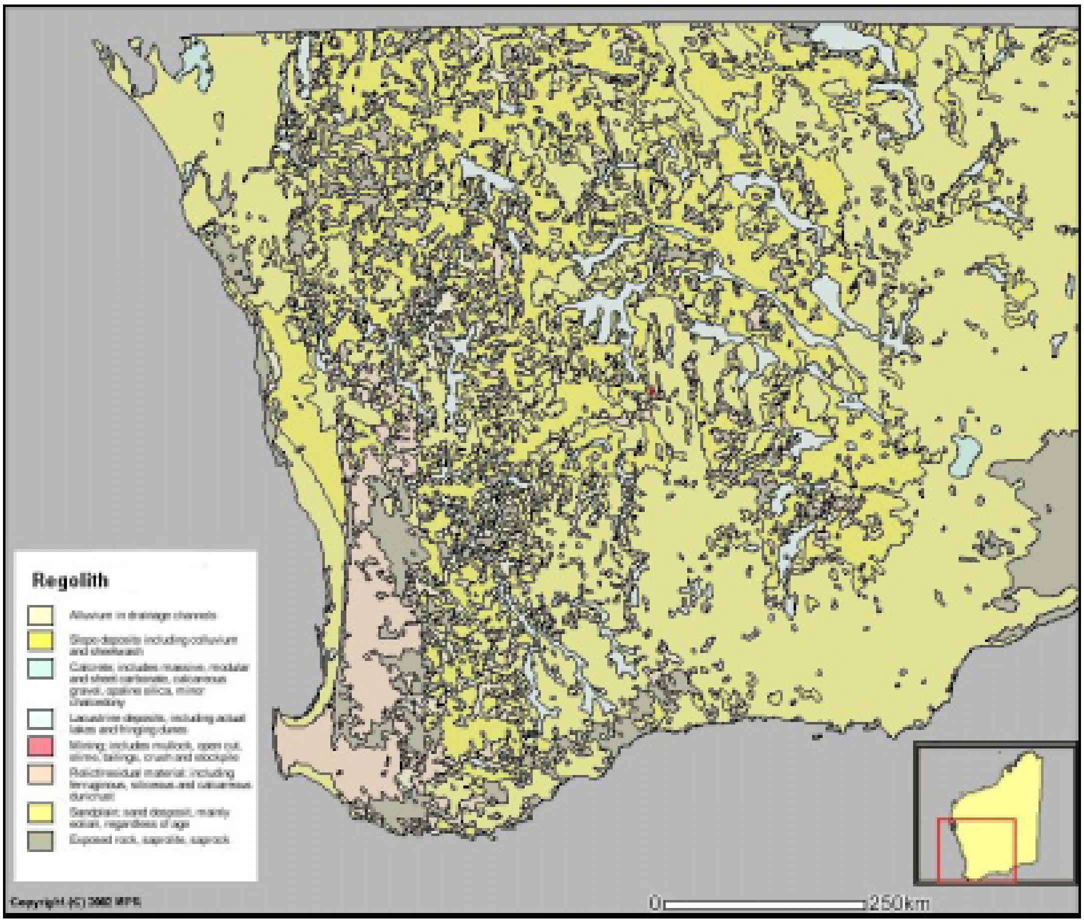

Figure J.1 Major regolith units of southwestern Australia (www.dme.wa.gov.au/geology)

Soils at the affected site control water infiltration as well as water seepage. It is therefore essential that soils be identified and some basic parameters be recognized. For example; the Southwest Hydrological Region has been divided into nine soil-landscape zones (Tille *et al*., 1995 and 1998). The major soils have been identified by Schoknecht (1997). For each soil group, the common soil properties and hydrological properties are detailed. The classification is adequate to give a very good idea of soil types and soil properties in each of these areas.

Geology

Regolith, solid geology and structures which define interconnectivity and barriers can be easily acquired from the Geological Survey of Western Australia maps and bulletins. Particulars of site geology and structures can be obtained from interpretation of the aerial photographs. With a site visit and examination of outcrops, all the necessary data required for an assessment of the site geology can be collated.

The use of soil maps and surveys and understanding geology of the area is needed to interpret the landscape and how geology impacts the hydrogeology of each catchment to understand the characteristics of groundwater flow. All this is essential for proper siting of relief and siphon wells.

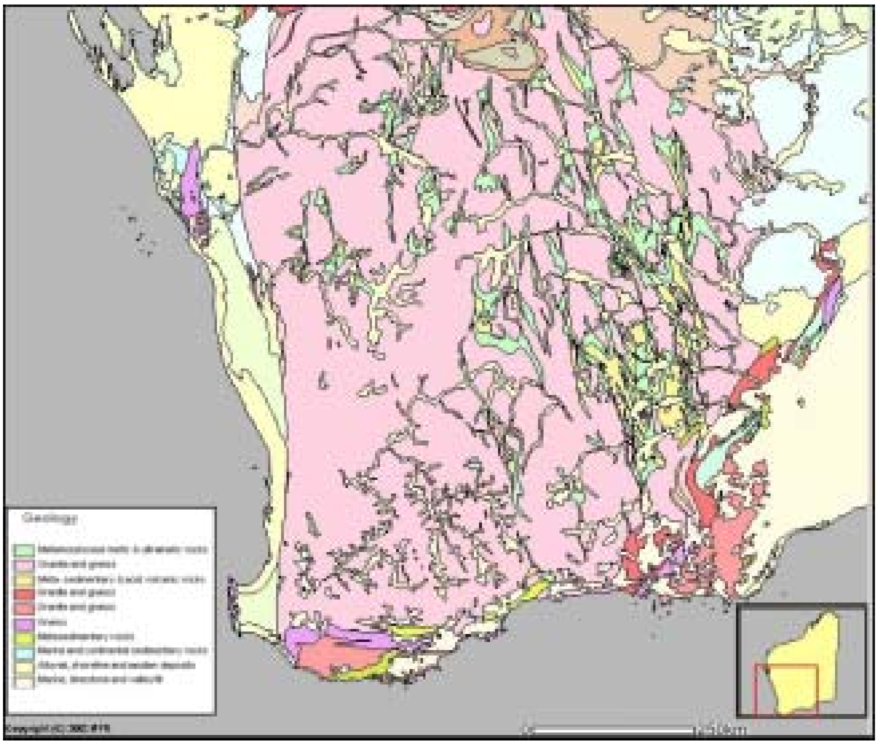

Figure J.2 Major geological units of southwestern Australia (after Myers & Hocking, 1998) (www.dme.wa.gov.au/geology)

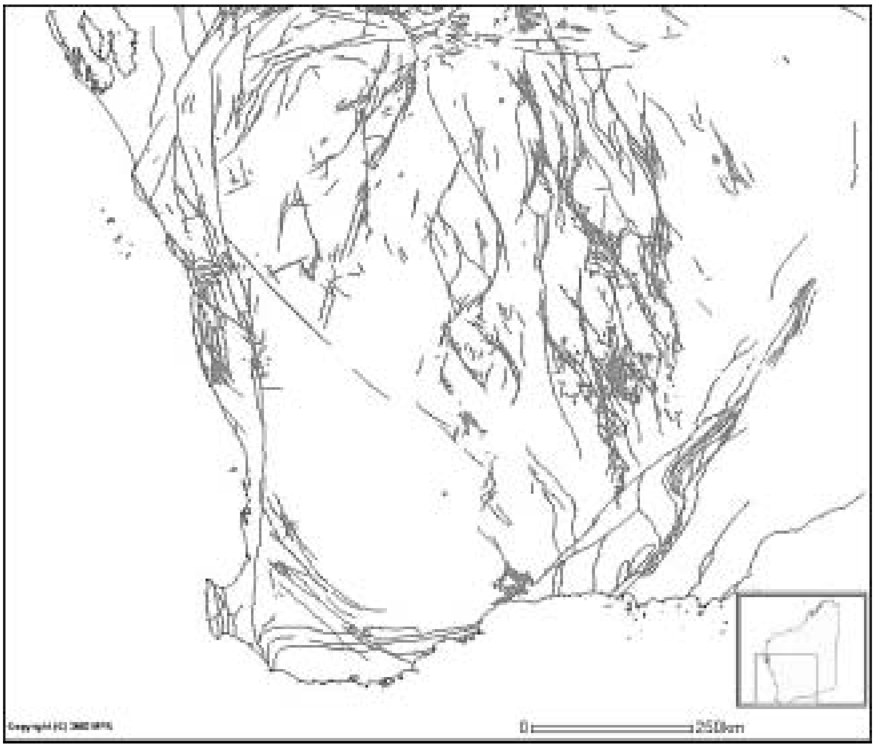

Figure J.3 Geological structure of southwestern Australia; major faults and folds mapped at 1:500 000 (www.dme.wa.gov.au/geology)

The role of geomorphology in positioning relief wells and siphons in southwestern Australia

Recent significant developments in Geographical Information Systems have been used to develop new methods for hydrogeomorphic classification of large catchments (Salama *et al*., 1994a, 1997). The methodology takes account of the important role geology plays in forming topography through differential weathering, erosion and deposition. These in turn influence the formation of geomorphic and hydrogeomorphic characteristics of the catchments, the hydrogeomorphic units reflected most of the major geological features of the area. (Salama *et al*., 1994b, 1994a, 1997).

Water levels are generally near the surface in lower areas of the catchment and water levels increase in depth with increasing altitude. The exceptions are confined aquifers, which show an inverse relationship between water level and aquifer depth.

Detailed analysis was carried out for the seven operational siphon sites in the Gordon catchment. The only parameter which was found to be affecting the operation of siphons, beside the hydrogeological characteristics of the aquifer, is the difference in height between the lowest water level in the siphon well and the discharge point; the greater the difference, the better the output (discharge).

All the siphon and relief wells constructed in the Gordon catchment of WA, as well as other sites in the eastern states, were found to be in the lower parts of the landscape, in existing discharge areas or in potential discharge areas. This does not overrule the fact that siphons can be constructed in upper parts of the landscape, but the fact that the water levels are deeper and although in most cases the groundwater is saline is not of major concern and will not cause a problem.

How to find out the amount of discharge to be disposed to solve the salinity problem

One of the most critical questions that need to be answered before any engineering solution be contemplated, is how much additional discharge we need to take out? To answer this question we designed a calculator for estimating the discharge area which can be caused by different rates of recharge in a catchment. This simple calculator can be used for estimating the amount of excess groundwater which needs to be discharged by any of the engineering solutions: siphon, relief well, pumping well or drain. It can also be used to estimate the number of trees to be planted to reduce the recharge in the upper parts of the catchment. It is based on Darcy's Law.

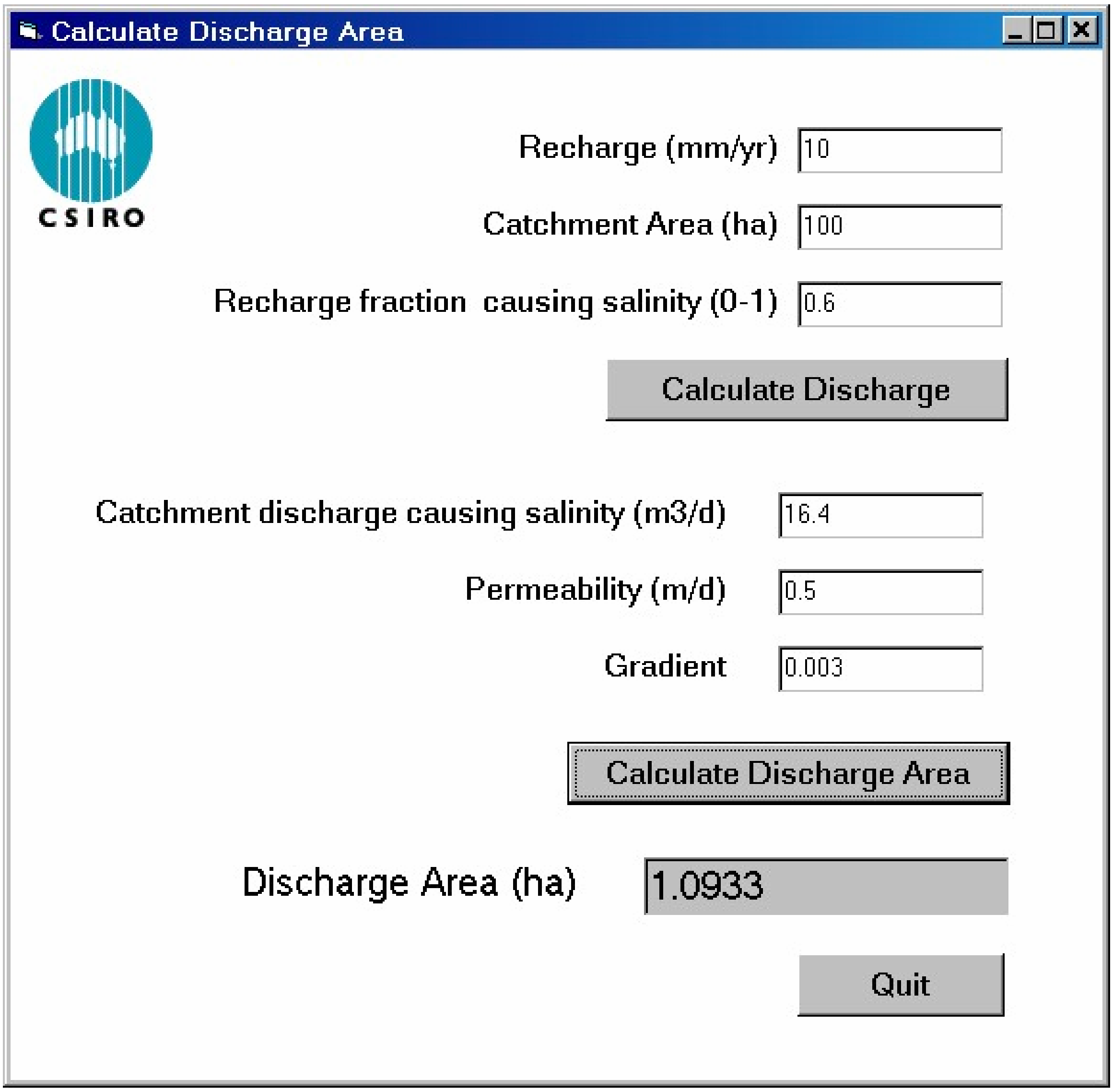

Figure J.4 Discharge Area Calculator

The Calculate Discharge button implements Equation J.3 to calculate the catchment discharge causing salinity, based on the input values for recharge, catchment area and fraction of groundwater flow in the aquifer which will emerge as groundwater discharge (the other fraction is assumed to flow into deeper aquifer or stream underflow).

$$c = (((w / 1000) \times (m \times 10000)) / 365) \times p \qquad \text{(J.3)}$$

Where c is catchment discharge causing salinity (m^3/day), w is recharge (mm/yr), m is catchment area (hectares), and p is the fraction of groundwater flow emerging as discharge causing salinity (the remainder is assumed to discharge directly to streams, and its value depends on the characteristics of the catchment hydrogeomorphology).

The Calculate button implements Equation J.4 to calculate the discharge area, based on the input values for catchment recharge causing salinity, permeability of the area through which groundwater discharge will take place, and gradient.

$$d = (c / (k \times s)) / 10000 \qquad \text{(J.4)}$$

Where *d* is the discharge area (ha), *c* is catchment recharge causing salinity (m^3/day), *k* is permeability of the area through which groundwater discharge will take place (m/day) and *s* is the gradient.

How to design a continuously operating siphon

As described earlier management of gas within the siphon line is considered to be of utmost importance in the maintenance of siphon flow. Siphon line gas management requires control of gas bubble transport, accumulation, and agglomeration and elimination of gas bubble entrapment. Gas bubble transport, accumulation, agglomeration, and entrapment are controlled by fluid flow velocity, gas buoyancy, siphon line grades and inside diameter discontinuities (i.e. fittings). The fluid flow velocity in the upward leg is not as critical as it is in the downward leg of the siphon line, and the upward leg fluid flow velocity should be balanced against minimisation of head loss to maximize overall flow rates. The direction of gas bubble transport, if any, in the downward leg of the siphon line is determined by whether transport due to fluid flow velocity or gas buoyancy is dominant. Fluid flow velocity tends to cause the gas bubbles to move downward in the downward leg of the siphon line towards the end of line. Gas buoyancy tends to cause the gas bubbles to move upward in the downward leg of the siphon line toward the siphon crest.

In order to utilise the minimum flushing velocity to maintain full flow in the siphon line downward leg, the fluid flow velocity must be dominant in the downward leg. That is, the fluid flow velocity must be greater than the required minimum. Additionally a continuous, downward, siphon line, grade (i.e. no localised high points) and the minimisation or elimination of fittings which produce discontinuities in the inside diameter of the siphon line, is necessary. The continuous downward grade and elimination of such fittings eliminates the accumulation, agglomeration and entrapment of gas bubbles in the downward leg of the siphon line.

To calculate the optimum velocity required for the continuous operation of a siphon, a simple calculator was designed. Knowing the optimum discharge of the well, and the expected drawdown at the specified rate, the difference in head can be entered and the optimum velocity for the optimum discharge can be calculated.

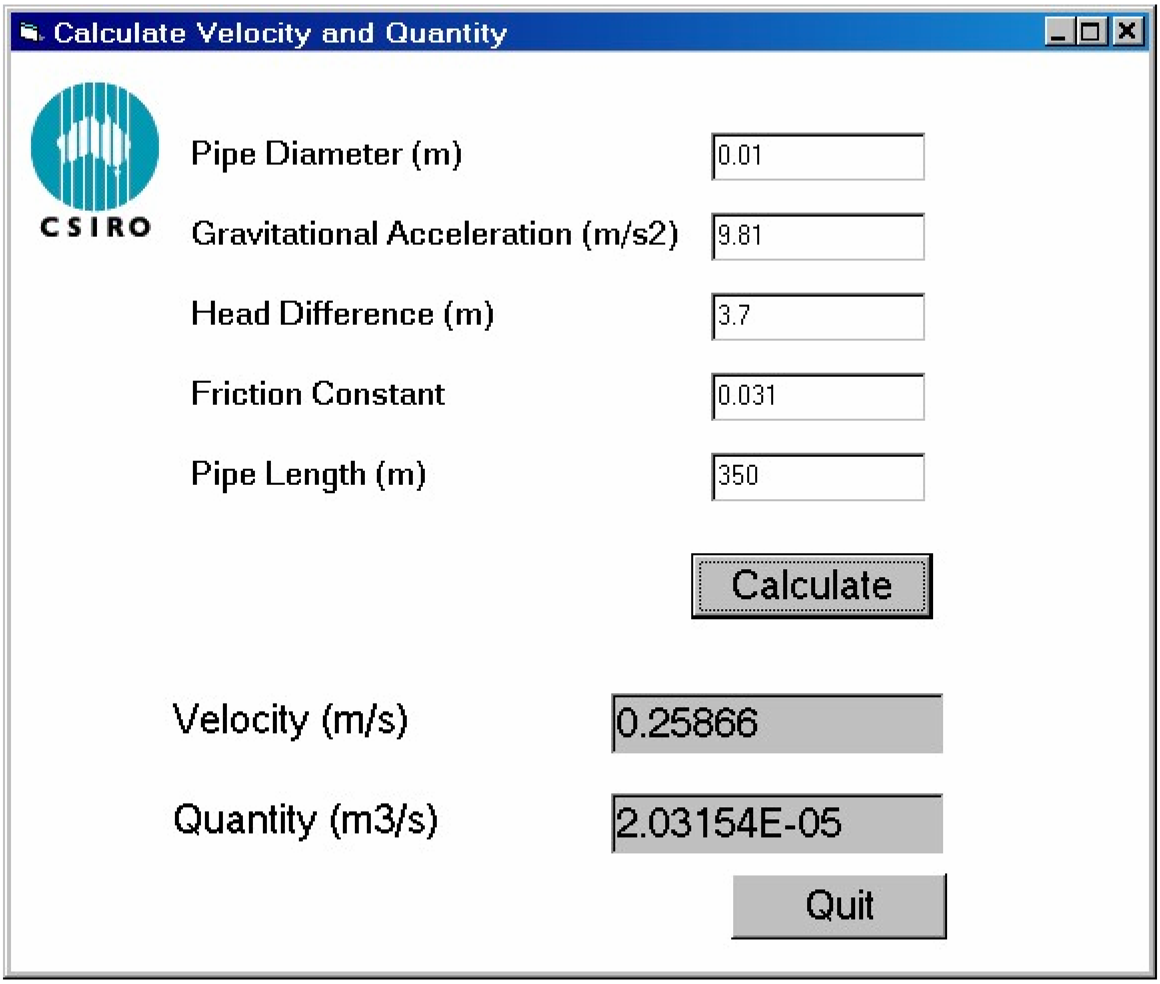

Figure J.5 Siphon Discharge Velocity and Quantity Calculator

The Calculate button uses the input values for pipe diameter, gravitational acceleration, head difference, friction constant and pipe length to calculate the discharge velocity and quantity from the siphon, based on Equations J.5 & J.6.

$$v = \sqrt{((d \times 2 \times g \times h) / (l \times f))} \qquad \text{(J.5)}$$

Where *v* is velocity (m/sec), *d* is pipe diameter (m), *g* is the acceleration of gravity (9.81 m/sec^2), *h* is the difference in head (m) between the pumping water level in the well and the siphon outlet elevation, *l* is the length of the pipe in metres, and *f* is the friction constant.

$$q = v \times \pi \times (d / 2)^2 \qquad \text{(J.6)}$$

Where *q* is the quantity of water discharging from the pipe (m^3/sec), *v* is the velocity of the water (m/sec), and *d* is the diameter of the pipe (m).

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