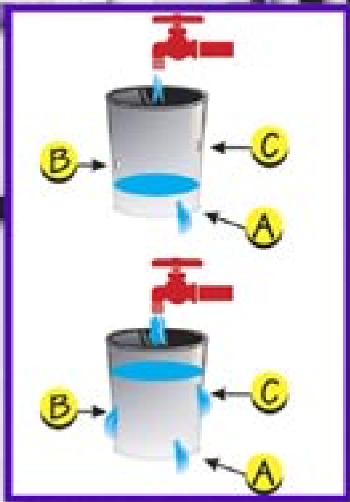
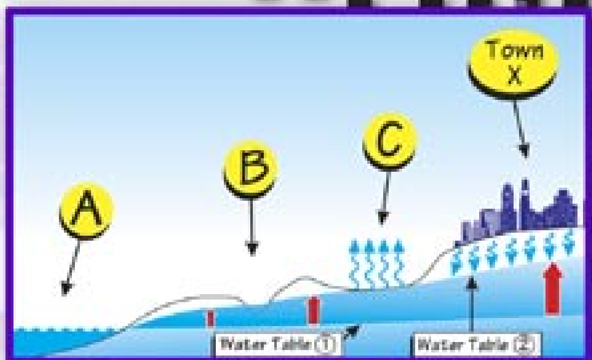
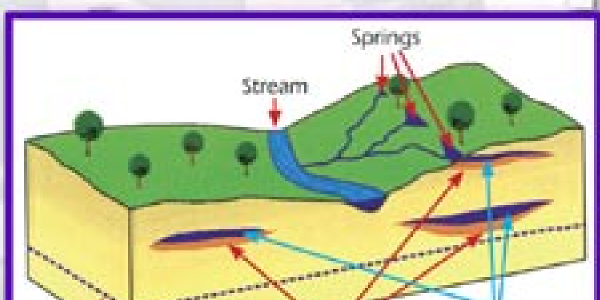
GROUNDWATER BASICS for UNDERSTANDING URBAN SALINITY







LOCAL GOVERNMENT SALINITY INITIATIVE

Department of
Infrastructure, Planning and Natural Resources

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Contents

1. Introduction

This booklet is part of the "Local Government Salinity Initiative" series and presents some basic groundwater concepts necessary for understanding urban salinity processes. Other booklets in the series contain information on urban salinity identification, investigation, impacts and management.

2. What is Groundwater?

If a hole is dug in loose earth material such as soil or sand, we may find that just below the surface the earth feels moist. This is often the case in sandy soils near the sea, or along the edges of bodies of water such as rivers and lakes.

At a greater depth, the material in the hole may feel wetter as the small spaces (pores) between the soil particles hold more water. Eventually, a depth may be reached at which the pores are so full that the water they contain will flow out into the excavation (Figure 1). The material at this point is saturated. Technically, we can say that we have passed from the unsaturated zone into the saturated zone.

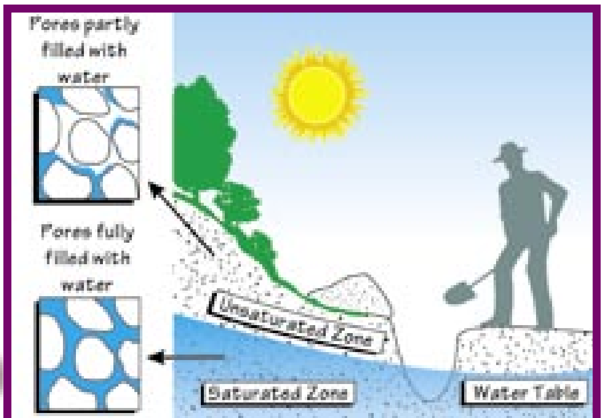

Fig 1. Finding Groundwater

The water flowing into the excavation is termed groundwater. Continue digging and the water in the pores will continue flowing into the hole until it reaches a constant level . This level is termed the water table.

The water table separates the unsaturated zone from the saturated zone (Figure 2). At any point along the water table, water pressure is equal to atmospheric pressure. At any point below the water table, water pressure is higher than atmospheric pressure. This pressure difference causes groundwater to flow freely. For example, when a hole is dug, water from the saturated soil will flow into the excavated hole.

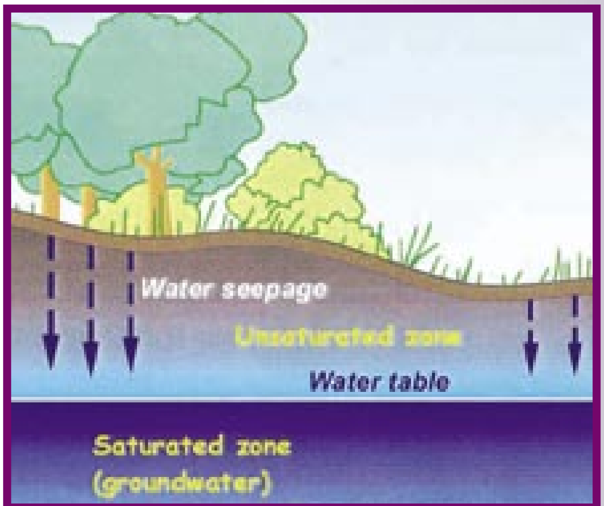

Fig 2. The position of the water table (Adapted from **Reference 2**)

Water tables and groundwater are not often found at depths as shallow as indicated in Figure 1. More commonly, they are found at depths of metres or tens of metres. In an urban environment, the removal of soil during the levelling of a site for buildings or sports fields may lower the land surface and bring it closer to the water table.

Although it doesn't contain groundwater, the unsaturated zone plays an important role in groundwater processes. It allows rain and surface water to infiltrate, percolate through its pores and move downwards, under the influence of gravity, until it eventually reaches the water table. Some of this infiltrating water will attach itself by molecular force to the walls of pores and openings. This water may return directly to the atmosphere by evaporation.

Plants also remove a considerable amount of water from the unsaturated zone via their roots, eventually releasing this water back into the atmosphere through small openings in their leaves and stems (stomata) in a process known as transpiration. Perennial, deep-rooted vegetation is capable of intercepting a much larger percentage of percolating water than annual, shallow-rooted crops and pastures (Figure 3). The combined effect of evaporation and transpiration is known as evapo-transpiration.

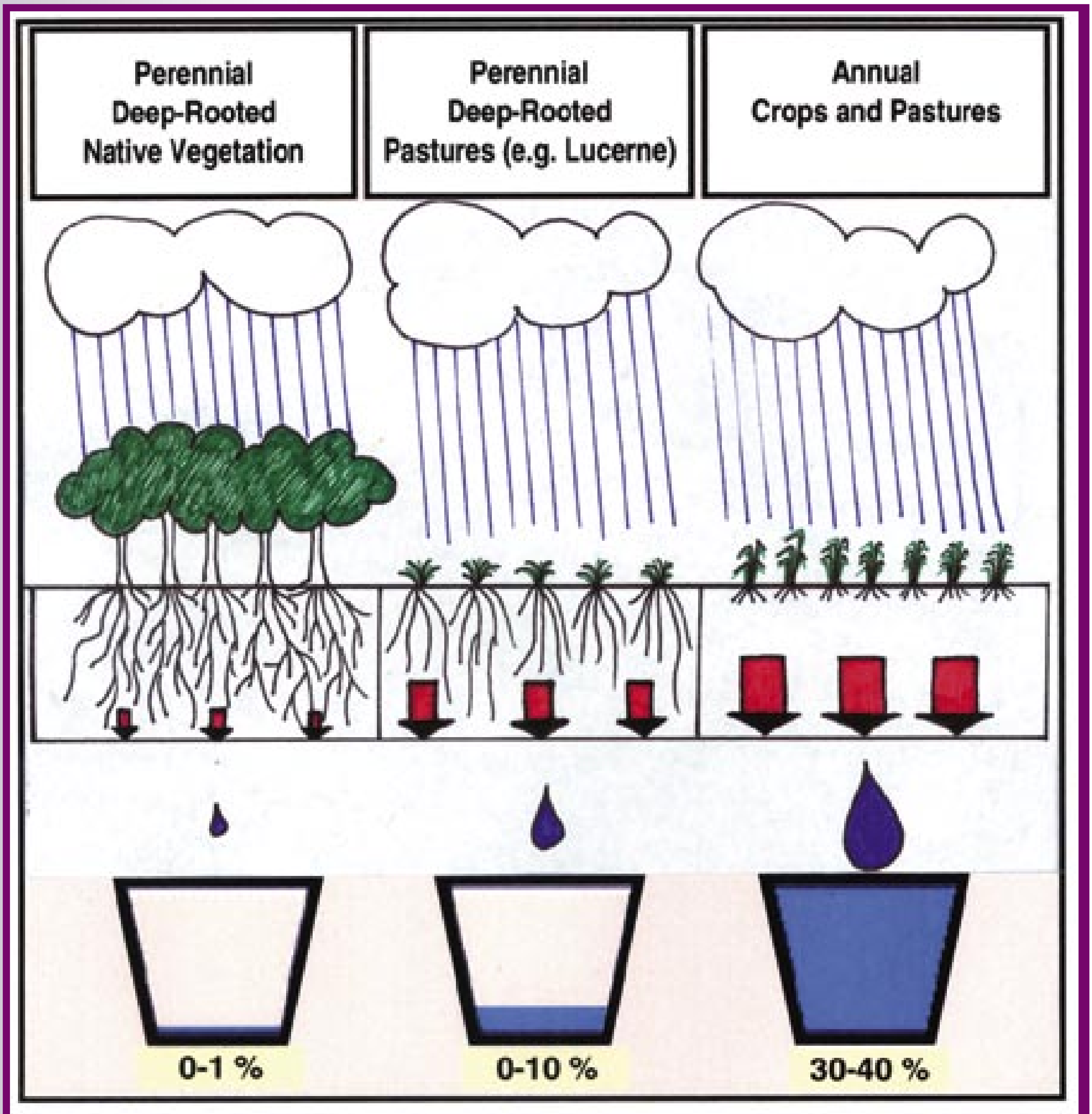

Fig 3. The reduction of rainfall infiltration by deep and shallow-rooted plants **(Reference 3)**

Many changes occur in this unsaturated zone during urban development. For example:

- extensive removal of vegetation can result in less transpiration and increased infiltration,
- installation of hard impervious surfaces such as roads and houses can decrease evaporation, and
- compaction by heavy machinery can decrease the void space between soil particles and affect the speed and direction of water movement in the unsaturated zone. Vertical water movement may be inhibited and a new "suspended" saturated zone may form.

All water reaching the water table is called recharge as it replenishes the groundwater stored in the saturated zone. Groundwater receives recharge not only from rainfall, but also from other sources such as rivers, lakes, river valleys affected by flooding, irrigation and leakage from stormwater, sewer and water supply systems.

3. The Importance of Groundwater

Fresh water is essential for the survival of humans and terrestrial animals and plants but its availability is limited. Figure 4 shows that about 97% of the world's water resources are salt water, most of this being stored in oceanic basins. Fresh water forms the remaining 3% of the earth's water, but most of this occurs as inaccessible ice stored in polar caps and glaciers (Figure 5).

Groundwater represents the second largest store of fresh water. Its total volume is approximately 30 times larger than the cumulative volume of water found in the world's rivers, streams, lakes, swamps and clouds. Groundwater is an important resource because it is comparatively safe to drink. If isolated from surface water, groundwater is free of viruses and other pathogens that affect human health. It is also generally free of contaminants generated by urban, industrial and agricultural activities. More than 1.5 billion people in the world rely on groundwater as their primary source of potable water.

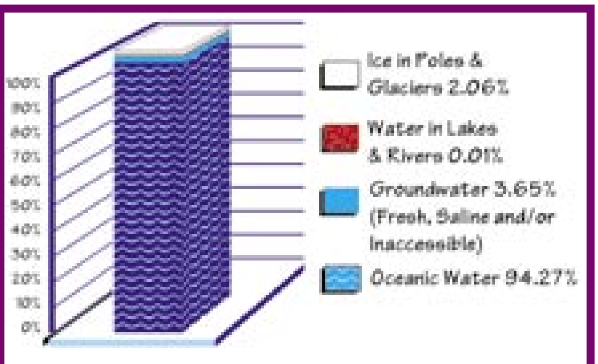

Fig 4. Distribution of the world's water

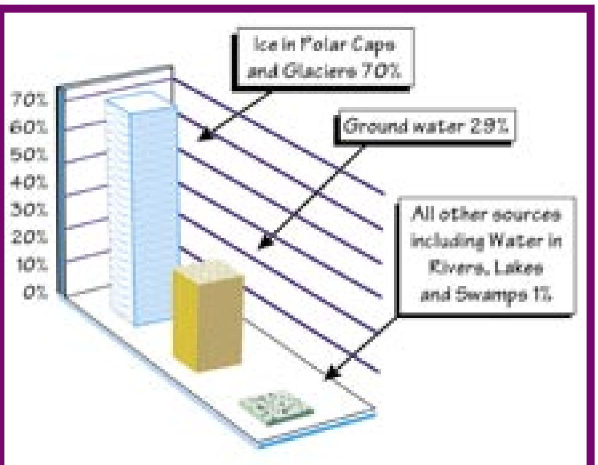

Fig 5. Distribution of the world's fresh water

4. The Hydrological Cycle

The hydrological cycle is a circulation system that lifts water vapour from both the land and sea through the process of evaporation, deposits it on land as precipitation, and returns it to the sea by way of rivers and groundwater (Figure 6). The cycle is powered by the energy of the sun, which melts ice and snow, transforms water into vapour and helps the wind transport clouds from the sea towards land. The cycle is also controlled by gravity, which accounts for much of the movement of water above and below the earth's surface.

Fig 6. The hydrological cycle, a pictorial representation **(Reference 6)**

The hydrological cycle transfers water between different stores, where the water may remain locked up for time periods lasting from days to thousands of years.

Figure 7 shows that each store can hold millions of cubic kilometres of water. By comparison, the volume of water circulating between stores is rather small, with only thousands of cubic kilometres moving from store to store every year.

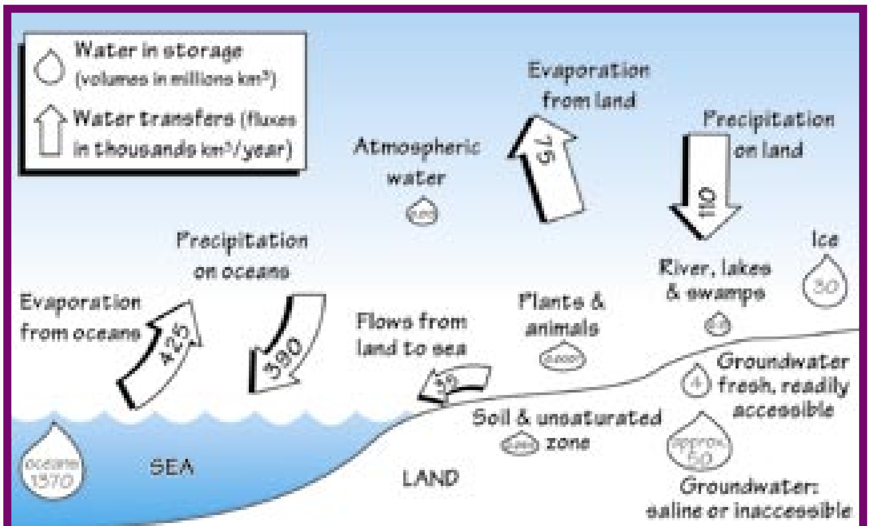

Fig 7. Water stores and water transfers from **Reference 7**

The concept of the hydrological cycle assumes that the movement of water maintains a water balance. As no new water is formed, the volume of water on earth remains constant. Accordingly, the rate at which water enters any of the cycle's stores eventually becomes equal to the rate at which water leaves that particular store.

With the exception of a few large basins, such as the Great Artesian Basin in Australia, groundwater is not often found in stores as large and continuous as the oceans or the polar ice caps. Groundwater tends to accumulate in independent and comparatively small stores, each with its own flow mechanisms, geological boundaries and points of water recharge and discharge. However, some stores are interconnected and many have independent links with the different components of the hydrological cycle.

Climatic variations and human activity affect stored volumes of groundwater. Therefore, in order to prevent or solve problems that arise in the use of groundwater, a full understanding of its dynamic nature is required. It is also necessary to understand the connections between groundwater stores and their relationships with the surrounding environment.

5. Water Table Changes

5.1 Changes Over Time

The dynamic nature of groundwater can be seen in the responsiveness of the water table to climatic events and human activities. During periods of low rainfall, for example, a water table will fall. On the other hand, during periods of abundant rainfall recharge, water tables will rise (Figure 8 and Figure 9).

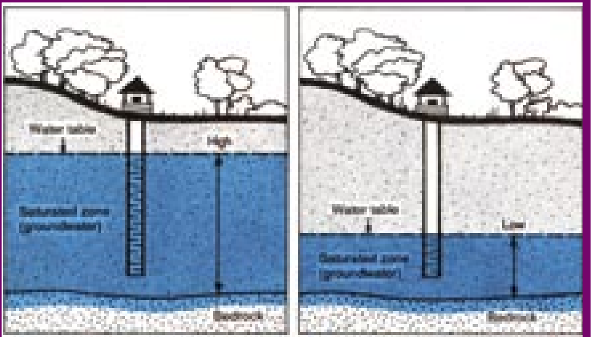

Fig 8. Water table changes with time **(Reference 8)**

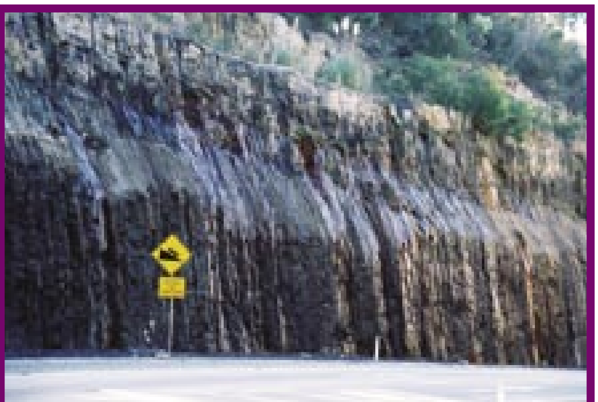

Fig 9. A raised ground water level may be evident in road cuttings after periods of abundant rainfall

The height of a water table, measured over time, can be plotted on a graph (a hydrograph). This information may indicate trends such as a rising water table after consecutive wet periods, a response to major climatic cycles or long-term changes.

Human activities can also have major impacts on the height of a water table. Water tables are falling in many parts of the world because of over-extraction, which has resulted in land subsidence in some regions. The "sinking" of Mexico City and Venice are classic examples of this type of impact on an urban environment. In other areas, the removal of vegetation, over-irrigation of golf courses, parks, gardens and crops, as well as leakage from water collection, water supply and sewerage systems often increase groundwater recharge and lead to rises in the water table.

For example, consider a town with:

- a deep groundwater store that receives recharge from some distant hills and discharges into a river, and
- a separate shallower but partly interconnected groundwater store that is recharged by leakage from the town.

During summer, excessive garden watering may result in increased recharge to the upper groundwater store. Over time, this may result in a flow of water into the deeper groundwater system, which in turn may result in more groundwater flowing from the deeper groundwater store into the river. However, if the river level rises, perhaps due to a release of water from a dam for irrigation purposes, water may flow from the river into the deeper groundwater system. As this store fills, drainage from the upper groundwater system may be prevented. The upper groundwater system may then fill as the excess irrigation water is still entering the system but no discharge is occurring (Figure 10a, 10b).

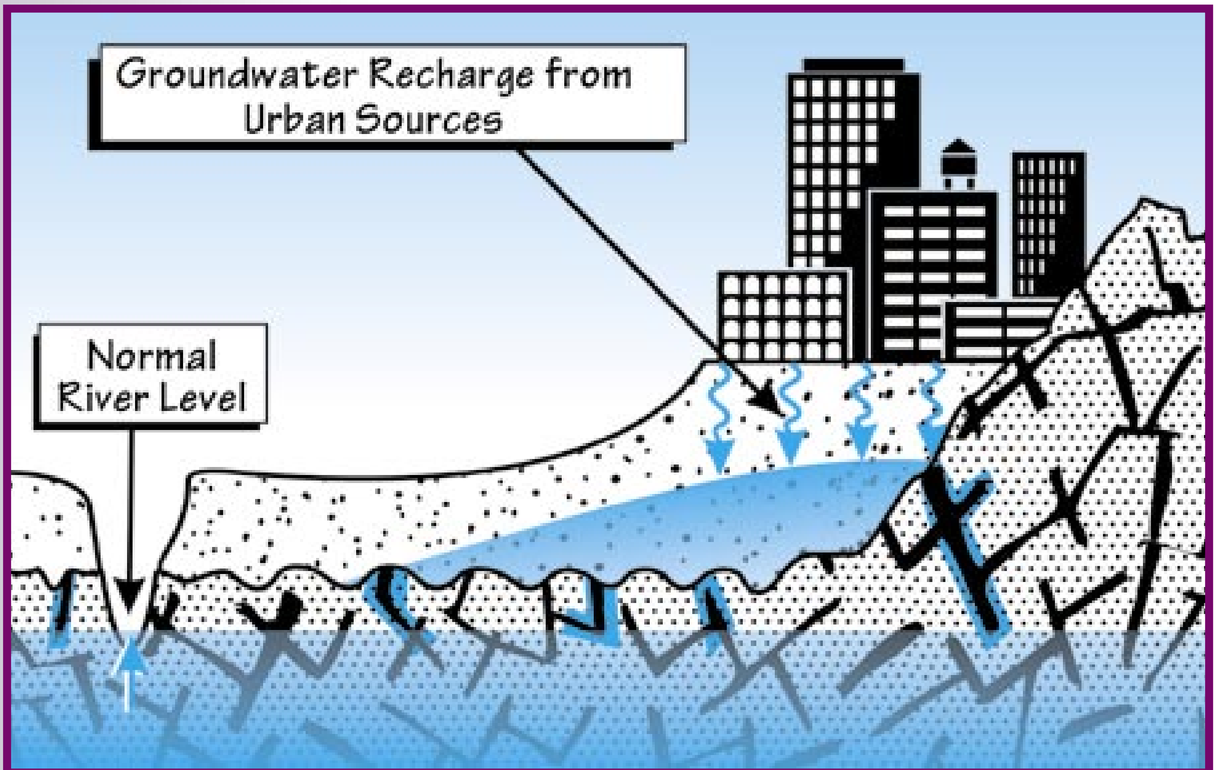

Fig 10a. *Summer garden watering when river low*

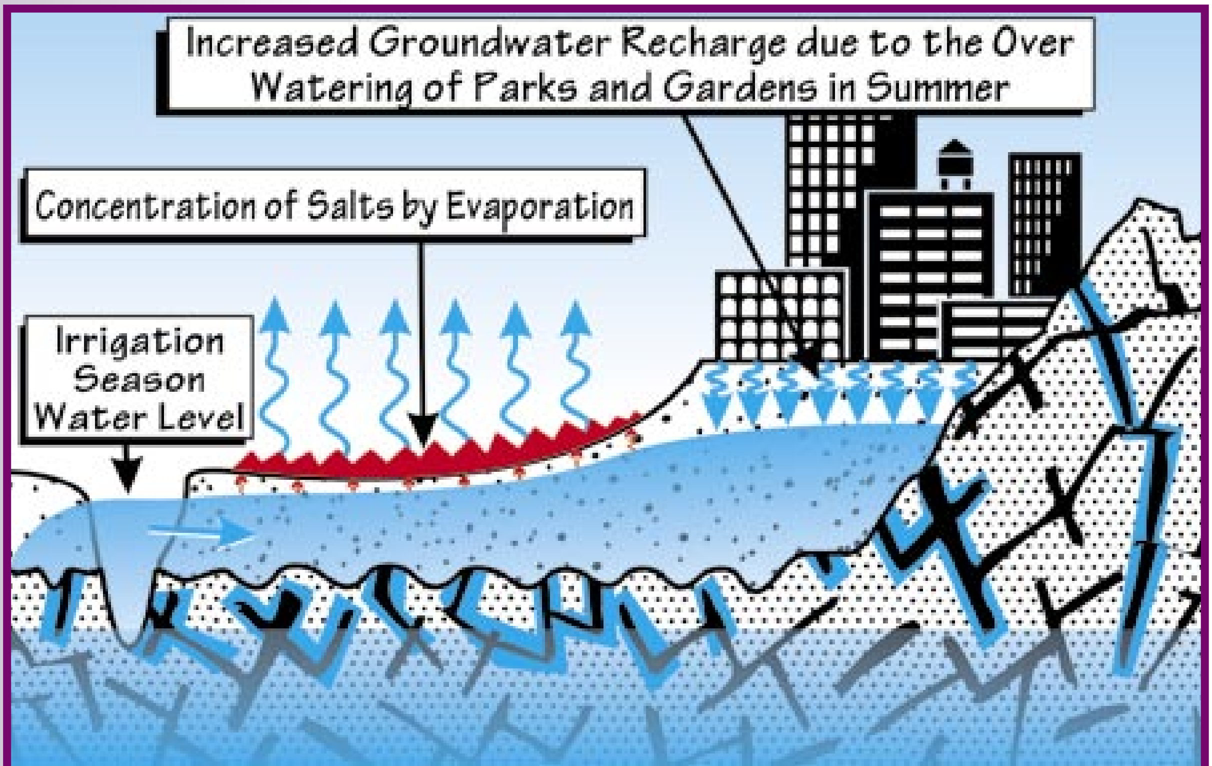

Fig 10b. *Summer garden watering when river high*

Eventually the upper groundwater system will discharge at the land surface. This may result in urban salinity impacts. To manage the impacts, it is important to understand the three processes of recharge (river water, rain in the hills, garden watering) as well as the connection between the two groundwater systems.

5.2 Regional Shape of the Water Table

The height of a water table in relation to the ground surface changes not only over time, but also from place to place. If many bores are measured simultaneously over a large region it is possible to see that the regional water table forms an irregular surface that mimics the main rises and depressions of the surface landscape in a subdued manner (Figure 11).

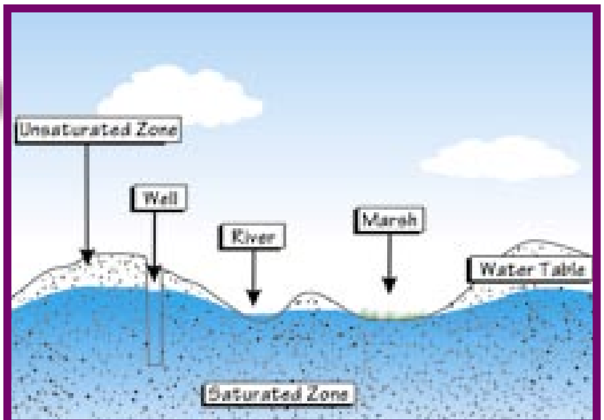

Fig 11. The water table and land surface. **(Adapted from Reference 7)**

5.3 Water Balance and Water Table Rises

The water table may intersect the surface of the land and discharge groundwater into lakes, springs, rivers and marshes (Figure 12) when the water table rises.

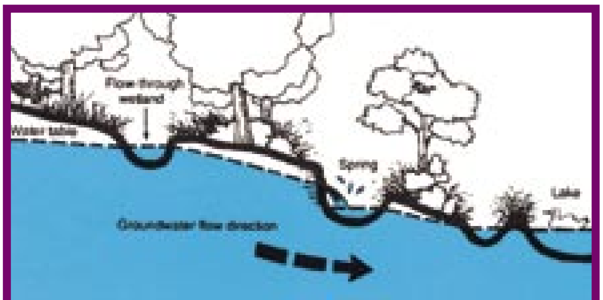

Fig 12. Groundwater fed surface water **(Reference 8)**

When the water table falls the same hydrological features may lose water to the groundwater system. (Figure 13). The water table will rise or fall in response to an increase or decrease in recharge.

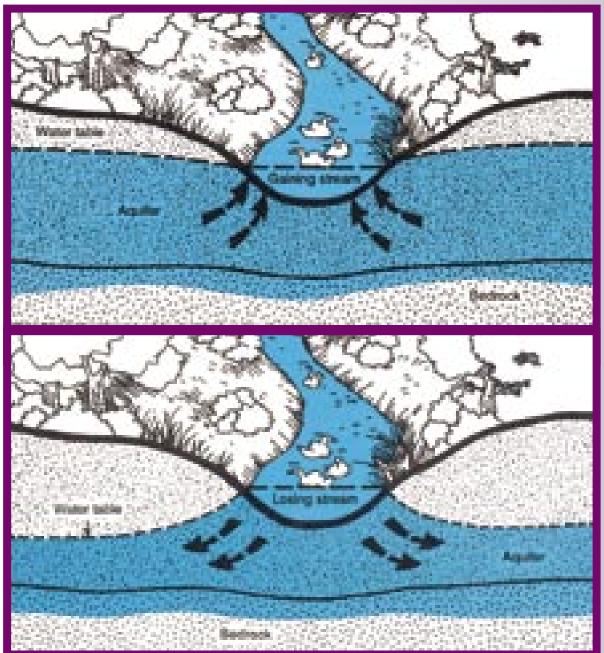

Fig 13. Groundwater. Gaining streams and losing streams **(Reference 8)**

If recharge increases, the water table will rise until the volume of recharge is matched by an equivalent increment in discharge – thereby satisfying the requirements of the water balance principle described in Section 4. Water tables respond to increased groundwater recharge in the same way water levels in a pierced bucket respond to the flow of a running tap (Figure 14).

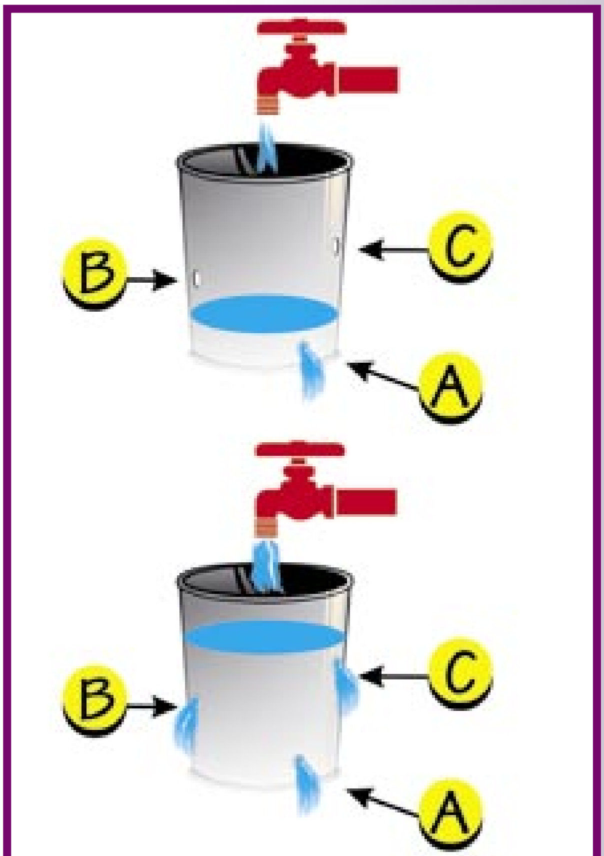

Fig 14. Inflows and outflows after the flow into a pierced bucket is increased

If the flow of the tap is increased, the water level within the bucket will rise and new perforations will begin discharging water. The level will stabilise when the flow of water leaving the bucket equals the flow of water entering the bucket.

Figure 15 illustrates how this may occur within a landscape. When town X was first established, the water table was located at position ① and groundwater was discharged into a lake located at A. Many years later, recharge water from the town's over-irrigated golf courses, parks and gardens, leaking water supply pipes and sewerage systems reached the water table. Effectively, town X became a new source of groundwater recharge, and the water table rose in response until it eventually reached position ②. Before reaching ②, the water table first intercepted the path of a river at B, and groundwater began to flow into the river. The water table then reached C, a depression where groundwater began to evaporate directly into the atmosphere, leaving precipitated salts on the land surface and forming an area of dryland salinity. The water table ceases rising when the total volume of increased discharge at A, B and C becomes equal to the total recharge volume added by Town X.

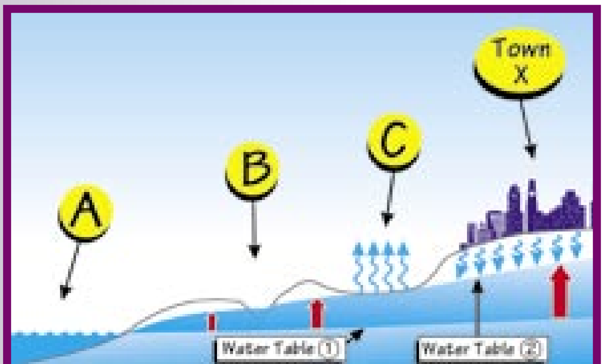

Fig 15. Same situation as Fig.14. The water table rises until the groundwater discharge matches the increased groundwater recharge produced by town X

6. Porosity

Soils, sediments (gravel, sand, silt and clay) and rocks, even when buried kilometres below the surface of the Earth, contain openings. Large openings or voids can be the size of caverns and have lengths of hundreds and even thousands of metres. However, small openings are more common. Pores between particles of clay or between shells of microfossils in rock (Figure 16) can be so minute that they are visible only through an electron microscope.

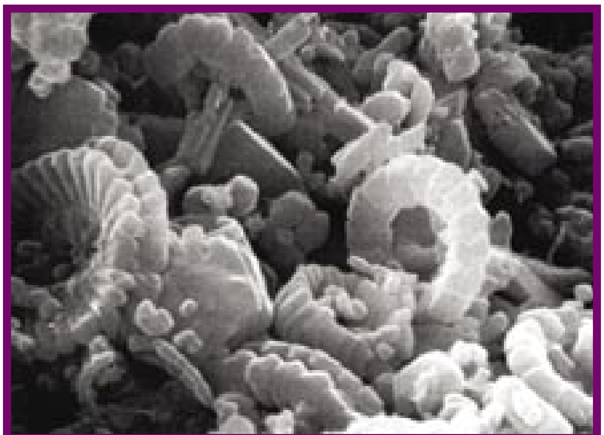

Fig 16. Electron photomicrograph of a low permeability rock formed by shells of micro-organisms. Although the rock's porosity is high - 46%, its pores are very small

The porosity of a material is the ratio or percentage of its pore spaces to its total volume. For example, if the porosity of a sandstone layer is 20%, this means that 20% of the layer's total volume is made up of pore spaces. Table 1 gives a rough indication of the porosity (η) of some common materials.

Table 1: Porosities of Common Earth Materials (Adapted from Reference 11)

Material	η (%)	Material	η (%)
Clay	45-55	Sandstone	10-20
Silt	35-50	Limestone	1-20
Sand	25-40	Shale	0-10
Gravel	25-40	Vesicular Basalt	10-50
Fractured Rock	0-10	Solid Crystalline Rock	<1

Small volumes of recharge can significantly raise the water table in materials of low porosity. For example, 20mm of rainfall will result in a 500mm rise in water level in a material with a 4% porosity ie. 100/4 x 20mm (Figure 17).

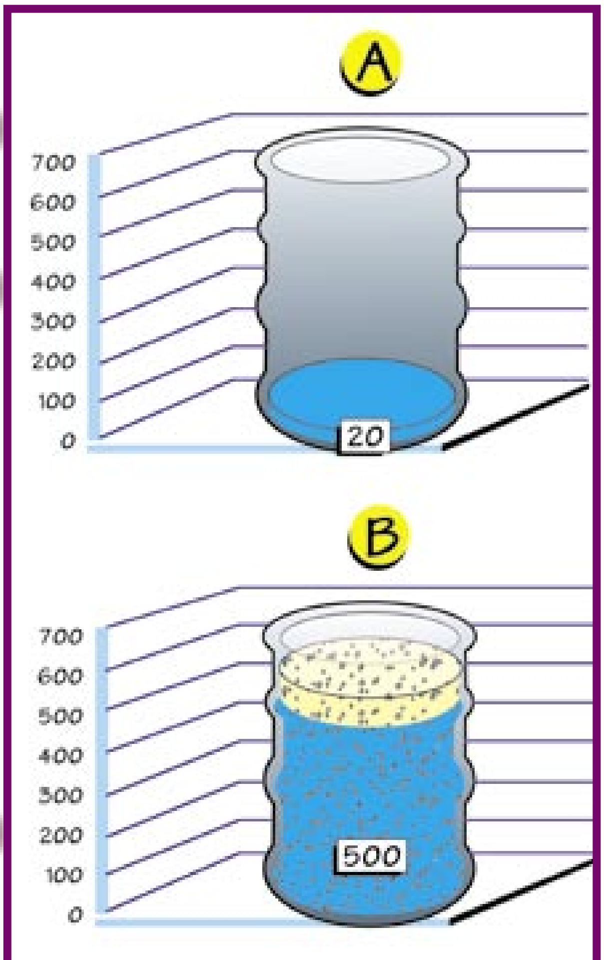

Fig 17. Effect of a 20mm rainfall on the water levels of two open drums. At the time of the rainfall, drum A was empty and drum B was full of sandy gravel with an η of 4%. After the rainfall the water level in A rose 20mm and in B 500mm (ie. 100/4 x 20mm)

Mixed sediments are common in the natural environment and generally have a low porosity. For example, when sand with a porosity of 20% is well mixed with gravel with a porosity of 20%, the voids between the gravel may be completely filled with fine sand. The porosity of the resulting mixture is then closer to 4% ie 20% of 20%. (Figure 18).

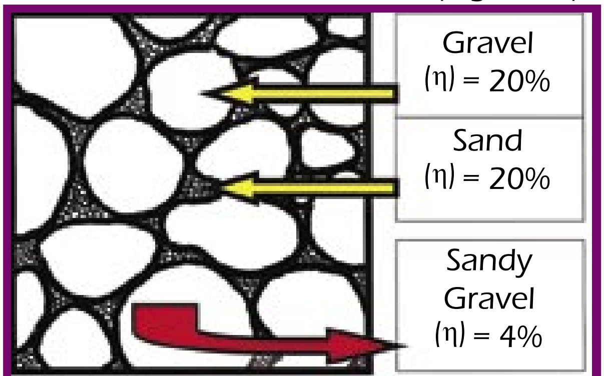

Fig 18. Depending on the arrangement of grains and pebbles, a mixture of two porous earth materi-als may not be porous

Small recharge reductions can have major impacts on the water table, particularly in areas underlain by low porosity materials. For example, in some urban areas, planting a tree, fixing leaky pipes, improving irrigation practices, and replacing sewage and stormwater structures that rely on infiltration can have a significant impact on water table heights, especially in low porosity materials. A recharge reduction of 35mm in a material with a porosity of 1% will result in a theoretical water table drop of 3.5m (100/1 *35mm).

7. Porosity in Sediments and Different Rock Types

The porosity of an earth material is called primary when it is incorporated into the material at the time it was formed, or secondary when it developed after the material was formed.

7.1 Primary Porosity

Sediments often include a large percentage of openings forming between boulders, pebbles, sand grains and particles of silt or clay. Sediments usually have a relatively large primary porosity. After sediments are deposited, subsurface water circulating between voids may precipitate cementing materials, such as carbonates or silicates, that reduce the size of the voids and thus their primary porosity (Figure 19a,19b).

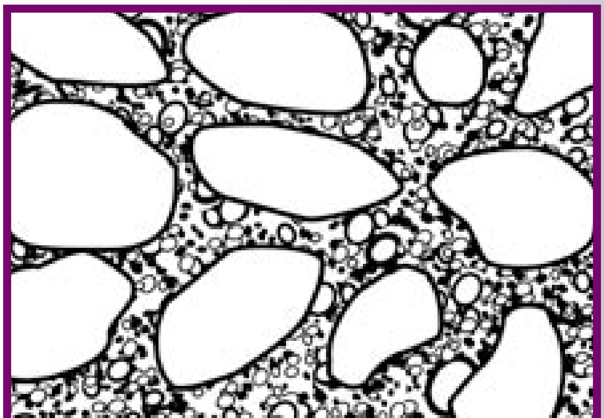

Fig 19a. Poorly sorted sediment of low porosity made out of a mixture of gravel (large particles),sand (small particles) and silt (here invisible). **(Adapted from Reference 12)**

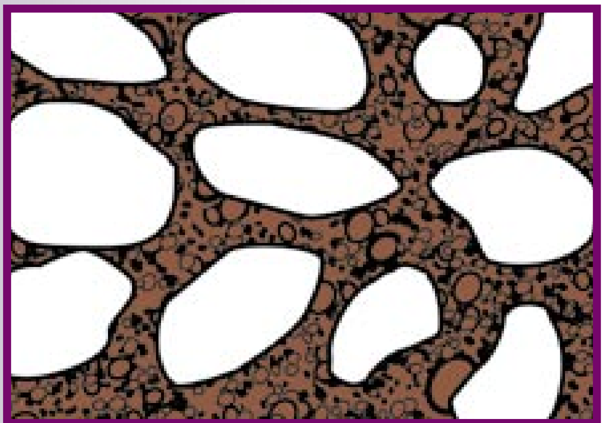

Fig 19b. Same material as in 19a but with its primary porosity partly or totally lost to cementation, or to mineralisation. The unconsolidated sediment in Fig 19a has become a sedimentary rock

These cementation processes, and the compaction of sediments when they are buried beneath additional layers of sediments, give origin to **sedimentary rocks** such as sandstone, siltstone or shale, where the primary porosity of the original sediments can be significantly reduced and even disappear completely.

Igneous rocks are formed by the cooling and solidification of magma (molten rock materials occurring deep below the surface of the Earth). When magma penetrates rocks forming part of the Earth's crust and cools down slowly without reaching the Earth's surface, it forms intrusive igneous rocks such as granite. These rocks are made of interlocked mineral crystals that occupy all available spaces and therefore have very low or no primary porosity.

Extrusive igneous rocks include lavas and deposits of ash and other materials ejected by volcanoes. These rocks are formed when the magma reaches the surface of the Earth. Their rapid cooling may develop contraction cracks (Figure 20) that are features of primary porosity. Empty vesicles once occupied by gases may also enhance their primary porosity.

Metamorphic rocks are formed when rocks buried deep below the surface of the Earth are transformed by pressure and heat release. The alteration and compression of metamorphic rocks can be so intensive that most of their original features, including their porosity, disappear. A few metamorphic rocks, however, are formed by contact with hot intrusive magma near the surface of the Earth. As they have not been subjected to high pressures, these rocks occasionally retain part of their primary porosity.

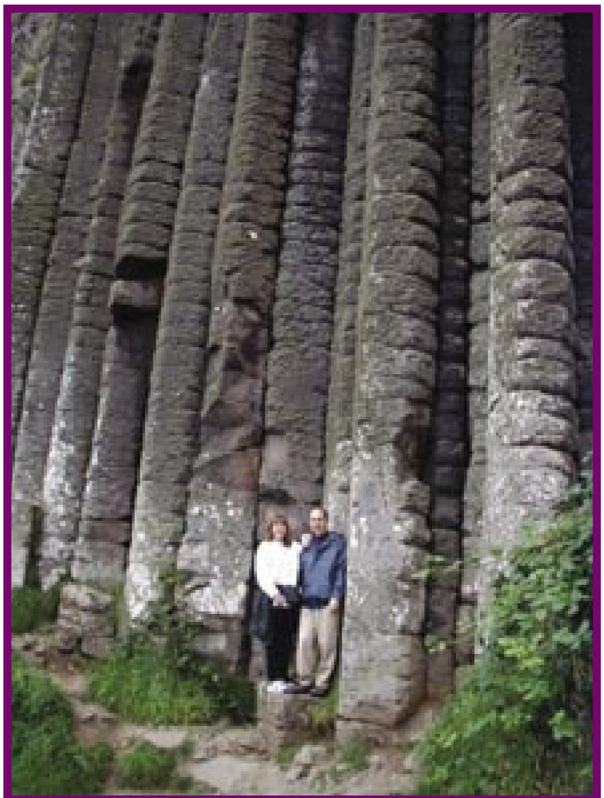

Fig 20. Vertical cooling fractures forming hexagonal columns in a basalt **(Reference 14)**

7.2 Secondary Porosity

Secondary porosity develops in all types of rocks when they become uplifted, faulted, bent, fractured, crushed and distended by geological processes. Faults, fractures and joints can develop through the movement of the Earth's crust or the release of tension associated with the removal of heavy rock materials by erosion. Once subjected to the influence of the atmosphere, rocks exposed to weathering processes may weaken and remove minerals, creating additional voids which further increase the size of fractures and joints. (Figure 21). The development of secondary porosity may significantly increase the primary porosity of sedimentary, extrusive igneous and some metamorphic rocks and will often interconnect voids that were previously disconnected.

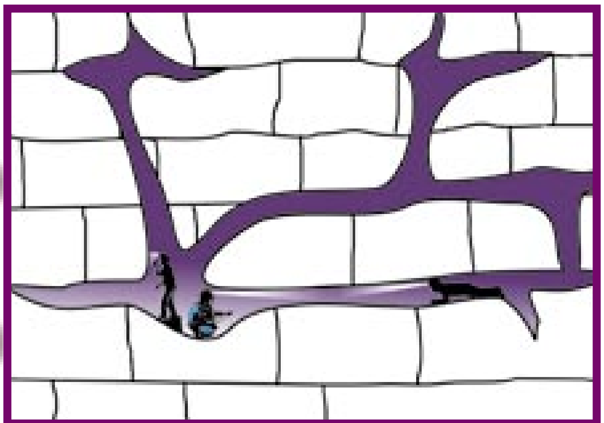

Fig 21. Cavities in limestone are an example of secondary porosity. They were developed by dissolution among fractures that cut through the rock after it was formed

8. Permeability

In Figure 1, a hole was excavated deep enough to penetrate the saturated zone and groundwater flowed into the hole until the level within the excavation was equal to the level of the water table. This flow could have taken minutes, hours or even days to fill the excavation. How quickly water fills the excavation depends on a property of the material known as its permeability. Materials that allow water to flow through them swiftly are said to be permeable. Materials that do not allow water to flow through them are said to be impermeable. In technical terms, the permeability of a material is the volume of water that passes through a unit area of the material in a unit of time. Measurements of permeability are made under constant water pressure conditions and expressed as the volume of water passing every second through a unit area (m^2) of the material or (m^3/second)/m^2. As (m^3/second)/m^2 is equivalent to m/s, permeability is measured in velocity units. In other words, the permeability of a material is the speed of the water that travels through it. Consequently, a material of high permeability is a material that allows water to travel through it at a relatively high speed.

To be permeable, a material has to meet three conditions:

1. it has to be porous,
2. its openings must be large enough to let water pass through them, and
3. its openings must be well interconnected.

8.1 Non-Porous Permeable Materials

Materials such as the cast iron of the bathtub in Figure 22 do not meet Condition 1 and can be considered impermeable. However, if the cast iron receives an impact, it can acquire secondary porosity in the form of cracks. If the flow through the cracks is large, the cast iron is, in fact, very permeable. In nature, this situation applies to many igneous and metamorphic rocks that are essentially impermeable but are none the less capable of letting pass volumes of water through fractures caused by geological processes.

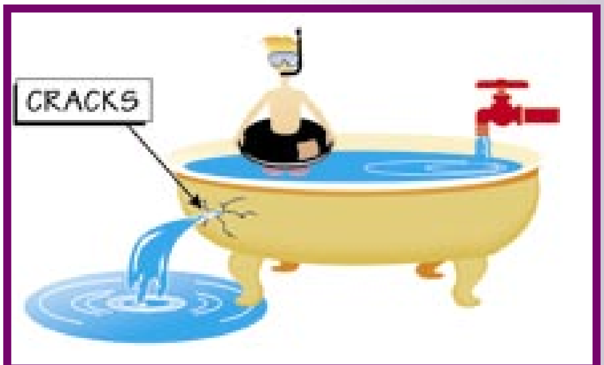

Fig 22. Problems with secondary porosity in an essentailly impermeable cast iron bath tub

8.2 Porous Impermeable Materials

Although clay materials have a high porosity, they are usually highly impermeable. This is because the pores between clay particles are very small and do not meet Condition 2. Molecular attraction binds clay and water molecules together, preventing any additional water molecules from passing through the pores. In some circumstances, however, clays can become permeable. For example, in effluent and other retention ponds lined with clay, ion exchanges that occur between solutes and the particles of clay may cause flocculation, a process by which dispersed clay particles group. A network of large interconnected pores may develop between the flocculi and the clay may become as permeable as clean sand. Alternatively, as water molecules evaporate and the clay dries out, its mass may shrink and form desiccation cracks (Figure 23). Water can flow through these cracks as easily as through the walls of the cracked iron tub in Figure 22.

Soils with a large volume of clay may become "sodic" if they receive water that contains a large proportion of sodium ions.

Fig 23. Desiccation cracks in clay **(Reference 24)**

Fig 24. Pumice: a very porous material, but also very impermeable due to the lack of interconnections between its voids

The sodium ions cause the clay particles to de-flocculate and disperse and fill any cracks. The soil becomes impermeable as well as incapable of supporting vegetation in a process that facilitates evaporation and erosion.

8.3 Poorly Connected Pores

If a material is very porous but the "necks" interconnecting its pores are too small to let water pass through, as in Condition 3 above, it may also be considered impermeable. An example is chalk, or limestone formed by the skeletons of micro-organisms (Figure 16), which has a high porosity of (46%) and can store large volumes of water. The interconnections between pores, however, are less than 1 micron wide and do not let water molecules easily pass through, giving the rock low "bulk" (ie average) permeability. Nevertheless, geological processes may develop secondary porosity features such as interconnected cracks, fractures and fissures, often enlarged by weathering and the carbonate dissolution process. Therefore chalk can become a very important water-producing formation.

Pumice is an example of an impermeable material containing large pores that give it a high porosity of up to 85% (Figure 24). Pumice is essentially solidified volcanic foam and has almost perfectly isolated vesicles that were formerly occupied by volcanic gases. The lack of connection between pores makes the rock impermeable. Since its high porosity gives pumice a low density, pumice can float and travel over the seas without sinking. It is often found on Australian beaches, far away from the remote volcanic centres where it originated.

9. Aquifers

Aquifers are earth materials that are both porous and permeable. Their porosity allows them to store groundwater, while their permeability allows the groundwater to 'flow' through the aquifer. This characteristic also gives them the capacity to release usable quantities of groundwater into bores, wells and springs.

The upper boundary of **unconfined aquifers** is the water table, which is at atmospheric pressure and mimics the undulating land surface (Figure 25).

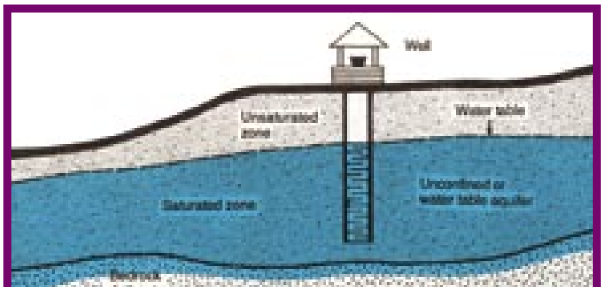

Fig 25. Unconfined aquifer, often called a "water table aquifer"

Some aquifers are not bound by the water table. Instead, they are found compressed between impermeable materials. These are called **confined aquifers**, or artesian aquifers. A bore that penetrates a confined aquifer is called an artesian bore. The water level within an artesian bore will rise above the upper limit of the material forming the aquifer because the pressure within the confined aquifer is higher than atmospheric pressure. The height at which water stands in a series of bores, or piezometers, located in a confined aquifer is termed the area's potentiometric surface (Figure 26).

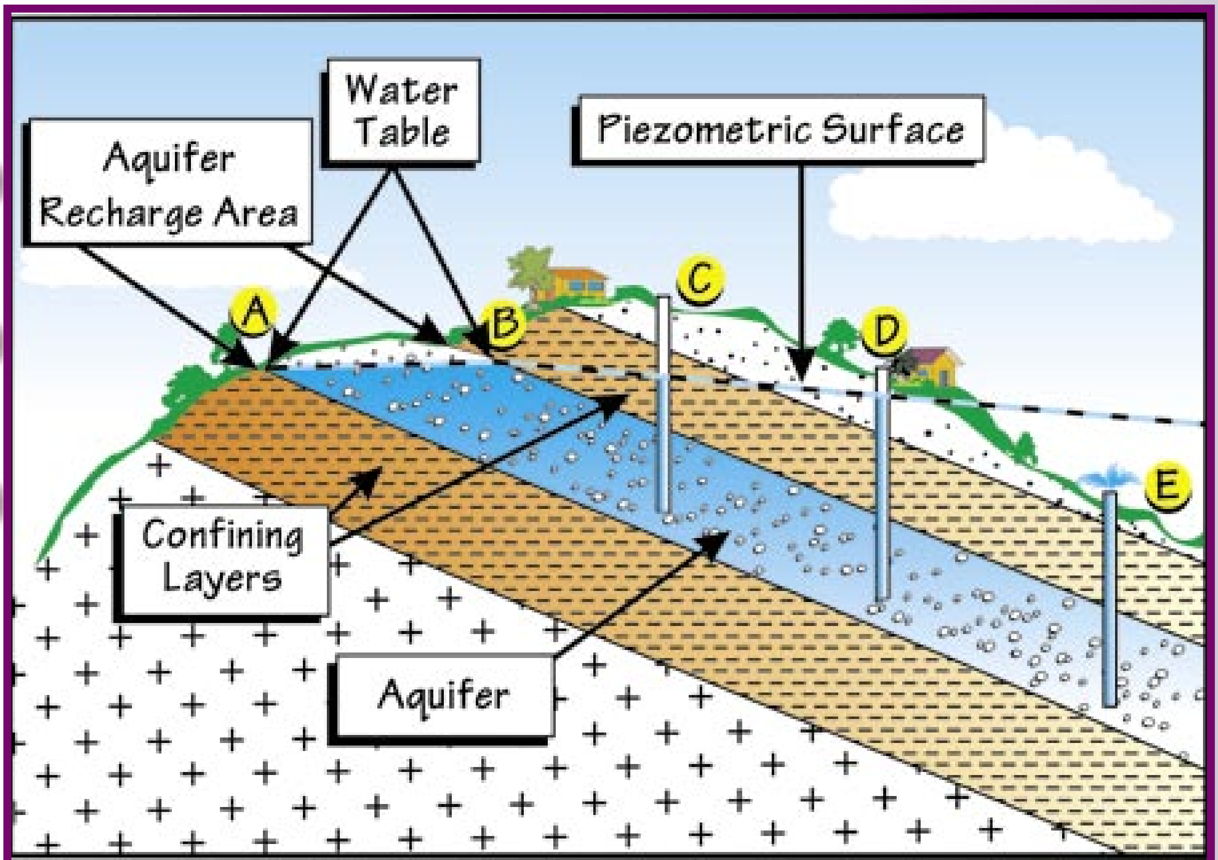

Fig 26. Confined aquifer. **(Adapted from Reference 8)**

Impermeable layers found in the unsaturated zone may prevent subsurface water from percolating down towards the water table. The percolating water may accumulate above the impermeable layer, fill pore spaces in this area and develop a saturated zone containing **perched groundwater**. Perched groundwater commonly occurs at a variety of depths between the soil surface and the regional water table, and frequently supplies seasonal springs (Figure 27).

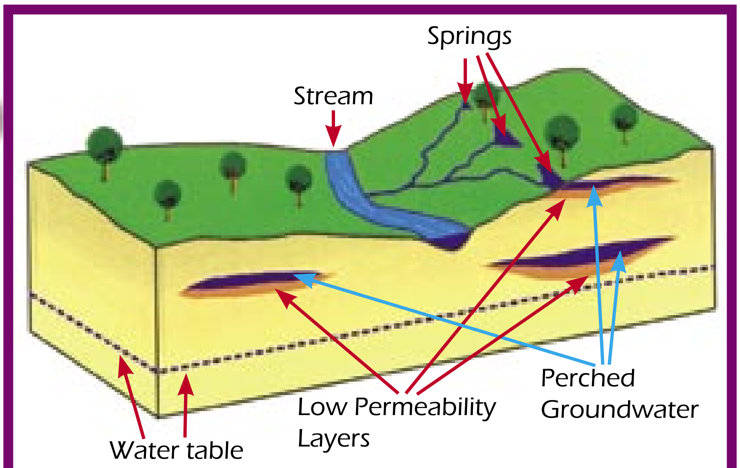

Fig 27. Perched groundwater. Adapted from **(Reference 16)**

A saturated zone of perched groundwater can vary in thickness from a few centimetres to many metres. Depending on the continuity of the underlying impermeable layer, it may extend laterally over a short or long distance.

Perched groundwater is common in many urban areas due to land management practices that allow water to leak and the formation of impermeable barriers during the construction of urban landscapes. Perched groundwater may be intersected during installation of underground services and by earth removal for site levelling. In this case, evaporation may result in the concentration of salt, so that perched groundwater becomes corrosive to infrastructure and damaging to vegetation.

Groundwater specialists generally distinguish between two types of aquifer: porous media aquifers, which include most aquifers with primary porosity, and fractured rock aquifers, which include most aquifers with secondary porosity.

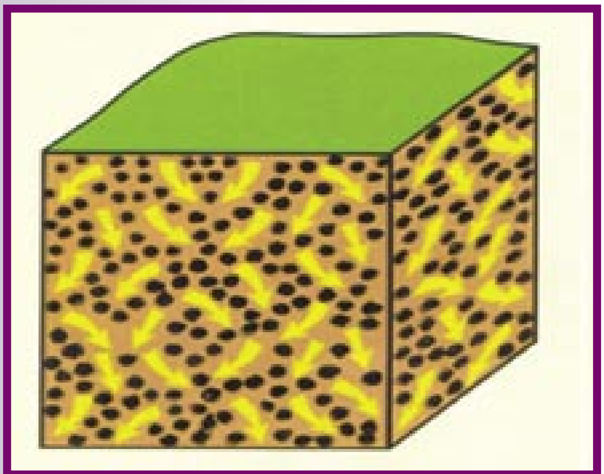

Fig 28. Water circulating through granular materials may follow intricate and complicated paths **(Modified from Reference 13)**

Figure 28 portrays the movement of water through the interconnecting voids of a porous media, which can be tortuous and very slow, particularly if the pores are small. Fractured rocks, on the other hand, may not be capable of storing large volumes of water as these openings can form less than 1% of their total volume. However, they can often transmit water quickly along their straightforward, open fractures (Figure 29).

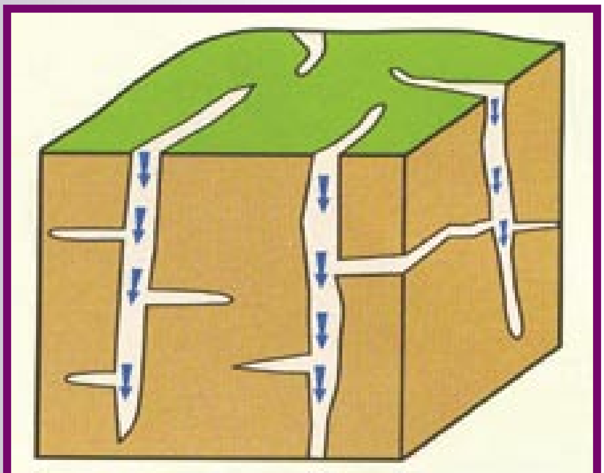

Fig 29. Water moving through the secondary porosity provided by fractures in a massive igneous, metamorphic or sedimentary rock may quickly follow straight line paths **(Modified from Reference 13)**

Fractured rock aquifers that occupy elevated areas of the NSW landscape can cause problems if deforestation and the associated processes of erosion remove their soil cover. Once stripped of their natural soil cover, fractured rocks become capable of capturing rainfall recharge and can easily transmit it to other earth materials such as the sediments of a valley. As explained by Figure 30, this process may raise the water table and be the cause of salinity problems.

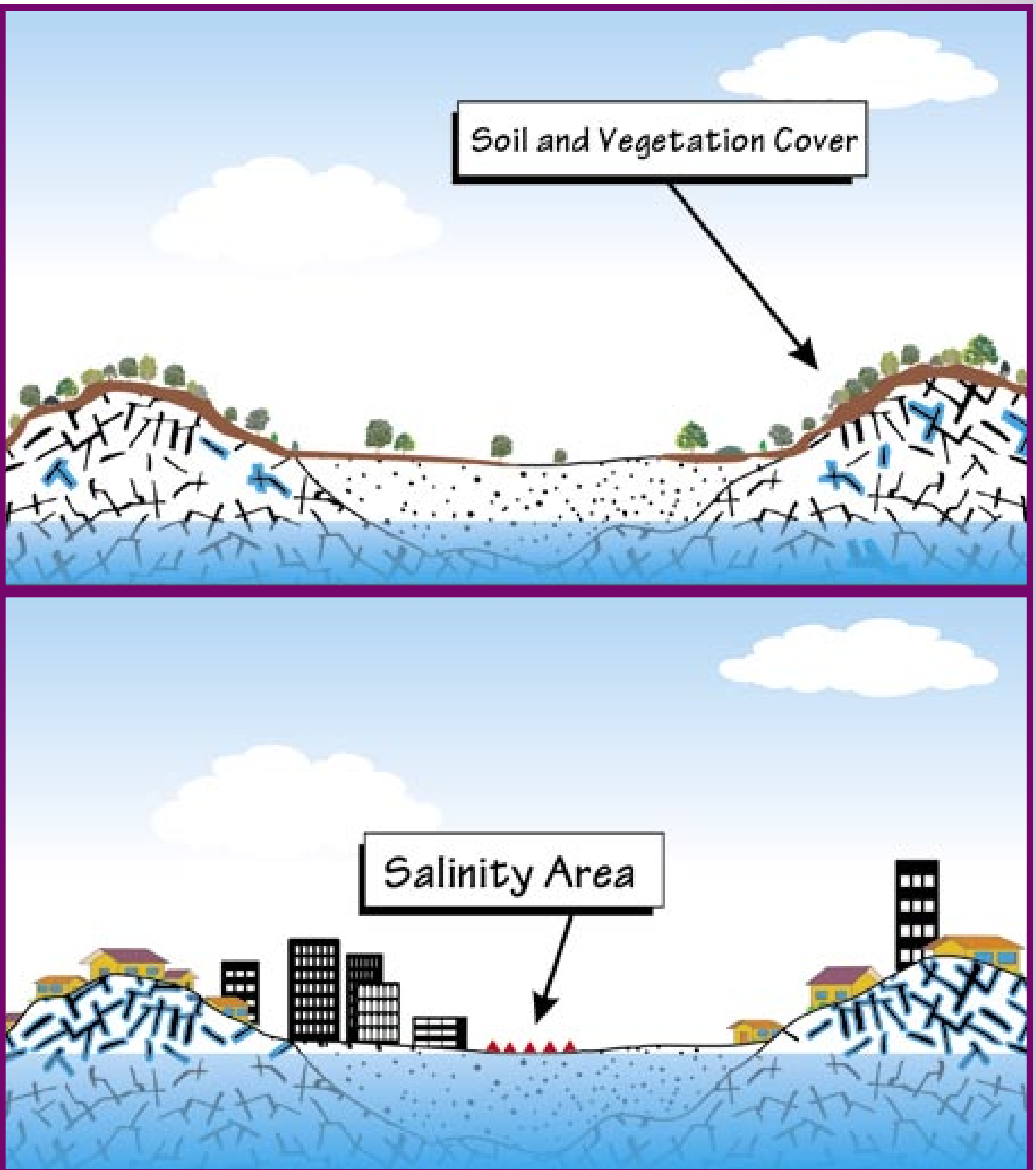

Fig 30. Typical situation of many salinity sites of NSW: the removal of vegetation enhanced the erosion of the soil that covered hills formed by fractured rock. The uncovered fractures become capable of accepting large volumes of rainfall recharge and transmit it to the lower parts of the landscape, where the water table rises. As the water table reaches the surface of the land, groundwater evaporates leaving dissolved salts behind and concentrating them. If the process is continuous, it can cause salinity problems

10. Salt Accumulation, How does it Happen?

Imagine a boiling kettle where a tap automatically replaces the water that evaporates (Figure 31). With time, even good quality drinking water in the kettle will become increasingly saline and salts will precipitate. The same principle applies to the accumulation of salts in the landscape, groundwater and oceans.

In urban areas, disturbances of the hydrological cycle caused by land-use change can result in groundwater rises followed by increased rates of evaporation and salt concentration. However, the salinity issues of today also reflect past evaporative processes (Figure 32).

Climatic events that took place hundreds or even thousands of years ago resulted in water tables close to the surface and in evaporative situations. Today, with a drier climate, evidence of this process is seen as bands of saline and sodic soil within the soil profile. Hotter and drier climates have also resulted in the evaporation of inland seas that once occupied much of Australia.

Fig 31. Evaporative salt concentration

Areas experiencing salinity problems are on occasion found near the shores of these ancient seas, or in areas where sea salts were deposited after being transported by wind over thousands of years.

Relatively recent geological events have also uplifted and exposed thick sequences of rock formed under the ocean. The seawater trapped in some of these rocks has not yet had time to be flushed out. In the urban environment, the reuse of effluent, importation of salty soils and building materials, as well as the change of natural flow paths, can make the distribution of salts in the landscape very complex.

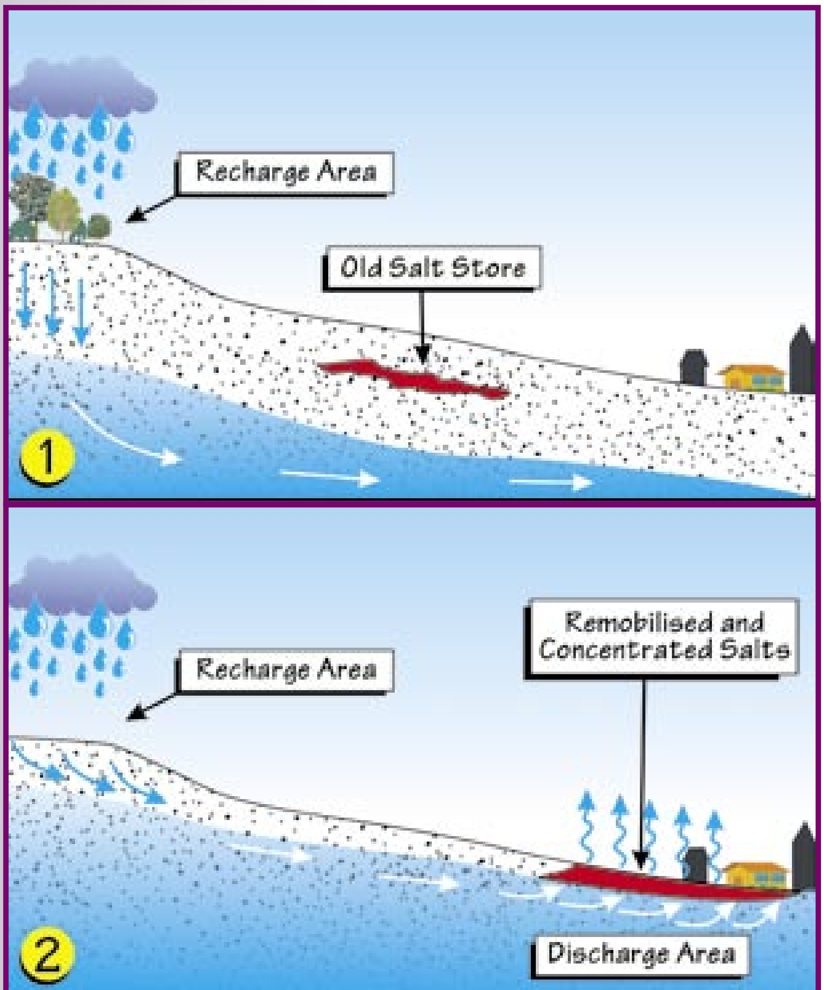

Fig 32. Salts deposited near the surface of the land during the past become re-mobilised and transported by groundwater that has risen

11. How does the Groundwater Reach the Earth's Surface?

11.1 Capillary Rise

If a small diameter tube is dipped in water, the water within the tube will rise by an amount inversely proportional to the tube's diameter (Figure 33).

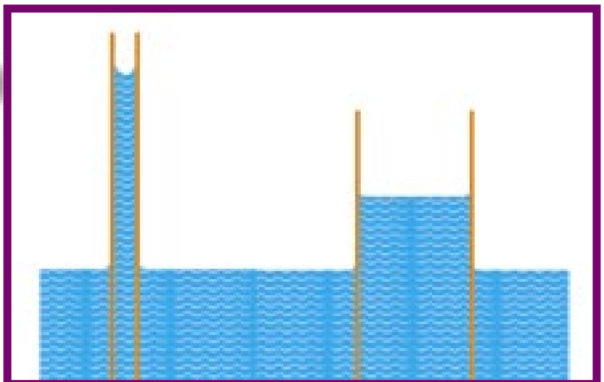

Fig 33. Water within a fine diameter capillary tube will rise much more than in a larger diameter tube **(Adapted from Reference 7)**

In a material such as clay, interconnecting pores behave as though they are bundles of small diameter tubes sticking out of the water table, thus forming the capillary zone (Figure 34). As the pressure of capillary water is less than atmospheric pressure, it does not flow into excavations and therefore is not groundwater .

In coarse material like sand and gravel, the capillary zone will measure only a few millimetres because the pores are large. However, in fine materials with very small pores, such as silt, chalk and clay, the capillary zone may rise many metres.

Figure 35 shows a building in Venice made of porous bricks with a capillary rise of several metres. Venice has sunk 20cm into the sea, and this has exposed the more porous bricks above the building's foundations to sea water from the adjoining canal. As these bricks contain very fine interconnecting pores, water and salt are able to travel several metres up through the brickwork.

Fig 35. Capilliary rise of sea water in an old building in Venice **(Reference 22)**

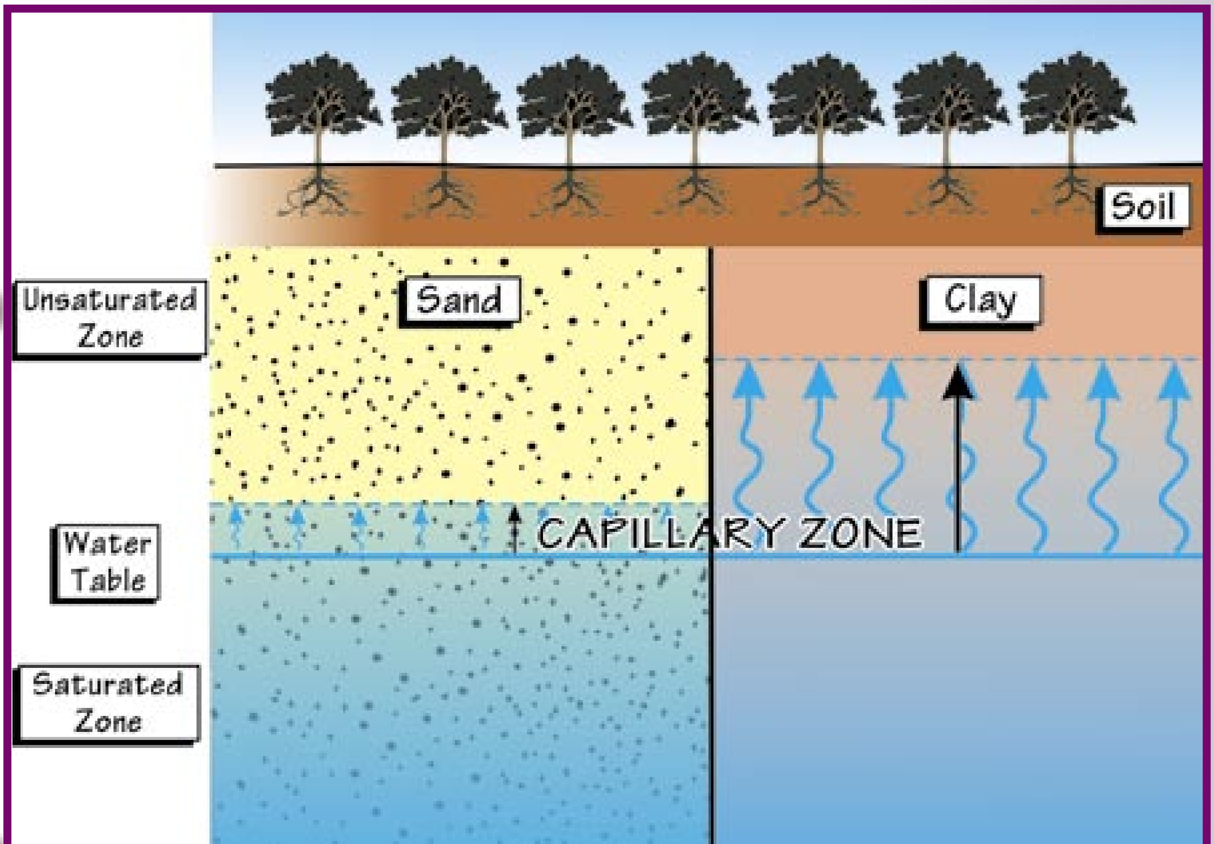

Fig 34. Water in fine materials will rise by capillarity much more than coarser materials **(Reference 12)**

As capillary action strongly enhances evaporation, its role in land salinisation processes is very important. The capillary fringe can move water continuously from the water table towards the soil surface. When water evaporates from the soil surface, it leaves behind the dissolved salts it carries. Upward movement of the water table or rainfall infiltration may dissolve some of these salt deposits into the groundwater system again, thus increasing the salinity of the groundwater over time. When the salinity of groundwater increases, evaporation may concentrate larger volumes of salts more quickly.

Water does not have to be drawn from a salty source for a considerable accumulation of salt to occur. The concentration of salt can result even when the water source is relatively fresh. Figure 36 shows a capillary fringe formed on the banks of the Macquarie River upstream from Dubbo, where the river salinity is less than 300 milligrams per litre. The accumulation of salts must have happened quite quickly as the river levels are constantly changing in response to water releases from Burrendong Dam and to water extraction for irrigation.

Fig 36. Capillary rise in the Macquarie River, upstream of Dubbo (**Reference 12**)

11.2 Faults

A fault is a fracture or fracture zone along which there has been displacement of the blocks relative to one another. Zones of fractured rock associated with faults can be quite permeable. When faults cut through artesian aquifers, groundwater may rise through the permeable zones of the faults making it easier to reach the surface of the land (Figure 37). Water that reaches the land surface through a fault may concentrate salts if climatic and topographic conditions favour evaporation and salt accumulation.

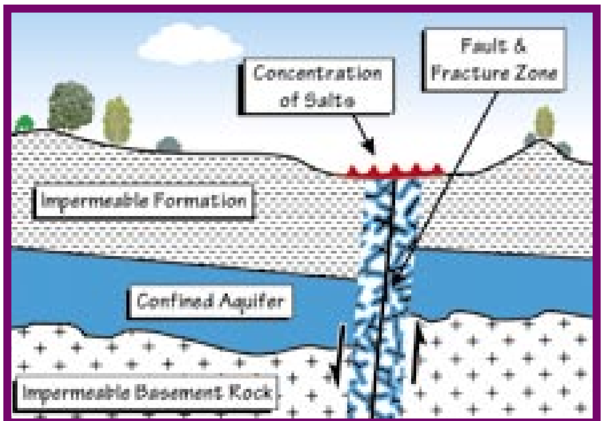

Fig 37. A fault and associated "crush" zone may be permeable enough to allow deep groundwater in a confined aquifer to reach the surface of the land

11.3 Restrictions to Groundwater Flow

Restrictions to groundwater flow can result in the discharge of groundwater at the earth's surface. For example, faults (Figure 38), intrusions such as dykes (Figure 39), and impermeable basement rock highs (Figure 40), can form underground "dams" which hold back groundwater flow. Over time, the accumulation of groundwater behind these barriers may result in the water table rising to the surface. If the water table reaches the soil surface, it may form a lake, a swamp or a spring that may feed a running stream. In semi-arid climates where evaporation is high and rainfall is not abundant enough to flush accumulating salts, areas overlying these natural "dams" become saline.

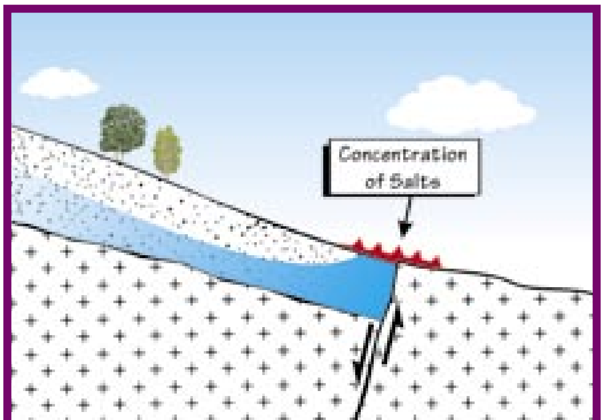

Fig 38. Fault lifting impermeable basement rocks and forming a major obstruction to groundwater flow

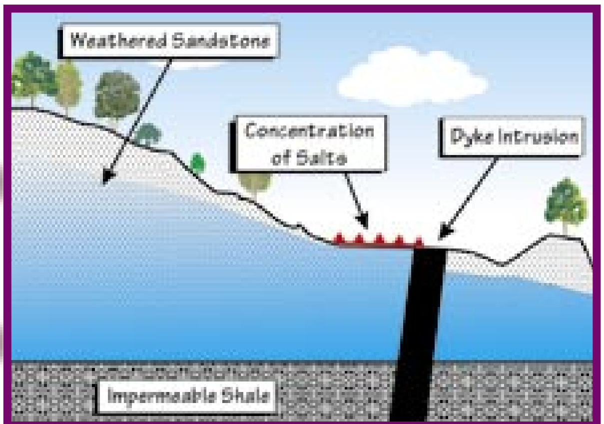

Fig 39. An intrusive body of rock, such as a dyke, may form a natural barrier to groundwater flow and act as a dam, lifting the water table until it reaches the surface of the land

Figure 40, shows how a geological groundwater flow restriction is compounded by the sub-grade of a road. Made of compacted clay, the sub-grade of the road presents an additional barrier to the flow of groundwater. In this example, once the water table rises, both structures (one synthetic, the other natural) will combine to enhance the concentration of salts.

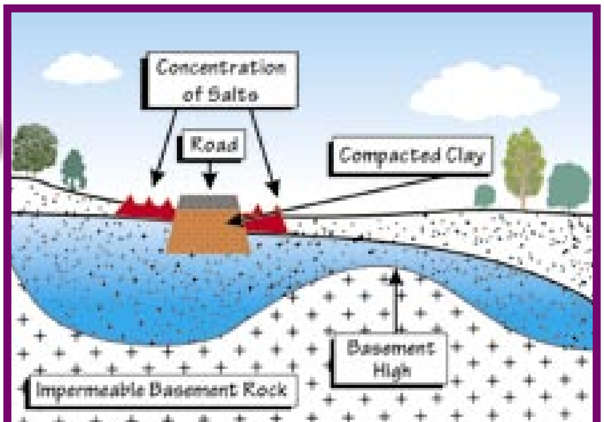

Fig 40. Man-made and natural features presenting barriers to groundwater flow and causing salinity problems in the case of an already high water table

Restrictions to groundwater flow may also result from the shape of landforms. A hydrological basin, for example, may have a very small outlet or no outlet at all. In the first case, water and salt will concentrate near the outlet (Figure 41). If there is no outlet at all, water and salts will concentrate near the lowest point of the basin (Figure 42).

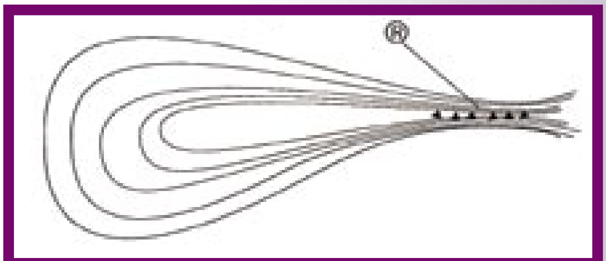

Fig 41. Basin with a very small outlet, where salts will concentrate near the outlet if the water table rises **(References 18 and 19)**

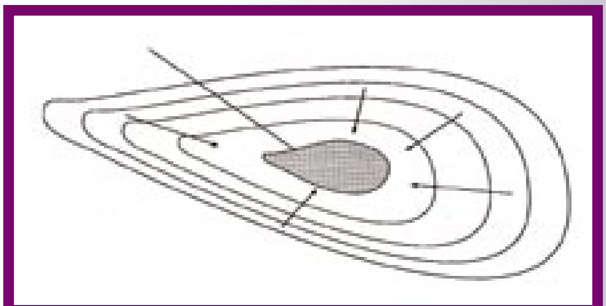

Fig 42. Closed basin with no outlet, where salts may concentrate near the basin's lowest point **(References 18 and 19)**

11.4 Contrasts of Permeability

Groundwater may also reach the surface as a result of a change in permeability. When groundwater is accumulating and moving from high permeability materials to lower permeability materials, a build up of groundwater will occur at the boundary.

Common examples include:

1. horizontal layers. This type of salinity problem often occurs where permeable layers such as fractured basalt or fractured sandstone layers overlay less permeable rock (Figure 43),

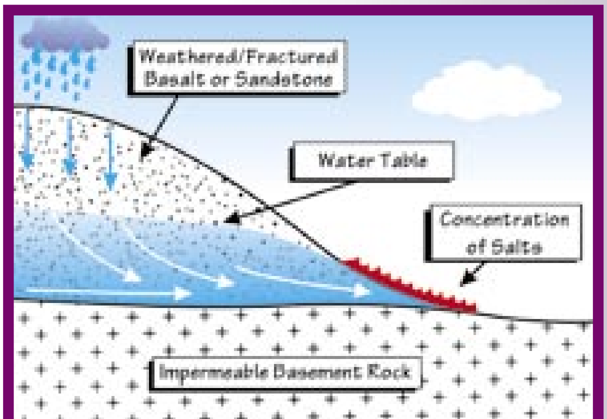

Fig 43. Groundwater recharge captured by a relatively permeable fractured rock aquifer meets an impermeable basement rock barrier and has to return to the surface forming an outbreak of salts

2. mixed rock types. This type of salinity often occurs where fractured intrusive rocks such as granite form hills that are surrounded by materials with very low permeability, such as shale. Recharge collected by the weathered fractured layer of granite cannot escape into the surrounding formation or into the non-weathered area of granite and evaporates at the base of the hills (Figure 44),

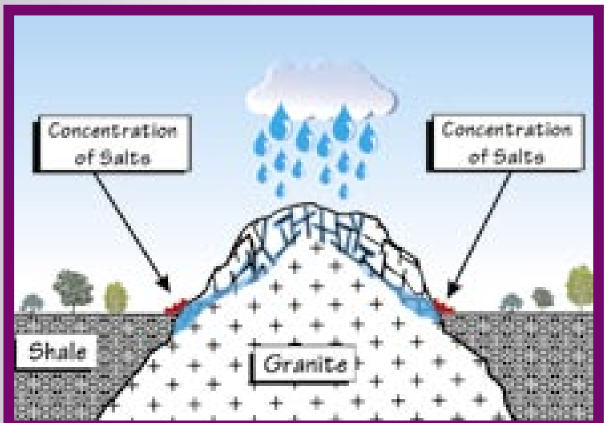

Fig 44. Fractured granite hill collecting rainfall recharge that has no outlet into other formations as the granite is surrounded by shale

3. duplex or texture contrast soils. Some soils have a distinct texture change between the upper and lower soil horizon so that water easily infiltrates the upper layers but moves slowly in lower layers. A perched water table may form on flat sites, while on sloped areas lateral flow along the boundary of the two permeabilities will result in a perched water table or groundwater spring further down the slope,
4. increased clay content. Soil transport processes on slopes usually result in a gradation of clay content within a particular soil type (Figure 45), so that a soil becomes less permeable towards the base of the slope, and
5. human interference. In the urban environment, changes in permeability are a common result of soil compaction, imported soil, and the erection of structures such as retaining walls and underground services.

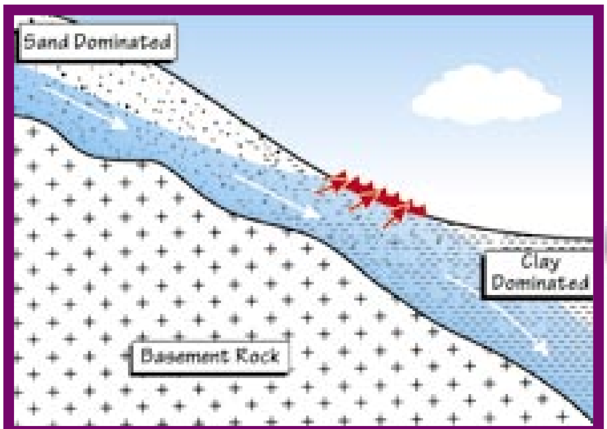

Fig 45. Restrictions to groundwater flow caused by changes of permeability within a layer of soil or rock **(References 18 and 19)**

12. The Development of Urban Salinity

Urban expansion often increases recharge and interferes with the natural movement of water above and below the soil surface. These changes may mobilise and concentrate salts within or next to urban structures. This can result in damage to roads, bridges, building foundations, water supply pipes, sewerage systems and electricity supply systems, vegetation in home gardens and public parks.

The three parts of Figure 46 portray the development of urban salinity. Figure 46a is typical of many towns established in sensitive environments such as river flats or enclosed valleys with forested hills. In such locations, groundwater prior to development is usually several metres from the land surface. Vegetation and associated soil cover prevent excessive groundwater recharge and there is a balance with the flow of groundwater into the river.

Mining, cropping and animal husbandry result in changes to vegetation and soil cover. Recharge increases, but discharge mechanisms into the river may not be able to cope with this additional flow. Groundwater banks up because of the change in permeability or constricted outlet. By the time a village becomes a town the water table has risen (Figure 46b).

As villages become towns and then cities, water consumption increases with population, with the development of industry and the establishment of parks and lawn-covered areas. Water-use further increases with the installation of water reticulation systems. Easy access to showers, washing machines, flushing toilets, swimming pools and air conditioners results in an increase in the average daily water consumption of individuals, from tens of litres to hundreds of litres.

The introduction of reticulated water systems facilitates the movement of large volumes of water through pipes and channels before storage for later use.

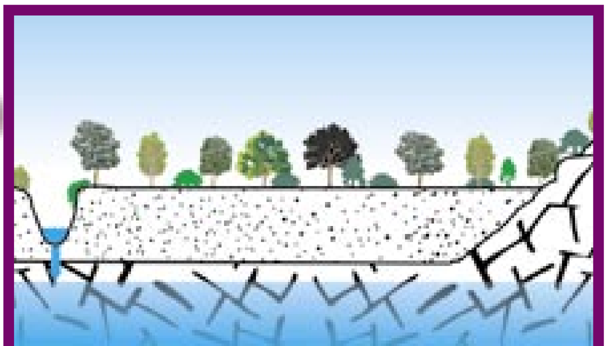

Fig 46a. Pre-development stage

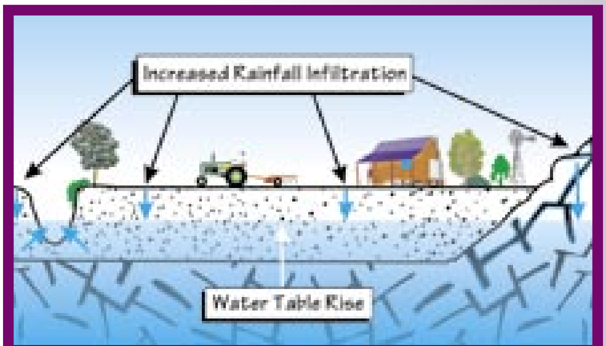

Fig 46b. Agricultural stage

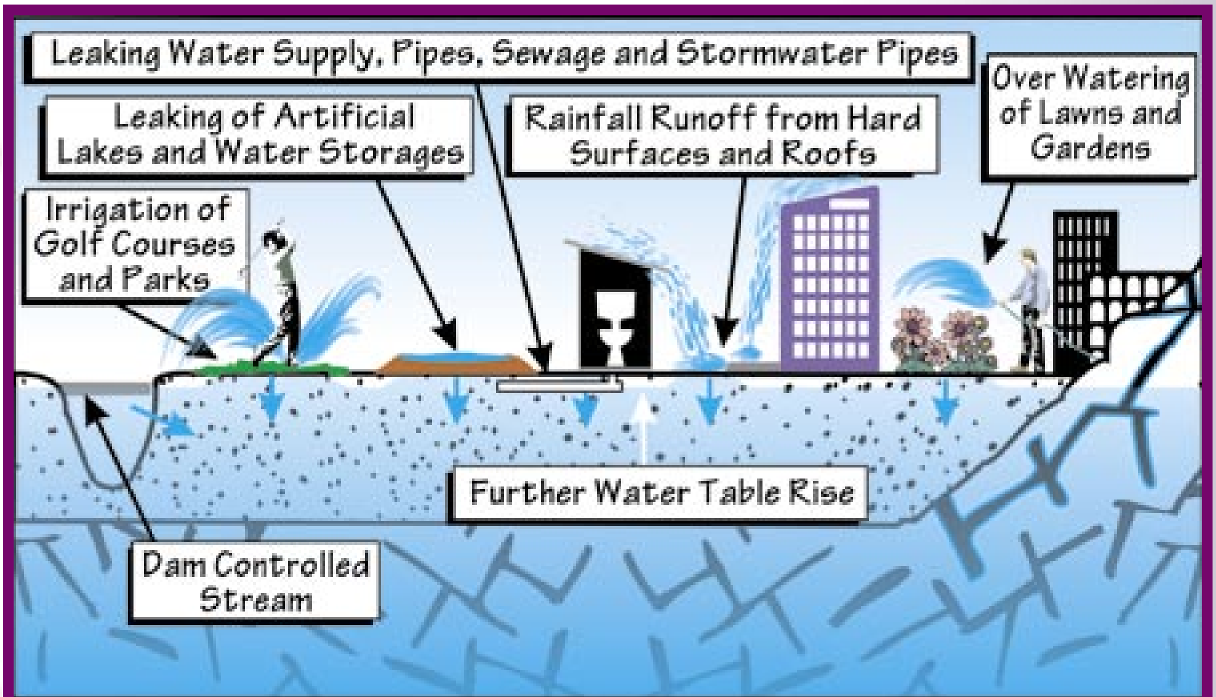

Fig 46c. Urban stage

All these parts of the system may leak. Even if the water is of good quality, importing water also means importing tonnes of dissolved salts.

Once used, the dirty water is treated in sewerage treatment systems which do not remove the salts added to the effluent from urine, detergents and industrial processes. The collection, treatment and disposal of treated wastewater and any leakage from these components change the urban hydrological cycle.

Further sources of recharge water include: rainwater collected, stored and disposed of from roofs and hard paved surfaces; water concentrated in small areas where plants have very little chance of intercepting and utilising such large quantities of rainfall; the over-irrigation of private and public gardens and golf courses; disruption of natural flow paths caused by excavation, fill, compaction and construction of foundations that changes the vegetation cover and type. The result is further rises in the groundwater table and interception with new discharge areas (Figure 46c).

Research in southern NSW has shown that recharge prior to European settlement was in the order of one mm per year. During agricultural establishment recharge was in the order of 15mm per year, while with urban development recharge is in the order of 50mm per year. It is not surprising that there is a high risk of salinity developing in urban areas.

13. Managing Urban Salinity

The management of urban salinity involves land-use planning, careful urban design and the introduction of construction and maintenance techniques which avoid adverse impacts on salinity processes and allow us to live with salt. An important part of urban salinity management focuses on reducing groundwater recharge with the intention of reversing the water table processes summarised in Figure 46 from Stage c to b and, if possible, to a.

Reducing the volume of recharge within urban areas involves many stakeholders including councils, industry, businesses and residents, who :

- avoid over-watering in public parks, sports fields, golf courses, gardens and other landscaped areas,
- replace lawn areas not needed for recreation purposes with native trees, shrubs and grasses that utilise rainfall efficiently and require little or no irrigation, and
- repair and replace leaky components of water supply systems, stormwater and sewerage systems.

This may involve:

- lining leaky storage areas such as dams, retention basins, lagoons and artificial wetlands,
- replacing broken pipes and fittings,
- removing rubble pits, septic tanks and other disposal systems enhancing infiltration,
- lining earthen drains and bio-ribbons, and
- establishing careful controls for effluent reuse/irrigation areas.

Recharge and discharge, flows and stores within the urban area may also be influenced by groundwater in the surrounding area, so that reducing the volume of recharge within the groundwater catchment surrounding the urban area may also be necessary. A hydro-geological investigation should be undertaken to determine the scale of the problem.

As well as determining the scale of the salinity problem, a hydro-geological investigation should:

- provide a conceptual model outlining the geological and hydrological framework controlling groundwater flow,
- identify and delineate the most important areas of primary recharge influencing the town,
- define areas affected or threatened by salinity and groundwater discharge,
- provide guidelines that could be used to reduce evaporation and/or groundwater levels at salinity affected sites. For example, assess the possibility of using de-watering bores,
- design an efficient network of piezometers and monitoring bores capable of measuring the long-term impact and the effectiveness of the measures undertaken to address the salinity problem, and
- produce hydro-geological maps to be used for urban planning in order to protect aquifers that become a supply source for town water and, most importantly, to control the expansion of existing salinity problems.

14. References

(1) Davies, S.N. and DeWiest, R.J.M., 1966. *"Hydrogeology"*. John Wiley and Sons, Inc., New York Press, New York, NY.

(2) Gill, R., 2002. *"ABCs of Groundwater"*. Published by Centre for Groundwater Studies: C/- Flinders University of SA, SoCPES.

(3) Image courtesy Prof. Phil Cocks, UWA. Reproduced from the web site of the State Salinity Council of Western Australia.

(4) Reshkin, K., Embleton, K. and Jones, D.D., 1998. *"Groundwater Primer."* US EPA Region 5 and Purdue University. Website: http://www.epa.gov/seahome/groundwater/src/title.htm.

(5) Clarke R., Lawrence, A. and Foster, S., 1996. *"Groundwater: A Threatened Resource"*. United Nations Environment Programme Environment Library No. 15, Nairobi, Kenya, 1996.

(6) Evans, J.M., 1984. in *"Water Science for Schools"*. US Geological Survey. Website: http://ga.water.usgs.gov/edu/watercyclegraphic.htm.

(7) Price, M., 1996. *"Introducing Groundwater"*. Chapman and Hall, London. 2nd edition.

(8) Raymond, L.S., 1992. *"What is Groundwater?"* Minnesota University Extension Service, University of Minnesota, Minnesota, USA.

(9) USGS, *"Water Science for Schools"*. http://ga.water.usgs.gov/edu/gwroadcut.html.

(10) Kozlowsky, Y. A., 1987. *"The Superdeep Well of the Kola Peninsula"*. Berlin: Springer Verlag.

(11) Driscoll, F. G., 1987. *"Groundwater and Wells"*. Johnson Division, St. Paul Minnesota 55112. 2nd Edition.

(12) Smithson, A., 2001. *"Groundwater and Salinity Processes"*. Power Point Presentation. Department of Land and Water Conservation, Central West Region.

(13) Love, A. and Cook, P., 1999. *"The Importance of Fractured Rock Aquifers"*. PIRSA Report Book 99/23.

(14) University of Maryland, BC USA Web Site

http://userpages.umbc.edu/~hories1/Ireland/Portrush/P9180006.jpg.

(15) Meinzer, O.E. and Hard, H.A., 1925. *"The Artesian Water Supply of the Dakota Sandstone in N. Dakota, with special reference to the Edgeley Quadrangle"*. US Geological Survey Water Supply Paper 520-E. Washington DC: US Govt. Printing Office.

(16) Centre for Groundwater Studies' Web Site. http://www.groundwater.com.au/glossary/content.asp.

(17) "Salinity – Some Common Questions" 2003 Queensland Government Website:

http://www.nrm.qld.gov.au/salinity/pdf/salinity_questions.pdf

(18) Anderson, J., Britten, R. and Francis, J., 1993. *"Dryland Salinity: The Causes". Department of Conservation and Land Management / NSW Department of Water Resources.*

(19) Coram, E., Dyson, P.R., Houlder, P.A and Evans, W.R., 2000. *"Australian Groundwater Flow Systems Contributing to Dryland Salinity"*. Bureau of Rural Sciences Project for the National Land and Water Resources Audit. Dryland Salinity Theme.

(20) Salas, G. and Smithson, A., 2002. *"Rainfall Controls on Standing Water Levels in a Fractured Rock Area of Central N.S.W., Australia"*. International Groundwater Conference, Darwin 2002.

(21) Oxford Brookes University Geology 2003 Website: http://www.brookes.ac.uk/geology/8320/volcan.html.

(22) State Heritage Branch, 1995 (1997 Reprint). "Rising Damp and Salt Attack". Department of Environment and Natural Resources. City of Adelaide. ISSN 1035-5138.

(23) DIPNR 2003 Web Site *"Salinity in New South Wales"* http://www.dlwc.nsw.gov.au/care/salinity/index.html.

(24) NSW Agriculture Image Library of Agricultural Subjects 0001 – 7500. Image 34. (04064).

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