22 REGIONAL RETENTION

22.1 GENERAL PLANNING AND ANALYSIS

Generally, the procedures of planning, designing and operating a regional stormwater retention/recharge scheme are based on various analytical methods incorporating the analysis of numerous field data and laboratory tests and the use of different types of models and optimisation techniques. All these investigations demand skill, experience, imagination and sound judgement on the part of the stormwater/groundwater technical specialists involved. The decision making in selecting a plan and the final layout should be considered as unique to the groundwater basin where no typical procedures can be established for all cases and conditions.

Solutions are available for certain elements, such as seepage characteristics from surface water (in ponds, lakes, streams, canals, pits, spreading basins, and irrigation water). Other elements may require more sophisticated approaches such as locating the best locations of wells to activate induced stormwater infiltration. In these cases numerical solutions (based on finite-difference and/or finite-element/system analysis techniques, (Chapter 12 and 14) would be used and different models would be attempted. The final most important stage is to synthesise these elements within the framework of management of the entire urban basin and come up with an acceptable plan. Such a plan should be flexible in order to adjust the operations whenever necessary, should be able to predict future impacts and should satisfy the users within the political, economic, legal, social and administrative constraints. Augmentation of water supply and restoration of the aquifer should always be considered and incorporated in these plans.

22.1.1 Recharge Basins

Stormwater recharge can be accomplished by the spreading methods either by flooding a basin, ditch and furrow or natural channel or by irrigation. Another general method is to fill recharge basins with water from nearby surface-water sources either by pumping the water or by diverting streams to the basins (Chapter 18). The primary purpose of these methods is to allow water to infiltrate into the soil from a relatively large area and over an extended period of time. High infiltration rates are desirable. However, infiltration rates decrease with time. At the beginning, infiltration rates are small because of dispersion and swelling of the initially dry soil particles. After passing this stage, infiltration rates increase as a result of the dissolving of entrapped air in the water. Finally the infiltration rates decrease gradually because of microbial growth unless the soil is treated with organic matter and chemicals. Alternating wet and dry periods in operating the basin allow more water to infiltrate over a certain period of time rather than continuously maintaining the water levels in these basins.

In the ditch or furrow method, the channels are usually shallow, flat-bottomed and closely spaced. Therefore, the surface water in these channels may be assumed interconnected and the infiltration would be similar to that of a large basin. Infiltration from a recharge basin produces a groundwater mound above the original water table such as that shown diagrammatically in Figure 22.1. The groundwater mound grows over time and once the infiltration stops, it decays gradually. The analytical methods (Glover, 1964 and Hantush, 1967) are recommended for estimating the behaviour of groundwater mounding.

Clearly, the dimensions of this mound are governed by the basin size and shape, recharge rate and duration and phreatic aquifer characteristics. Most solutions are based on the usual assumptions of homogeneous and isotropic aquifers, vertical recharge at a uniform rate, the top of the mound does not contact the bed of the spreading basin and the height of the mound is small in relation to the initial aquifer saturated thickness.

The shape of a mound beneath a square recharge area can be expressed by dimensionless parameters as shown in Figure 22.2 (Bianchi and Muckel, 1970). Here *h* is the mound height (see Figure 22.1), *S* is the storage coefficient of the unconfined aquifer, *W* is the recharge rate, *t* is time since recharge began, *L* is the length of one side of the recharge area, *T* is transmissivity *(KD)* of the aquifer and x is a coordinate distance from the centre of the recharge area.

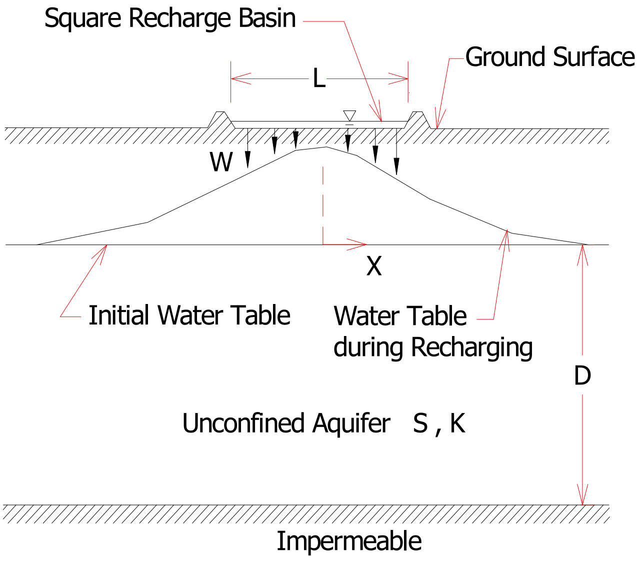

Figure 22.1 Recharge Mound Beneath a Square Spreading Basin (Todd, 1980)

For example, if water is spread in a square basin 100m on a side at a uniform rate of 0.5m/day, what will be the height of the groundwater mound at the edge of the basin after 15 days? Let T = 800 m^2/day and S = 0.15; then,

$$\frac{L}{\sqrt{4Tt/S}} = \frac{100}{\sqrt{4(800)(15)/0.15}} = 0.25$$

At the edge of the basin x/L = 0.5. Given these two dimensionless parameters, hS/Wt = 0.070 from Figure 22.2. Thus,

$$h = \frac{0.070wt}{S} = \frac{(0.070)(0.5)(15)}{0.15} = 3.50m$$

Similar solutions are available for circular and rectangular spreading basins and for basins above sloping water table. If recharge ceases at time t_o, dissipation of the mound can be calculated by superposing hypothetically on the flow system at $t = t_o$ a rate of uniform discharge equal to that of the percolation rate. The algebraic sum of the two mounds yields the mound shape at any time after the end of recharge. It follows that as time after t_o becomes large, h approaches zero.

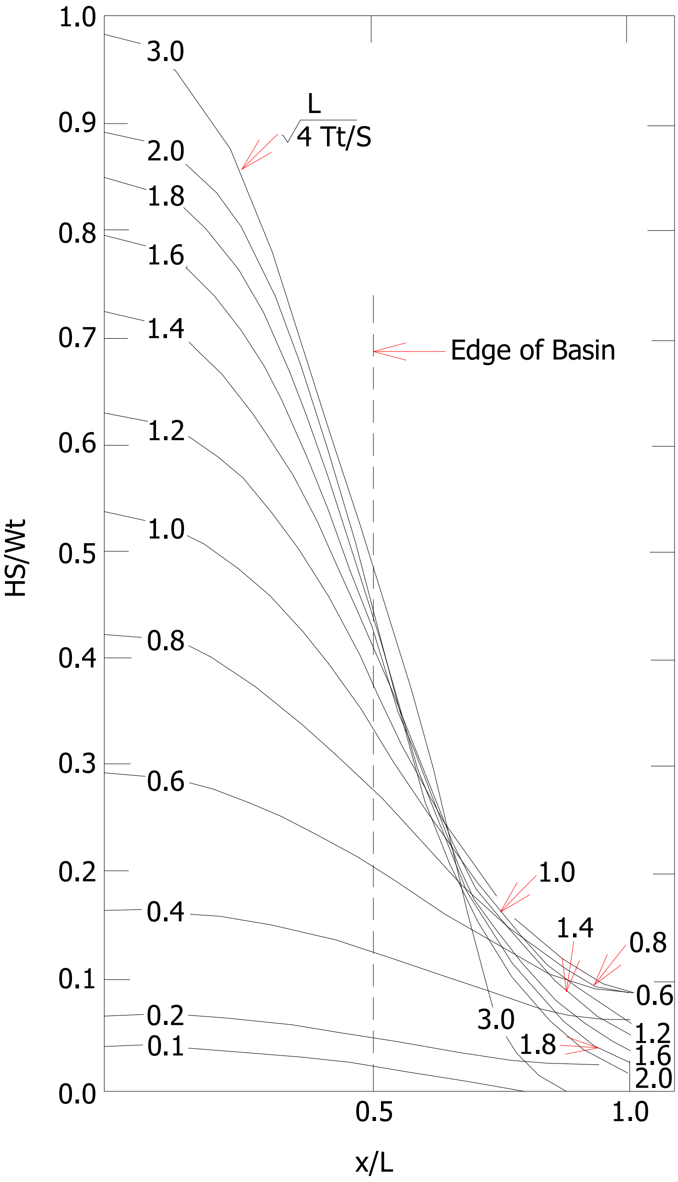

Figure 22.2 Dimensionless Graph Defining the Rise and Horizontal Spread with Time of a Water Table Mound Beneath a Square Recharge Area (Bianchi and Muckel,1970)

22.1.2 Recharge Wells

While well pumping produces a pattern of a radially converging flow to the well, with a drawdown of the water table, or the piezometric surface, a recharging well produces pattern of radially diverging flow from the well and a build-up of the water table, or the piezometric surface. The modifications, which have to be introduced in the well equations, are straight forward. However there are important difference which sometimes cannot be overlooked. When pumping takes place, silt and fine material, if present in the formation, is removed from it in vicinity of the well, where the average flow velocity ($V_r = Q_r / 2\pi r B n$) is sufficiently high. These fines are removed with the pumped water. A zone of increased permeability is thus created around the well. Actually this is a standard procedure (called well development) in a newly drilled well. Pumping operations at a rate which is higher than that normally planned for the well, are carried out for some time, until the pumped water is clear, containing no fine material.

In a recharging well, however, we always bring impurities into the formation. These impurities may include fine material, organic matter and air. At some distance from a recharging well, the velocity of the water reduces to the point, which results in the settlement of silt, and fine particles carried in the water. The permeability of the formation is reduced. Dissolved contaminants carried in the water may interact with the solid skeleton (e.g. base exchange in soils containing clay and silt) and/or with the indigenous water in the aquifer and produce clogging of the formation. Air bubbles are carried in the water and lodged in small pores. Air, dissolved in the water is released from solution as the pressure drops in the casing or in the formation itself, forming bubbles, which are also lodged in the small pores. Organic matter and bacteria may produce a growth on the well's screen. Altogether, we have a phenomenon of reduction of effective flow area and clogging. Because of the higher velocity and pressure gradients near the well, part of the reduction of permeability occurs at some distance from the well. A zone of reduced permeability is thus created near the well. The permeability continues to drop with the increase in volume of recharged water. This produces an additional build-up, which has to be taken into account when calculating build-up recharge relationships. For the sake of completeness, we should also mention the possibility that as a result of the method of drilling, the permeability in the immediate vicinity of a well is reduced (skin effect). For example, when the drilling fluid (mud) used in conventional rotary techniques penetrates the formation and is not completely removed upon completion of drilling.

For steady flow of recharge into confined aquifer (Figure 22.3) the equation is:

$$Q_r = -2\pi r K(r) B \frac{d\phi}{dr} \qquad 22.1$$

Where Q_r is the constant rate of recharge. The build up/non-build up steady state expressions are respectively recommended as:

$$\phi(r_w) - \phi(R) = \frac{Q_r}{2\pi B}\left\{\int_{r_w}^{r_e} \frac{dr}{rK(r)} + \ln\frac{R}{r_e}\right\} \qquad 22.2$$

$$\phi(r_w) - \phi(R) = \frac{Q_r}{2\pi B K_o} \ln\frac{R}{r_w} \qquad 22.3$$

Which corresponds to $K = K(r)$ for $r_w < r < r_e$ and a constant $K = K_0$ for the entire region $r_w < r < R$. R is the radius of influence where practically no build-up is observed and r_e is the effective radius. The additional build-up thus obtained is due to clogging. When the permissible build-up is limited, this means that the recharge rate Q_r has to be reduced. When the reduced recharge rates become uneconomic, cleaning operations have to be undertaken in order to restore the recharge capacity of the well.

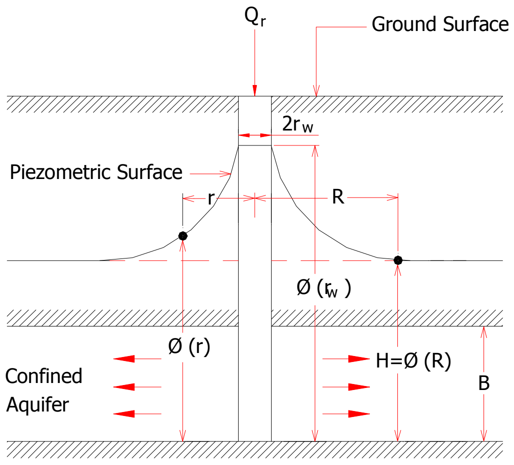

Figure 22.3 Steady Recharge into Confined Aquifer

22.2 RECHARGE BASIN DESIGN

This facility design consideration is similar to the quantity infiltration basin and wet pond. Stormwater must <u>always</u> be pretreated prior to discharge to this facility.

Appropriate soil conditions and the protection of ground water are among the important considerations, which may limit its use. See Chapter 21 for a description of General Limitations.

This basin will typically be located 'off-line' and be an integral component of the quality control and detention system.

Drainage areas can be larger than 50 ha and basin depths generally may exceed 4 m.

22.2.1 Design Criteria

The design procedure described in Part E and G, Chapters 20, 21, 34 and 35 should be used to design this type of basin system.

(a) General

The construction of structures, materials allowed, accessibility for maintenance, safety measures, easements and hydraulics design methods shall be the same as those required for detention basins given in Chapter 20.

(b) Soil Investigation

A minimum of one soils log shall be required for each 450 m^2 of infiltration basin area (plan view area). Each soils log shall extend a minimum of 1 m in depth below the bottom of the proposed basin, describe the soil series, the textural class of the soil horizon(s) through the depth of the log and note any evidence of high ground water level, such as mottling. In addition, the location of impermeable soil layers or dissimilar soil layers shall be determined.

(c) Infiltration Rate

The design infiltration rate, f_d, will be equal to one-half the infiltration rate found from the soil textural analysis.

(d) Overflow route

An overflow route must be identified in the event that the basin capacity is exceeded. This overflow should be designed to meet minimum requirement for preservation of natural drainage system.

(e) Runoff Treatment

Runoff from the 3 month ARI design storm is to be completely treated prior to discharge to this basin.

(f) Slopes

Basins should be located on flat land only

(g) Buildings

Basin should be located away from the buildings

(h) Surface Area

The infiltration surface area (A_s) used for sizing basin shall be computed by measuring the surface area (plan view area) below the maximum design water surface.

(i) Outlets

The bottom elevation of the low-stage orifice should be designed to coincide with the prescribed one-day infiltration capacity of the basin. All other aspects of the principal outlet design and the emergency spillway shall follow the details provided for detention basins.

(j) Drawdown Time

Recharge basins shall be designed to completely drain the intended stored runoff within one day following the occurrence of the 10 year ARI, 24 hour design storm and within two days of the 100 year ARI, 24 hour design storm (with appropriate correction factors). Thus, a maximum allowable drawdown time of 48 hours is permissible.

(k) Groundwater Mound

The maximum groundwater mound under the centre of the basin is limited to 1.5 m below the base of the basin.

(l) Vegetation

The embankment, emergency spillways, spoil and borrow areas and other disturbed areas shall be stabilised and planted in accordance with Chapter 39 and 42

22.2.2 Construction Criteria

(a) Construction Schedule

The sequence of various phases of basin construction shall be coordinated with the overall project construction schedule. A program should schedule rough excavation of the basin with the rough grading phase of the project to permit use of the material as fill in earthwork areas. The partially excavated basin could serve as a temporary sediment trap or pond in order to assist in erosion and sediment control during construction. However, basins near the final stages of excavation should never be used prematurely for runoff disposal. Drainage from untreated, freshly constructed slopes within the subcatchment area would load the newly formed basin with a heavy concentration of fine sediment. This could seriously impair the natural infiltration characteristics of the basin floor. Final grade of an infiltration basin shall not be attained until after its use as a sediment control basin is completed.

Specifications for basin construction should state the earliest point in construction progress when storm drainage may be directed to the basins and the means by which this delay in use should be accomplished. Due to the wide variety of conditions encountered among projects, each should be separately evaluated in order to postpone use as long as is reasonably possible.

(b) Excavation

Initial basin excavation should be carried out to within 400 mm of the final elevation of the basin floor. Final excavation to the finished grade should be deferred until all disturbed areas in the catchment have been stabilised or protected. The final phase of excavation should remove all accumulated sediment. Relatively light-tracked equipment is recommended for this operation to avoid compaction of the basin floor. After the final grading is completed, the basin floor should be deeply tilled by means of rotary tillers or disc harrows to provide a well-aerated, highly porous surface texture.

(c) Lining Material

Recharge basins can be open or be lined with a 150 mm to 300 mm layer of filter material such as coarse sand or a suitable filter fabric to help prevent the buildup of impervious deposits on the soil surface. The filter layer can be replaced or cleaned when/if becomes clogged. When a 150 mm layer of organic material is specified for disking or spading into the basin floor to increase the permeability of the soil, the basin floor should be soaked or inundated for a brief period and then allowed to dry subsequent to this operation. This induces rapid decay in the organic material and prevents the organic matter from becoming hydrophobic, loosening the upper soil layer.

Establishing a healthy stand of vegetation on the basin side slopes and floor is recommended. This vegetation will not only prevent erosion and sloughing, but will also provide a natural means of maintaining relatively high infiltration rates. Erosion protection of inflow points to the basin shall also be provided. Removal of accumulated sediment is a problem only at the basin floor. Little maintenance is normally required to maintain the infiltration capacity of side slope areas.

Selection of suitable vegetative materials for the side slopes and all other areas to be stabilised and application of correct amounts of fertiliser and mulches shall be done in accordance with Chapter 39 and 42.

22.2.3 Maintenance

(a) Inspection Schedule

When recharge basins are first placed into use they should be inspected on a monthly basis and more frequently if a large storm occurs in between that schedule. During the wetter months inspections shall be conducted monthly. Thereafter, once it is determined that the basin is functioning in a satisfactory manner and that there are no potential sediment problems, inspection can be reduced to a semiannual basis with additional inspections following the occurrence of a large storm (e.g. approximately 50 mm in 24 hours). This inspection shall include investigation for potential sources of contamination.

(b) Sediment Control Effect on Vegetated Basins

The basin should be designed with maintenance in mind. Access should be provided for vehicles to easily maintain the forebay (presettling basin) area and not disturb vegetation, or resuspend sediment any more than is absolutely necessary.

Cleanout frequency of recharge basins will depend on whether they are vegetated or non-vegetated and will be a function of their storage capacity, recharge characteristics, volume of inflow and sediment load.

Grass bottoms in infiltration basins seldom need replacement since grass serves as a good filter material. If silty water is allowed to trickle through the turf, most of the suspended material is strained out within a few yards of surface travel. Well established turf on a basin floor will grow up through sediment deposits forming a porous turf and preventing the formation of an impenetrable layer. Grass filtration works well with long, narrow, shoulder-type depressions (swales, ditches etc.) where highway runoff flows down a grassy slope between the roadway and the basin. Grass planted on basin side slopes will also prevent erosion.

(c) Sediment Removal From Non-Vegetated Basins

Sediment is most easily removed when the basin floor (or presettling basin) is completely dry and after the silt layer has mud-cracked and separated from the basin floor. It is recommended that hand raking and removal be done if possible to avoid compaction of the infiltration media by equipment. Large-tracked vehicles should not be used in order to prevent compaction of the basin floor.

(d) Tilling of the Non-Vegetated Basin Floor

All accumulated sediment must be removed prior to tilling operations. As tilling is required periodically and at least once annually, the frequency of sediment removal will be reduced to small operations on a regular basis.

Tilling may be necessary to restore the natural infiltration capacity by overcoming the effects of surface compaction and to control weed growth on the basin floor.

Rotary tillers or disc harrows will normally serve this purpose. Light tractors should be employed for these operations. In the event that heavy equipment has caused deeper than normal compaction of the surface, these operations should be preceded by deep plowing. In its final condition after tilling, the basin floor should be level, smooth and free of ridges and furrows to ease future removal of sediment and minimise the material to be removed during future cleaning operations. A levelling drag, towed behind the equipment on the last pass will accomplish this.

To enhance infiltration capacity, tilling should be done. To control vegetative growth, an additional light tillage may be necessary during the growing season. Precautions must be observed to avoid working any of the sediment accumulation into the basin floor as a part of a light cultivation for weed control. Any cultivation or tilling operation must be preceded in all cases by careful sediment removal.

(e) Side Slope Maintenance

Maintenance of side slopes is necessary to promote dense turf with extensive root growth, which enhances infiltration through the slope surface, prevents erosion and consequent sedimentation of the basin floor and prevents invasive weed growth.

Seed mixtures should be the same as those recommended in the Erosion and Sediment Control (Chapter 39).

The use of low-growing grasses will permit long intervals between mowings. Mowing twice a year is generally satisfactory. Fertilisers should be applied only as necessary and in limited amounts to avoid contributing to the pollution problems, including ground water pollution that the infiltration basin is there to solve. Consult the local extension agency for appropriate fertiliser types and application rates.

22.2.4 System Operation and Maintenance

Operation and maintenance of the facilities should be such that the maximum amount of water is recharged in a given time at a reasonable cost. This can be accomplished in several ways depending on the types of surface and subsurface materials in the recharge area and the quantity and quality of the water available for recharge. The efficiency of the operation can be affected by the shape and depth of the facility and the extended and interaction with other surface spreading facilities.

(a) Surface and Subsurface Conditions

Studies for selection of a recharge site should have reviewed the soils maps of the area to assure that the soils were sufficiently open and deep to permit continuing recharge. A geological study should have been made to insure that layers of clays (or layers of low hydraulic conductivity) do not exist below the recharge facilities to unduly restrict the downward percolation of the recharged water to the main body of ground water. The study should also have predicted whether or not a ground water mound or water logging will occur. Piezometers (water table observation wells) should be installed at reasonable distance from the recharge facilities to measure ground water levels in the vicinity. After the facilities are in operation, water level measurements can be used to detect high water levels that may occur and cause damage to nearby structures such as highway depression and basements of buildings, and to plants susceptible to excess water.

(b) Water Quality

Three significant barriers to efficient artificial recharge are bed load, suspended sediment (turbidity), and pollutants in the incoming water. The deposition of the coarser material classed as bed load sediment decreases the storage volume of the ponds and the time between cleanings. Settling basins placed ahead of the recharge ponds will capture the bed load and make removal and disposal easier. The suspended sediment, primarily clays and silts that constitute turbidity, will result in a rapid reduction in the recharge rate as the suspended material accumulates on the surface and the near subsurface of the recharge area. If excessive turbidity is present, a choice will have to be made between frequent drying and cleaning to renew the basin recharge rates and reduction in turbidity before the water is introduced into the recharge area. The implementation of this later choice will result in an operating criteria that will set a limit on the turbidity of water to be recharged. The choice of criteria will have to consider the availability of water, its turbidity, and the economics of renewing the recharge rate through cleaning and disposal of the accumulated silts and clays.

Some operators allow only waters of 10 nephelomatric turbidity units (NTU) or less to be recharged; any waters containing turbidity in excess of that amount are rejected. However, water to be recharged can be treated to reduce the level of turbidity. The methods of pretreatment most commonly used include coagulants, such as polyelectrolytes, in separate settling basins and the use of grass/soil filter.

Treatment to remove turbidity does not, however, remove chemical compounds that may be in solution and should not be recharged. In areas where the upstream watershed is being urbanised, the runoff is likely to contain heavy metals and other contaminants washed from paved or other hard surface. The concentration of these undesirable constituents will be greater in runoff caused by the first rains after a dry period. Such water could be rejected as being unacceptable for ground water recharge. When recharge ponds are used for additional purposes such as supporting a fishery, the effect of water quality and water treatment on the other purpose should be examined. When the water to be recharged is imported and of different quality than local surface water, the possibility of adverse effects on the recharge rate due to chemical reaction between the imported water and the native soils should be evaluated. The result of such reactions includes sealing of the recharge area and loss of recharge potential.

(i) Settling Basin

The coarser materials in stream flow are transported by the velocity of the stream. These materials will drop out when the velocity is reduced, e.g. by diversion into a large settling basin. The removal of suspended particles causing turbidity will usually require use of flocculants (or coagulants) that include a wide range of chemicals such as metal salts; hydroxides such as alum, ferric chloride, and lime; and organic polymers. The use of polyelectrolytes, simple mixing procedures, settling basins, and skimming weirs can be cost effective means of reducing turbidity levels.

Disinfection of waters may be necessary if the site accommodates water that may pose a health hazard when reused. If utilised, disinfectant is commonly introduced upstream from any settling basin in order that dead aquatic species will be removed in that basin before it reaches the recharge facility. The use of either flocculents or disinfectant should be with the advice of an experienced chemist.

Laboratory trials may be necessary prior to use of flocculants because doses of the chemical will have to be matched to several site conditions, such as water temperature. If the recharge facilities are also used for recreational purposes, this use must be considered in selecting the type of disinfection or other chemicals used.

(ii) Grass/Soil Filters

Grass/soils filters can be used in recharge basins downstream of settling basins to remove the remaining fine colloids and organics. They can also be effective without a settling basin for pretreatment. Development of the filter requires that the soil be stabilised and an adequate grass cover grown before water is applied. The type of soil and grasses used to be designed to meet local soil and water inflow conditions and usually require some trial and error test plots.

(iii) Filter Media

Both granular filter material, such as sand, and geotextile filter fabric can be used where existing surface materials are not appropriate for the bottom of the recharge pond. Geotextiles can be used on the sloping sides that are to be wetted to prevent wave erosion.

Granular filter material used to cover the pond bottom can be removed when recharge rates decline and new material added. With careful maintenance this system should last indefinitely as long as the media is removed before fine materials pass through the media to the underlying soil. To ensure long life, the granular material should be selected (designed) with care and should consider the size of the fine materials to be trapped.

The type of geotextile filter media to be used must take into account the fine material to be trapped. Information is available from manufacturers on the performance and maintenance of geotextiles under differing conditions. If fabric is used on a ground not free of sharp or angular materials a 150 mm cushion of sand should be provided above and below the fabric to minimise tearing of the fabric. When the recharge rates decline to an unacceptable level, the portion of the sand covering the geotextile filter that has become clogged will have to be removed. Determining when to remove and replace a portion of the sand cover, or the entire cover and the geotextile filter should be the subject of an economic study.

(c) Basin Operations

There are two general types of operation of off-stream recharge facilities. One is a 'wet/dry cycle' and the other is a 'constant head operation'. The first consists of filling the basin and the turning off the inflow. The water in the basin is allowed to infiltrate into the soil and, after a few days, the basin is empty. The bottom of the basin then is allowed to dry and aerate and to reach an aerobic state. This process is then repeated until such time as the time the basin takes to drain by infiltration has lengthened to an unacceptable time. Then the basin will have to be emptied, allowed to dry, and the material that has been deposited on the bottom removed.

The constant head method of operation maintains a full basin on a continuous basis. That is, the basin is filled and the rate of flow of influent water is maintained at a rate approximately equal to the rate of recharge from the basin. This operation is continued until the recharge rate lowers to an unacceptable level. Then the basin must be emptied, allowed to dry, and the deposited sediment removed. In some cases, it is possible to empty the basin, let the basin dry out, and restart the recharge operation without removing the deposited sediment. However, the recharge rate will be slightly lower than the original rate.

When the basin is kept full of water over an extended period of time, algae and aquatic weed growth may occur. The algae growth will come and go, depending on sunlight and water temperature, turbidity, nutrients and other factors. As the algae dies, it settles to the pond bottom and reduces the recharge rate. The algae can be controlled chemically by the use of copper sulfate or alternative compounds, depending on the pH level of the water. In some situations the copper ion precipitates out on the pond bottom and may cause problems. Very low levels of copper can cause death of fishes. There are other chemical that can be used to control algae but the effects of each on ground water quality, recharge rates, and public health need to be considered. Algae growth can be reduced by using deeper ponds. Ponds in the range 4-4.5 m deep may have cooler water than shallow ponds and will permit less light penetration to the bottom.

As a result they are less likely to support algae growth. Deeper ponds also reduce weed growth.

(d) Ground Water Mounding

The ponding of water and resultant infiltration creates a mound in the ground water table directly below the pond. Also, when subsurface soil layers of low hydraulic conductivity exist that restrict the downward movement of the recharged water, localised perched water table mounds may be created. If any of these mounds grow upward to the point where their upper surface nears or reaches the bottom of the pond the rate of infiltration will decrease. The rate of infiltration will then be limited to the quantity of lateral flow from the mound. It is therefore wise to have observation wells near the ponds to measure the depth to ground water and to aid in evaluating the potential impacts of a rising water table on infiltration rates.

(e) Basin Cleaning

Regardless of the type of recharge operation conducted, the rate of recharge is ultimately reduced to unacceptable levels by the buildup of clogging material on the basin bottom. This clogging material consists of the turbidity filtered from the recharging water and, in some cases, the organic remains of weed and algae growth. The clogging material must be removed to restore the facility to its original recharge rates. Prior to cleaning, the basin should be allowed to dry as much as possible. Once a decision is made to clean the basin it should be drained as quickly as possible. Drainage pipes at or near the basin bottom expedite the draining time. For deeper ponds, consideration should be given to the potential for slope failure if water levels are lowered too rapidly. Ponds using grass/soil and media/fabric filters require the use of special cleaning techniques such as special mechanical equipment or hand labour. The pond bottom should be thoroughly dried before cleaning operations are initiated.

The optimal amount of cleaning would remove only the accumulation of surface material that has reduced the recharge capacity of the facility. Normally, most of the fine-grained material that induce turbidity in the recharge water and the decaying weed and algae growth is filtered within the basin bottom. However, but some of this material penetrate a few centimetres into the basin bottom. Therefore, some of the native basin bottom material must also be removed to restore the recharge rates. In general, less than 150 mm of material must be removed.

Cleaning can be significant operational cost, considering that the removal of 150 mm of material amount to about 1,500 m^3 of material per hectare of basin bottom. Self-loading scrapers may be used in such cleaning operations. These scrapers can remove several centimetres of material without the aid of any additional pieces of equipment. Further, the self-loading scraper is a relatively lightweight equipment and runs on large rubber tires, reducing the compaction of the basin bottom during the cleaning operation. An alternative to using self-loading scrapers is to withdraw the basin bottom material using a motor grader or small bulldozer blade. This withdrawned material can be left on the basin bottom for one or two cleaning periods without any significant adverse effects on infiltration.

Regardless of how the basin bottom is cleaned, the equipment should be operated in a manner that result in the least number of runs over the same area, thus reducing the potential compaction of the basin bottom material. Different combinations in size of equipment (load per square meter) and number of passes required should be considered to obtain the least basin bottom compaction. When the cleaning operation is completed, discing or ripping of the pond bottom from 50 to 300 mm deep is sometimes used to overcome the compaction that took place during the cleaning operation. Ripping of the basin bottom must be weighed against the fact that turbidity in the recharge water will filter out in the cracks of the deep ripping, making the bottom seal thicker and requiring greater depths of later removal of pond bottom soil material to restore recharge rates. Occasionally a soil sample down to 0.6 m or 1.0 m should be taken to check on the depth of compaction that may have occurred. If compaction is found at these depths it may be advisable to use a tractor and ripper that can reach these depths. After such deep ripping the basin bottom should be smoothed to reduce the potential problem of deep filtration noted previously. As basins are cleaned, they will become deeper because of the necessary removal of some native material during each cleaning. There has been some experimental work done that placed sand or pea gravel on the basin bottom. This material was removed, cleaned, and replaced when required in lieu of removing native material from the pond bottom. This process has worked in some situations, but the method is not universally accepted.

22.3 RECHARGE WELL DESIGN

22.3.1 Introduction

Four types of recharge wells are recommended as shown in Figures 22.4 and 22.5 (ASCE, 1996)

1. a single-injection well is used when only one aquifer is being recharged
2. a dual-injection well is used for independent recharge of two separate aquifers
3. a triple point injection well would be used for independent recharge of three separate aquifers
4. a composite-injection well can be used for recharge of several aquifers from one source

With free water table conditions and porous formations between the ground water table and the ground surface, injection wells compete with surface recharge basins for economy. For any given set of circumstances, the most economical and advantageous method (either surface recharge basins or injection wells) should be employed. Wells offer the economy of minimum land-area requirements. They can be located along existing major water conveyance facilities, avoiding the need to construct additional conveyance facilities and can be on or near roadways or public rights of way, further minimising land cost.

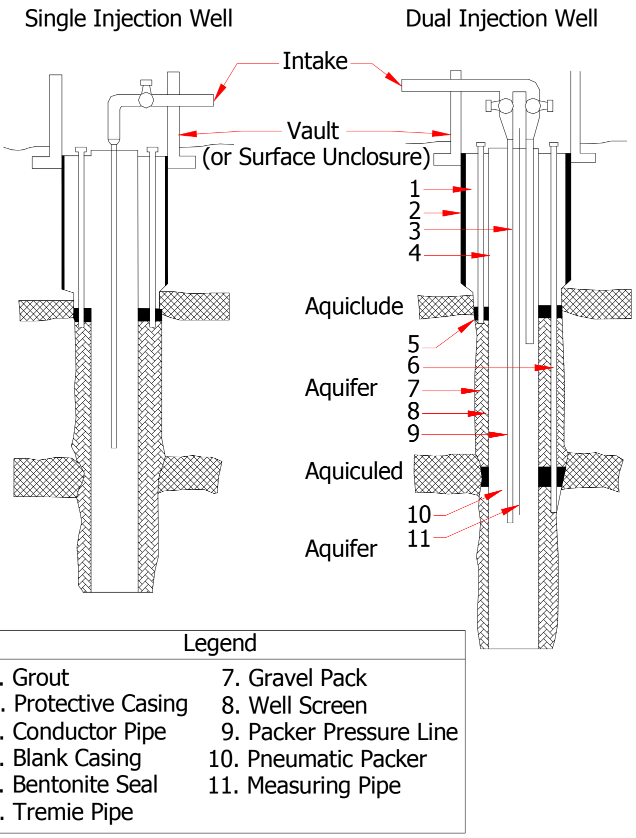

Figure 22.4 Single and Dual Level Injection wells

Injection wells can provide high recharge rates in areas where alternating layers of high and low hydraulic conductivity exist, since they take advantage of the high horizontal hydraulic conductivity and transmissivity of an aquifer and bypass the vertical restrictions caused by the finer grained strata of low hydraulic conductivity. Although an individual recharge well may have a high recharge rate, several such wells are usually required for a recharge facility. The interaction of these wells should be considered in the design but will not be certain until confirmed by pilot tests and finally by operation of the recharge wellfield itself. Experience indicates that injection wells require continuous water treatment BMPs, including filtration, and that periodic redevelopment and maintenance are necessary. The cost of maintenance is an important factor in the evaluation of economy.

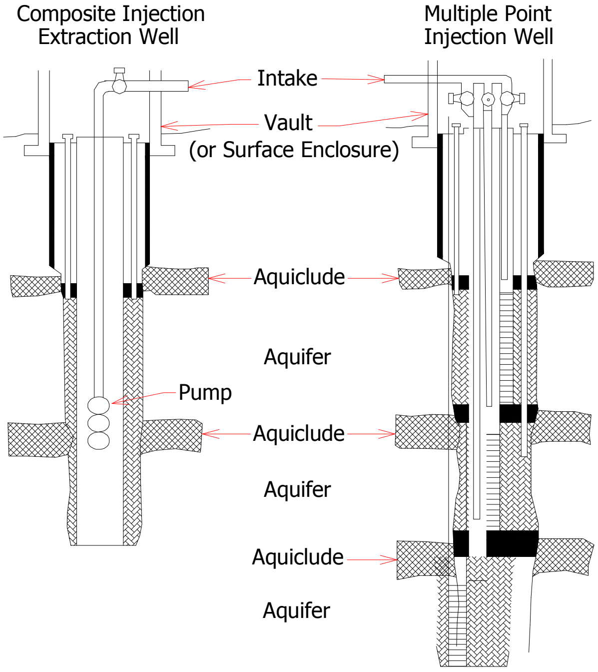

Figure 22.5 Composite Injection-Extraction Well and Multiple Point Injection Well

Injection well operating experience has included the use of recharge waters of various quality characteristics. All water used for recharge through injection wells must be free of all turbidity or dissolved gases and must be sterile. Injection wells have been used at numerous places throughout the world to inject imported, treated potable water from surface and ground water sources, treated or untreated lake or river water, and reclaimed stormwater or waste water.

Under some conditions existing wells can be used for both recharge and pumping. Generally the recharge rate will be about one-third to one-half the pumping rate.

22.3.2 Injection Rates

Injection rate quantities vary with aquifer characteristics, well design and construction, quality of recharge water, quality of aquifer water, and operating practices. Those responsible for the operation of recharge facilities should be familiar with the design criteria of the wells. Although the principles of design are the same as for extraction wells, the physical conditions of operation and types of failure are different and knowledge of the design is critical to determining the reasons for loss of recharge capability if it occurs.

22.3.3 Hydraulics

Injection of water below the saturated zone of an aquifer raises the free ground water surface in the vicinity of the well and creates an "injection mound". When water is injected into a confined aquifer, the pressure is increased against the confining aquitard in the vicinity of the injection well. The injection mound is then described by the configuration of the resultant potentiometric (pressure) surface.

For a single well, the injection mound can be considered as the mirror image of the cone of depression for a pumping well and is termed the cone of recharge or impression. Accordingly, the formulae for pumping wells can be used to estimate the configuration and movements of the cone of recharge for one or more injection wells. When the aquifer is confined, non-equilibrium formulae are applicable. For water table, i.e., unconfined aquifers, equilibrium formulas are applicable. The data necessary include the radius of influence, transmissivity, storativity, and drawdown at various distances from the recharge point. The data can be obtained from records of pumping and observation wells in the aquifer but the result of calculations using these data should be checked by field measurement in observation wells during conditions of recharge to evaluate departures from theoretical calculations.

The term injection head is used to describe the hydraulic head or pressure an injection well needs to inject water into an underground formation. It may be considered the reverse image of the drawdown of a pumping well when clogging tendencies at the well and aquifer interface are at a minimum. The "injection head" may be defined as the height of the column of water within the injection well casing above the static ground water table. This is the head required to overcome friction losses encountered as the water moves from the well out into the aquifer. The hydraulic losses include the loss from pump to the well screen, through the well screen, loss in gravel pack material, loss due to clogging at aquifer interface, and loss due to the velocity of water flowing through the aquifer near the well.

The limitation on injection head will vary greatly depending upon the absence or presence of a confining layer, the strength of the confining layer, the extent of the hazard to surface installations from water logging in the vicinity of the well, and perhaps other special considerations for a given location. The rate of change in injection head has been termed the clogging rate and is used as an indicator of the need for redevelopment of the recharge well.

22.3.4 Well Design and Construction

(a) Well Design

A thorough understanding of the geology and hydrology of underground formations involved is a prerequisite to good well design and to obtaining good results for a recharge project. Aquifer properties should be obtained by analysis of samples taken from test holes and by test pumping of wells. Particle-size distribution, porosity, specific yield, hydraulic conductivity, and transmissivity should be determined.

The considerations for choosing a well diameter for an injection well are similar to those used for pumping wells. The larger the diameter of the well, the better can be the match with the hydraulic characteristics of the adjacent formation. Consideration must be given to the velocity of outward flow in the immediate vicinity of the injection well casing, in the same way that consideration of inflow velocity is made for a pumping well. The injection well casing must be large enough to accept the conductor pipe and other facilities that might be placed in the well and to provide ample room for redevelopment equipment. Of course, the larger the well casing, the greater will be the cost of the well.

Similar limitations as to depth arise with injection wells as well as for pumping wells; that is, the cost of the well per metre of depth increases as the well deepens. Other than cost, there is no apparent reason to limit the depth of injection wells. Obviously the depth of the well will relate to the aquifer to be recharged.

The type of well chosen for a given location is normally similar to that which would be chosen for a pumping well. Depending on the nature of the formation, the injection well might have an artificially placed filter pack or a natural filter pack. The function of the filter pack is to retain much of the aquifer material, and the function of the well screen is to retain the filter pack. Samples of the formation at well screen level should be sieved to determine particle-size distribution. The gradation of the filter pack would be chosen to control the migration of fines from the formation to the well. A natural filter pack may be developed from the information if size gradation is adequate.

Filter pack thickness from 80 mm (minimum) to 230 mm (maximum) have been found effective for pumping wells with a natural filter pack. The screen openings should be chosen to retain 30-60% of the aquifer material. For artificially placed filter packs, screen openings should be chosen to retain at least 90% of the pack. The filter pack and aquifer particle-size distribution curve should be made parallel and the filter pack should be the coarser material. The filter pack 70% retained size should be four (4) to six (6) times that of the aquifer material. The factor 4 is used if the aquifer is fine grained and uniform and the factor 6 is applied to aquifers with coarser and more non-uniform materials

(b) Well Drilling

Injection wells can be drilled by any of three common methods: cable tool, conventional rotary and reverse rotary. The cable tool method has been used considerably because of the relatively clean nature of the resulting drill hole. However, in hard formations, the cable-tool hammer may force finely ground particles into the face of the borehole. An example of this is in limestone formations. Drilling by this method becomes more expensive as the holes deepen. Also, drilling by the cable-tool method limits the choice of well casing to those materials that have a high compressive strength, notably the common steel casing.

The conventional rotary drilling method has been used extensively for injection wells in all types of formations. Modern drilling fluid additives that limit the life of the drilling mud may be used to prevent mud damage to water bearing formations when bentonite based muds are used. Satisfactory injection wells can be drilled by careful and thorough development techniques that remove the fine materials associated with the drilling fluid and the mud cake that develops on the borehole wall.

The reverse rotary method of drilling is also widely used. In this method water is the usual drilling fluid. The cuttings from the bottom of the hole are forced upward through a large diameter drill stem at velocities that usually do not require the carrying ability of the dense drilling mud of the conventional rotary method. Sometimes when highly permeable strata are encountered, clay is added to reduce the loss of drilling water. Experience indicates that the reverse rotary drilling method, together with careful placement of the gravel packing and careful development procedure, often results in the most satisfactory injection well.

Drilling by either the conventional rotary or reverse rotary method provides the opportunity to use other types of well casing besides steel. This may be particularly advantageous if corrosion problems exist.

A detailed log of formation materials encountered should be taken during drilling to assist in the effective completion of the well. When the presence of several separated layers requires accuracy in determining formation limits, geophysical methods of logging, such as electrical logging or nuclear logging, can be used. Acoustic logging may be used where necessary to locate fracture zones in dense rock. Where applicable, caliper logs, temperature logs, and conductivity logs may be used. Subsurface exploration methods are described in more detail in "Ground Water Management" (ASCE, 1987).

(c) Well Details

The well casing can be the usual types of steel or plastic used in regular pumping well construction. When the injection well is part of a sea water barrier or operates in a saline aquifer, it may be in a highly corrosive environment. To minimise corrosion problems, wells have been cased with pipes of such non-corrosive materials as stainless steel, asbestos cement, plastic, fibreglass and concrete. Current information on the possible health hazards and regulations concerning some of these materials should be reviewed before selecting one of them. Well screens should be of stainless steel, alloyed materials, plastics, or fibreglass to minimise corrosion.

Perforations or screened sections of the casing are set to match the formation. The size of the perforations or screen openings is related to the size of the filter pack or the natural formation. Total area of perforations should be large enough to reduce flow velocity to reasonable levels at the expected injection rate. If the thickness of the formation allows, additional perforation or screened area should be provided to minimise well clogging effects.

An essential feature of an injection well is the conductor pipe required to carry the injection water into the well to a point beneath the water surface inside the well casing. The conductor pipe may be the pump column in a production well. In any case it is essential to prevent the entrainment of air bubbles which, if carried into the filter packing of the well and the aquifer formation beyond, can result in clogging and reduced injection rates.

A full flow in the conductor pipe can be assured by designing the size of the pipe so that friction loss is comparable to the distance the water must drop. However, this procedure limits the range of flows that can be used. Another method is to place a back pressure valve at the bottom of the conductor pipe. A third method is to make the influent injection water pipe airtight with no vacuum release valves. Thus, when the initial body of air is pushed from the conductor pipe by the flow of injection water, no additional air is available to become entrained within the flow. Although there are theoretical considerations of dissolved gases being released from the water due to reduced pressures, there is experience in the operation of the projects that indicates this type of pipe is satisfactory.

(d) Well Construction

In subsurface formations under pressure, the injection well will have penetrated one or more confining layers of fine materials having very low hydraulic conductivity. The annular space between the well casing and these layers may provide a channel for considerable leakage of native water into or out of the confined layer or of injected water from the confined aquifer to overlying materials. The problem can be eliminated by grouting the annulus in these confining zones. A conductor pipe will be necessary to provide replacement material to the gravel pack below the grout seal. If the well is not constructed with a gravel pack a grout seal can be obtained by the use of two packers, grouting through slots in the casing, and then drilling the grout out of the inside of the casing.

The use of down-hole tools to cut perforations in well casings previously set in place is to be discouraged if the aquifer material is fine because of the amounts of sand that will enter the casing and have to be removed during development. The use of acetylene torch to cut slots should also be discouraged where fine aquifer materials prevail since it is difficult to obtain narrow or uniform slots in this manner. In most cases the cost of the recharge operations justifies the use of carefully designed well screens based on the particle size distribution of the aquifer material and filter pack, if any.

22.3.5 Redevelopment and Prevention of Clogging Process

Although clogging is problematic and expensive in some cases, it is an intrinsic part of aquifer recharge operations and can be overcome completely by appropriate pretreatment and injection well maintenance. The aim of redevelopment is to return well performance to its prior state by restoring the hydraulic properties of the aquifer. Provision for redevelopment should be made during well construction.

A variety of mechanical and chemical methods have been used for redevelopment. Mechanical methods include pumping, (typically at a rate higher than recharge), jetting with compressed air (also known as air lifting) or water, or sectional flush pumping (pumping from access tubes located within the gravel pack). There are also some adaptions of these including alternate recharging and pumping and continuous pumping and surging. Chemical methods include the addition of acids, flocculants (e.g. Calcium Chloride), disinfection and/or oxidising agents (e.g. chlorine).

Redevelopment is undertaken periodically, as often as daily, depending on how quickly recharge rates decline. It has proven to be effective as a routine operational method for unclogging wells.

Mechanical methods are based on physical agitation of the porous media. Increasing the energy increases the likelihood of success of redeveloping the well. Pumping has met with varying degrees of success. Alternative recharging and pumping (also known as multiple reversals) is considered a very effective method. Sectional flush pumping has been successful, but only effective when the gravel pack is substantially clogged. Jetting with air work best when clogging is not allowed to build up. Initial jetting may produce only low flow rates until the filter cake around the well is dislodged. Water jetting offers little penetration and hence is only effective for redeveloping the area close to the well. Increasing the injection pressure may increase recharge rates, but more often only exacerbates clogging or creates upward flow around the well casing. Microbial clogging generally occurs only in the immediate vicinity of the injection well and can therefore be redeveloped effectively. The removal of organic matter or disinfection of the source waters minimises microbial activity around the well. In most cases chlorine is used, probably because of its acceptance in reticulated potable waters, however other chemicals such as Chloramines and Hypochlorites have also been used. Chlorine is added in regular doses or in some cases a continuous trickle flow is maintained. The use of disinfectants can produce harmful disinfection by-products. This suggests that if microbial clogging is not limiting to aquifer storage recovery (ASR) and if organic were an issue, then it may be advantageous not to disinfect source waters.

Chemical additions usually rely on dissolving the clogging agents. They tend to be more expensive and are used less than mechanical methods. Acids have been used to good effect in carbonate aquifers. In some cases injection waters, which dissolve aquifer materials, can offset clogging incurred by other factors or alternatively can mobilise particles, leading to clogging. However acids may dissolve iron from corroded casing which later precipitates to cause clogging. Therefore before chemicals are added consideration should be given to the likely formation products in the area treated.

Salts such as calcium chloride have been injected into groundwater, successfully alleviating clay swelling and dispersion and restoring aquifer permeability. Due to the difficulty of remediating aquifers clogged in this manner, prevention is better than cure. At sites where potential problems are envisaged, laboratory column studies using core materials and source water could be performed to identify the extent of clogging and remediation strategies.

The prevention of clogging from air entrainment and gas binding is relatively straightforward. Gaseous binding through the introduction of air is not usually an issue in unconfined aquifers where gases readily escape from the saturated zone. In confined systems air entrainment can be minimised by not allowing injectant to cascade. This can be achieved by placing the intake pipe below the static water levels and fitting a flow control valve to ensure a positive pressure is maintained at a sufficiently high pressure to compensate for changes in temperature, thereby keeping gases. Keeping nitrate and organic carbon concentrations low when injecting into anoxic aquifers will limit denitrification. Where gas binding does occur, the same techniques used to remove clogging by sediments are effective.

Severe clogging can be prevented by appropriate pretreatment BMPs of the injection water (i.e. reducing suspended solids, organic matter and microorganisms), as well as by frequent redevelopment of the well. In practice there is a trade off between the costs associated with pretreatment and the type and frequency of redevelopment. The extent of pretreatment also depends on the nature of the aquifer. For example, injection of turbid waters into a highly permeable limestone aquifer may have little or no impact on aquifer permeability, however there may be considerable impacts of such waters on less permeable aquifers such as fine sands.

An important outcome of the review of international practices is that recharge of high quality source water to high permeability aquifers (with sound recharge techniques), results in minimal clogging problems. However with well redevelopment, non ideal source waters and aquifers can be used without clogging being a barrier to success. Table 22.1 provides a summary of the various forms of clogging, means of minimisation or prevention and redevelopment techniques.

22.3.6 Summary of Aquifer Injection Guidelines

- guidelines have the objectives of preventing irrecoverable clogging, protecting or improving groundwater quality, and providing recovered water which meets the water quality criteria for its use
- the precautionary principle applies - pollution prevention rather than remediation is an imperative
- aquifer treatment is an extension of surface pretreatment of source waters and may be taken into account if it is sustainable and can be reasonably estimated
- guidelines have been developed which adhere to the Malaysian groundwater protection guidelines and water quality guidelines, and rely on scientific evidence for treatment provided by the aquifer
- a demonstration licence is recommended for new ASR sites and requires an environmental management plan which predicts environmental impacts of ASR, and describes monitoring and means of dealing with contingencies
- monitoring should be tailored to the site to provide assurance that objectives are met, and the data and reports are pooled nationally to assist with future ASR design and improvement of these guidelines
- contingency plans are required to deal with changes in availability and quality of source water, changes in demand for water and inadvertent groundwater contamination
- license renewal would be subjected to a performance review

Table 22.1 Summary of Forms of Clogging and Means of Minimisation, Prevention and Redevelopment

Form of Clogging	Minimisation/Prevention	Redevelopment
Filtration of suspended solids	Minimise suspended solids	Pumping, surging and jetting
Microbial growth	Minimise organic matter, disinfection	As above plus disinfection and acids
Chemical precipitation	Recharge water compatible with groundwater	pH changes
Clay swelling and dispersion	Low clay aquifer	Add flocculants
Air entrapment	Avoid cascading, positive pressure intake, high pressure feed	Pumping surging and jetting
Gas binding	Prevent denitrification in porous media by disinfection, nitrate removal	As above
Mechanical jamming and mobilisation of aquifer sediments	Avoid susceptible aquifers	Unknown