Chapter 2 — Hydrologic controls on salinity

Water is the dominant medium for salt movement in the environment. When water is removed from the environment by processes that exclude salt, such as evaporation and transpiration, salt is deposited and accumulates over time (Figure 15).

Evaporation occurs at the soil/atmosphere interface where groundwater seeps at the soil surface or where the watertable is close enough to the soil surface for capillary action to draw water to the surface. Another source of salt accumulation is evaporation of surface water. This is important in areas where salt is not regularly flushed out of the catchment, such as in Lake Eyre.

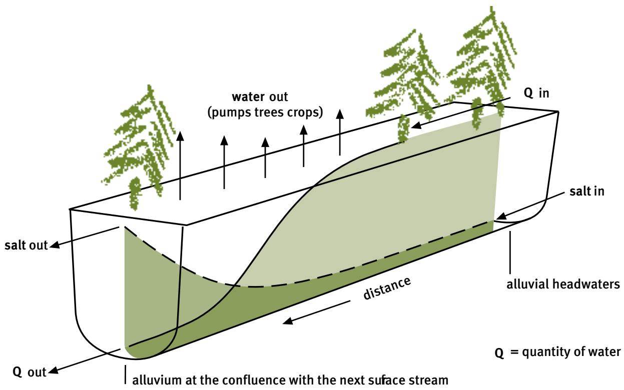
Transpiration occurs at the soil/root interface where plants absorb water from the soil, generally excluding salts dissolved in the water so that these salts accumulate in the root zone. When vegetation has root systems reaching to a deep watertable, salt accumulates at greater depths in the soil profile or over a larger depth range above the watertable.

Hydrologic equilibrium results from a balance between climate (largely rainfall and temperature) and the development of a landscape (including weathering/soil formation and vegetation pattern). The presence of a discharge area indicates that the rate of water movement into the groundwater of the catchment exceeds the rate of water movement out of the catchment. Thus, only hydrologically sensitive catchments (without effective vegetative or soil water storage buffers) will exhibit waterlogged or saline discharge areas.

Soil hydraulic properties govern the height to which the capillary fringe of the watertable can rise within a given soil. When the capillary fringe intersects the soil surface, soil hydraulic properties also determine the maximum rate at which groundwater and dissolved salts can be transported to the soil surface. If the daily evaporation rate exceeds the supply of groundwater to the soil surface, the soil dries and capillary rise is greatly reduced.

In undisturbed areas, the native vegetation is generally in equilibrium with the natural hydrology of an area. Trees normally utilise all the available water and remove water from the area by evapotranspiration. A small proportion of rainfall (less than 10%) evaporates from the surfaces of grasses and the leaves of trees. In this situation, the vegetation is able to cope with and moderate the effects of variations in seasonal and yearly rainfall.

Figure 15. Evaporation, transpiration, and the role of vegetation in catchment water and salt balance (adapted from Dowling & Gardner 1988). Used with permission from CSIRO.



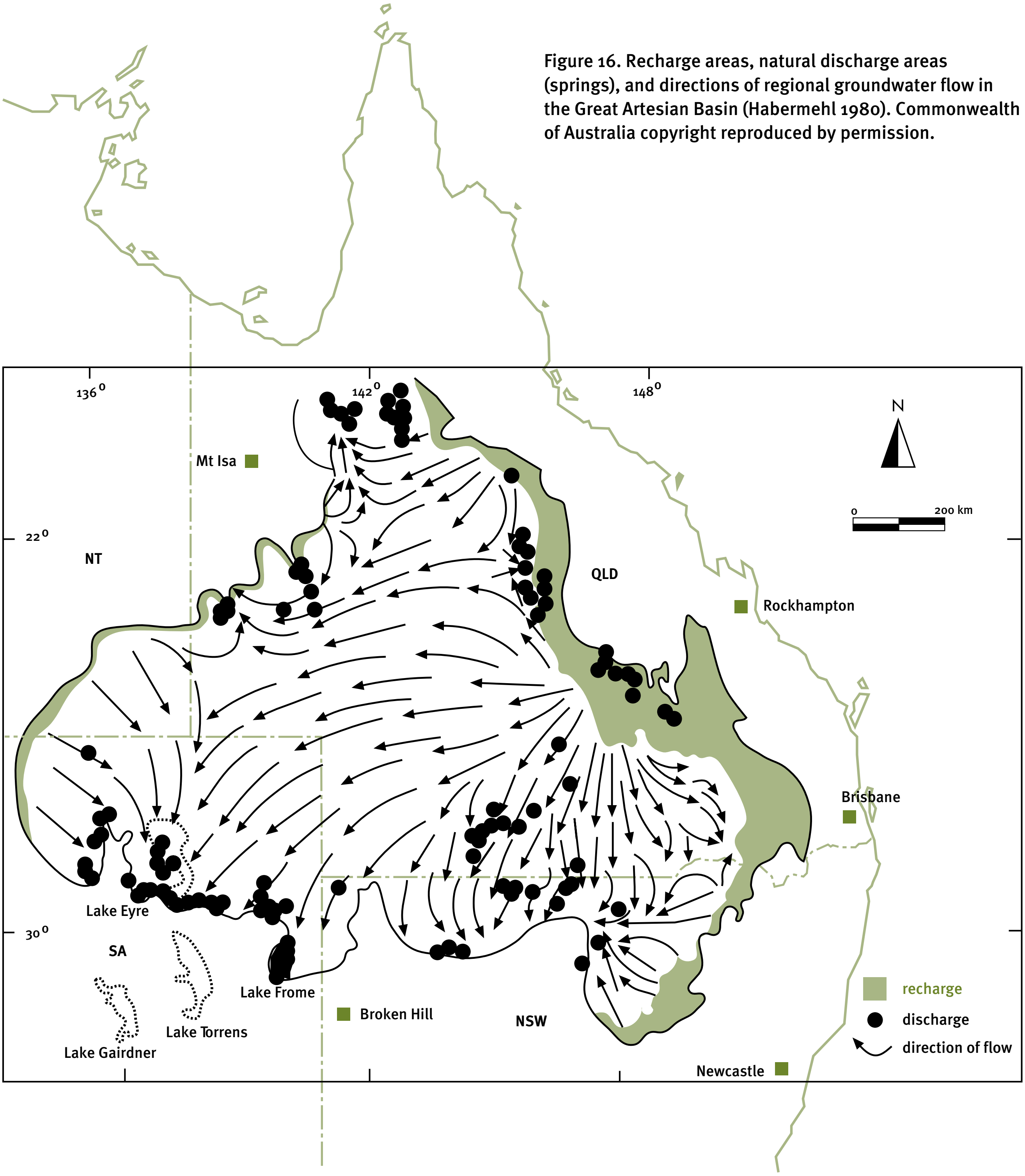
When trees are removed, water usage in the system generally decreases, runoff slightly increases, and the resulting excess water may percolate through soils and weathered rock into the watertable. If lateral drainage is poor, the level of the watertable will rise, establishing a new hydrologic balance in the system. The salinity of the groundwater may increase as additional salt is dissolved from weathered rocks and soils not previously below the watertable.

Thus vegetation provides a buffer in the system, with the capacity to utilise the available water in the landscape. There are limits: if rainfall is so low that plants cannot grow or reproduce (for example, the Sahara Desert and to a lesser extent the Simpson Desert), vegetation will be limited or absent; if rainfall is so great that it exceeds the ability of any vegetation to utilise the water (that is, the rainfall exceeds the potential evapotranspiration capacity of plants which is determined by the radiation energy), there will be an excess of water. In the second case, the landscape adjusts to the extra water through geomorphological processes such as enhanced weathering, erosion, gully formation, and increased baseflow in streams.

Groundwater movement model

The spatial distance between areas where recharge and discharge occurs will vary from catchment to catchment. In some cases, these areas may overlap; in others, the recharge and discharge areas may be separated by thousands of kilometres, as in the case of the Great Artesian Basin (Figure 16). In Queensland, the distance between recharge and discharge areas is usually in the range of a few hundred metres to several kilometres.

Figure 16. Recharge areas, natural discharge areas (springs), and directions of regional groundwater flow in the Great Artesian Basin (Habermehl 1980). Commonwealth of Australia copyright reproduced by permission.

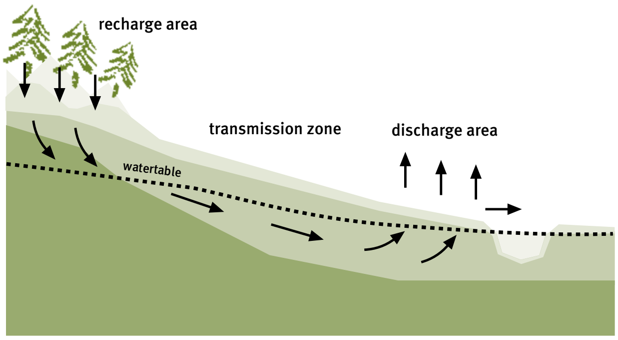


A simple conceptual model is useful for understanding how water moves salt through the landscape. In this model, which focuses on the movement of **groundwater**, the landscape is divided into areas where water predominantly enters groundwater (recharge), moves laterally (transmission), and exits from groundwater (discharge). The model is illustrated in Figure 17.

Recharge

Recharge is the process of water entering the groundwater. Recharge areas are areas where the net movement of water is into the groundwater. Relatively permeable areas of the landscape, usually on the upper slopes and on shallow soils, act as recharge areas.

Figure 17. A simple conceptual model which considers a landscape in terms of recharge, transmission and discharge areas.



The critical parameters in determining the rate of recharge are soil properties and depth, rainfall and evaporation patterns, and vegetation type. Soil properties influencing recharge include:

- characteristics of the macropores, which transport water to the groundwater when the soil is saturated
- the drainable porosity of the soil, which is the capacity of the soil to release water between saturation and the point where water ceases to drain readily (field capacity)
- plant available water capacity, which is the capacity of the soil to retain water between an upper limit determined by the field capacity and a lower limit when water becomes unavailable to plants (wilting point).

The effectiveness of vegetation in exploiting available soil water, particularly at depth, varies depending on factors such as growing season, rooting depth, drought tolerance, and vegetation density.

Recharge is maximised where:

- soils are shallow overlying fractured rocks
- soils are highly permeable, or outcrops of fractured rock occur
- vegetation is shallow-rooted or absent
- the rainfall pattern is characterised by rainfall in excess of evapotranspiration for a period of the year.

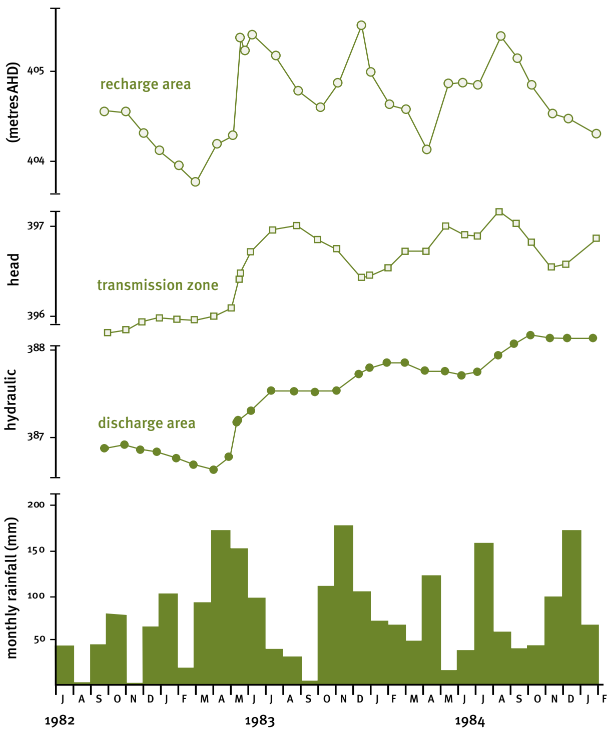
The depth to the watertable in a recharge area is usually considerable. Watertable level tends to respond quickly to rainfall with marked seasonal fluctuations (Figure 18).

Transmission

Transmission areas occur where the dominant movement of water within the groundwater is approximately parallel to rather than toward or away from the soil surface. Transmission areas generally occur in areas of intermediate and decreasing slope. Soils are deeper and less permeable than those in recharge areas.

The depth to the watertable in transmission zones is usually less than in recharge areas, with less marked seasonal fluctuations (Figure 18).

Figure 18. Typical seasonal fluctuations in hydraulic head in recharge areas, transmission zones and discharge areas for one site on the Darling Downs (after Thorburn et al. 1986).



Discharge

Discharge areas are areas where the net movement of water is upwards/outwards from the ground. They generally occur where there is some hydrologic restriction to downslope water transmission, causing water to flow toward the soil surface where it 'discharges' from the groundwater. Discharge areas often occur where the ground is flat or poorly incised. In a range of landscape types that are particularly susceptible to watertable salting, discharge areas occur in characteristic positions in the landscape (described in ***Landform feature identification*** page 39). Soils in discharge areas are generally deeper and less permeable (because of higher clay content) than in recharge and transmission areas. This is because past weathering products of upslope areas accumulate in discharge areas.

The watertable in a discharge area is usually at or near the soil surface, with subdued seasonal fluctuations compared with recharge and transmission areas (Figure 18). Waterlogging and salinity usually manifest in discharge areas. Salt accumulates when water is removed by evaporation and transpiration and salt is left behind. However, land use changes and landscape features in recharge, transmission and discharge areas will determine the extent and severity of salting in discharge areas.

During rainfall periods, surface salt accumulations in discharge areas are leached downwards into the root zone, particularly if the watertable is low following a number of drier than average years. During a subsequent wetter than average cycle, salt accumulated in the root zone will be moved upwards by the rising watertable. Thus, through a series of wet and dry cycles, salts continue to accumulate in the soils and groundwater in discharge areas.

The form of salting in a discharge area depends on the rate of upward water movement to the soil surface compared with the rate of evaporation at the soil surface. Three situations can result:

- If water moves upward through the soil more quickly than it evaporates at the soil surface (rate of water rise exceeds evaporation rate), a seepage will develop. The salinity of the seepage will depend on the salinity of the groundwater.
- If the capillary fringe of a shallow watertable moves water to the soil surface at approximately the same rate as evaporation removes water from the soil surface, salt will accumulate on the soil surface at the maximum rate. Salt will be more concentrated in this situation than in the case of a permanent or seasonal seepage, which would allow any accumulated salt to be periodically flushed away.
- If water evaporates from the soil surface more quickly than it moves upward through the soil and if the watertable is deep enough that capillary rise to the soil surface is not significant, vegetation may maintain the area in hydraulic balance without any salt concentration at the soil surface. However, salt will accumulate in the root zone as plant roots continue to take up water and exclude salt. The magnitude of this accumulation will depend on the salinity of the groundwater and the extent to which rainfall flushes salt away from the soil surface or leaches salt through the soil.

On the basis of current experience in Queensland, areas where the watertable is less than 6 metres deep under undisturbed vegetation have the greatest potential to develop watertable salting when subject to clearing or other land development. Deeply incised creeks can prevent watertable rise, but these do not usually occur in areas susceptible to salting.

Groundwater encountered in topographic positions above valley floors is usually associated with **perched watertables**. These form when downward percolating water (from rainfall and runoff) is held up by impermeable layers in the weathered zone. The water in the perched water body may slowly percolate through the barrier into the deeper regional groundwater and/or move laterally to toeslopes and/or be used by vegetation through evapotranspiration. Water in a perched water body builds up following significant rainfall events, and may be present for weeks or a few months. Irrigation can produce perched watertables in a similar manner.

Discharge is maximised where:

- the watertable is at or very close to the soil surface (salt accumulation is generally greatest when the watertable is permanently between 0.5 and 1.5 metres below the soil surface)
- the soil surface is bare or sparsely vegetated
- soil properties at the site allow a maximum rate of water movement through the surface layers.

Salt mass balance

Salt mass balance refers to an equilibrium between salt entering and salt leaving the catchment. For instance, salt entering the catchment in the form of a large volume of water with low salt concentration, such as rainfall, can be in balance with salt leaving the catchment as a trickle of outflow of very high salt concentration (refer Figure 19). The accession of salts from weathering and rainfall and the export of salts through stream flow and groundwater discharge are in equilibrium. In periods of adjustment between changing inputs or outputs, there will be a change in the salt storage in the landscape until the new equilibrium is attained. The salt storage may increase or decrease or, most commonly, salt mobilisation will cause a translocation of salt within the existing storage.

This is described by the steady state mass balance equation:

$$Q_i c_i = Q_o c_o \qquad \text{1}$$

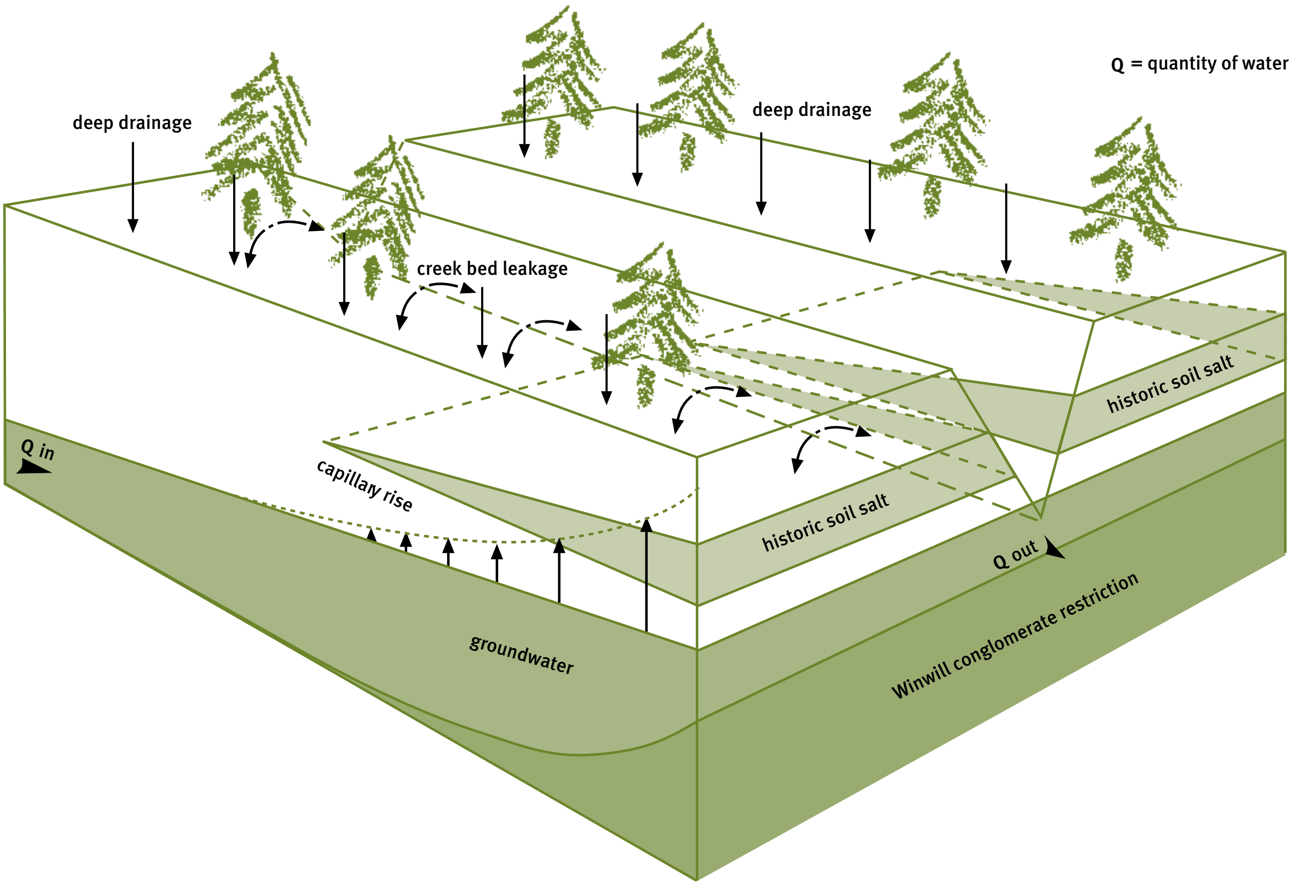
where

Q_i	is	quantity of water entering the system
c_i	is	salt concentration of the water entering the system
Q_o	is	quantity of water leaving the system
c_o	is	salt concentration of the water leaving the system.

Parameters

This steady state equation can be expanded to incorporate other processes that control the movement and quantities of salt in the system, such as dissolution and weathering. In the following figure (Figure 20), mass balance inputs and outputs are indicated on a diagrammatic section through a catchment:

Figure 19. Schematic diagram of salt balance in a landscape system based on the Lockyer Valley where the Winwill conglomerate forms a geological restriction to groundwater flows (Gardner 1985a).



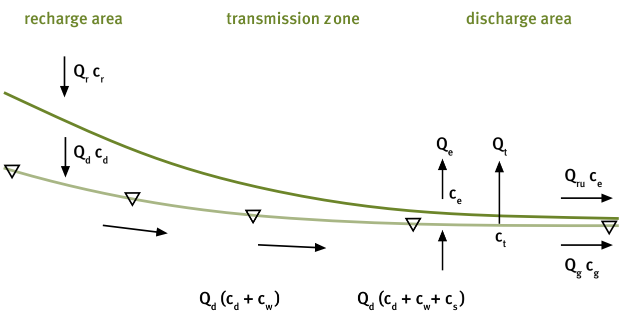


Figure 20. Diagrammatic section through a catchment indicating mass balance inputs and outputs (Shaw 1993).

where

Q_r	is	quantity of rainfall
Q_d	is	quantity of water draining below the root zone
Q_e	is	quantity of water evaporated from the soil surface in the discharge area
Q_t	is	quantity of water transpired by vegetation in the discharge area
Q_g	is	quantity of groundwater flowing away from the discharge area (subsurface outflow)
Q_{ru}	is	quantity of surface runoff across the discharge area
Q_s	is	quantity of surface seepage flowing away from the discharge area (including base flow in drainage lines intercepting the discharge area)
c_r	is	salt concentration of rainfall
c_d	is	salt concentration of the water draining below the root zone
c_w	is	salt concentration of the water attributable to rock weathering and dissolution
c_h	is	salt concentration due to the dissolution of historic salt storage in the discharge area
c_e	is	salt concentration due to salt on the soil surface resulting from evaporation
c_t	is	salt concentration in the root zone of vegetated areas due to transpiration
c_s	is	salt concentration of water seeping from the groundwater in the discharge area (including base flow in drainage lines intercepting the discharge area)
c_g	is	salt concentration of the groundwater flowing away from the discharge area (this is equivalent to the sum cd+cw+ch+cs).

Table 2 Expected range of values for parameters in Figure 20 for salt-affected catchments in southern Queensland. Each value is also expressed as a ratio of Q_d (quantity of water draining below the root zone in dominantly recharge areas) and cd (the concentration of this drainage water) as appropriate.

Quantity				Concentration			
Symbol	Range (mm/yr)	Typical value (mm/yr)	As a ratio of Qd	Symbol	Range (dS/m)	Typical value (dS/m)	As a ratio of cd
Q_r	300–2 000	800	27	c_r	0.02–0.2	0.003	0.1
Q_d	2–150	30	1	c_d	0.1–0.5	0.3	1
				c_w	0.1–1.0	0.6	2
				c_h	1–100	15	50
Q_e	100–2 000	800	27	c_e	1–500	30	100
Q_t	100–1 500	500	17	c_t	1–20	12	40
Q_g	variable	small	-	c_g	$\sum(c_d+c_w+c_h+c_s)$	10	33
Q_{ru}	50–200	100	3				
Q_s	very low	small	very small	c_s	c_g-c_c	10–30	33–100

Typical values

Ranges of values that can be expected in salt mass balances in southern Queensland have been compiled using information from salt-affected catchments in these areas (Shaw 1993). The catchments from which this information was gathered received summer-dominant rainfall of between 600 and 1000 mm/yr with class A pan evaporation of around 2000 mm/yr. These values are shown in Table 2.

From the data in Table 2, three processes stand out as contributing to salting: the mobilisation of historic salt, evaporation and transpiration. The mobilisation of historic salt can contribute 50 to 100 times more salt than rainfall. Evaporation from the soil surface and evapotranspiration by vegetation are significant processes concentrating salt as well as removing water from the catchment.

Rate of water movement in the landscape

The rate at which water moves through porous materials (soils or aquifers) in the landscape depends on the hydraulic conductivity of the material through which the water is flowing, the hydraulic gradient driving the flow, the area available for flow, and the period of flow. This is described by Darcy's Law (which expresses flow per unit area per unit time):

$$Q/A = K\Delta H \quad \textbf{2}$$

where

- Q/A is volume of water flowing through a unit cross-sectional area per unit time (example units are $m^3/m^2/day$)
- K is hydraulic conductivity of the porous medium (for example, m/day)
- ΔH is hydraulic gradient in the aquifer (for example, m/m).

Parameters

Hydraulic conductivity

Hydraulic conductivity refers to the property of a soil or other porous material to conduct water. Hydraulic conductivity is characteristic for different materials, and depends on the pore size distribution of the material's matrix.

The hydraulic conductivity of soils is quite variable and is greatest when soils are saturated. Rainfall entering a recharge area wets the soil.

The water content of the soil increases until the soil is saturated. At this stage, water can move directly through the macropores and may bypass part or all of the soil matrix. Macropore characteristics differ with soil types; for instance, macropores in swelling soils operate for only a short time until swelling reduces their size. Water drains readily from the soil until the water content approximates field capacity. At water contents less than field capacity, water movement usually becomes very slow (and is treated as negligible in the following calculations). The long-term (saturated) hydraulic conductivity of soils in significant recharge areas is in the order of 10 to 100 mm/d (0.01 to 0.1 m/d).

The hydraulic conductivity of an aquifer transporting water would be in the order of 0.5 to 10 m/d. In comparison, at a point in the catchment where salting occurs because groundwater flow is restricted, the hydraulic conductivity may be 10 times less (0.05 to 1 m/d).

Hydraulic gradient

The hydraulic gradient, the driving force acting on the groundwater, is the difference in hydraulic head between two horizontal points (usually points of recharge and discharge) over the horizontal length over which this difference occurs. In an unconfined aquifer, the hydraulic gradient is effectively the gradient of the watertable.

In a permeable soil, the vertical gradient driving recharge is mainly gravity; for every metre of saturated soil depth, there is a hydraulic head of 1 m resulting in a hydraulic gradient of 1 m/m. For water moving horizontally, the driving gradient is the slope of the watertable, so groundwater flow is much slower. The hydraulic gradient of water moving in the groundwater is commonly in the range of 1:100 to 1:1 000 m/m.

The transmission of actual water (or salt) molecules from the point of recharge to the point of discharge takes quite some time. For example, in the Burdekin Irrigation Area (left bank) in north Queensland, the hydraulic gradient is approximately 1:2 300 m/m (11 m difference in hydraulic head between recharge and discharge areas; 25 km from recharge area to discharge area, in this case, the sea). Employing Darcy's Law, a molecule of salt in this catchment would take in the order of 300 years to travel from the recharge area to the sea. (A rule of thumb for water movement through an aquifer is one to two metres per week.)

However, salting obviously occurs over much shorter time periods than this. This is because water added to the groundwater system as recharge transmits pressure in the groundwater to the discharge point; it is the equalisation of this pressure that causes the watertable to rise in discharge areas.

Based on these examples of the influence of gradient on water flow, most salting outbreaks will result from the mobilisation of historic salt moving vertically within the soil profile rather than the inflow of salt from naturally saline aquifers.

Area

The surface area of a catchment through which water enters the groundwater as recharge is often much larger than the area through which groundwater can flow out of the catchment. For example, a 1 000 ha catchment with developed salting may have restricted subsurface outflow through an aquifer perhaps 100 m wide by 5 m deep. Thus, potential recharge is occurring over a surface area of 10 x 10^6 m^2 (although not all recharge will be at high rates), whereas outflow is occurring through a cross-sectional area of 500 m^2.

Time period

In summer rainfall areas, soils are typically saturated for only a few days each year. For saturated hydraulic conductivity to operate, there must be free water at the soil surface to be conducted through the larger pores. This may occur for only two to five days each year. In comparison, a groundwater aquifer is saturated all year round and can conduct water every day of the year.

Table 3. Illustrative hydraulic parameters for a generalised salted catchment of 1000 ha, with bare or seepage areas establishing a hydrologic equilibrium between recharge and discharge.

Parameter (and units)	Symbol	Recharge	Subsurface outflow
Hydraulic conductivity (m/d)	K	0.006	10
Hydraulic gradient (m/m)	ΔH	1/1	1/100
Area (m^2)	A		
recharge = surface area		10 x 10^6	
discharge = cross-sectional area			5 x 10^2
Time period (d)	t	2	365
Volume of water		**120 ML/yr**	**18.2 ML/yr**

Interaction of parameters

In an unsalted catchment at hydrologic equilibrium, recharge will be balanced by subsurface outflow. However, in a salted catchment the rate of recharge will exceed the rate of subsurface outflow. The volume of outflow may be restricted by the cross-sectional area of the aquifer at the point of discharge or by reduced hydraulic conductivity.

Discharge areas develop only after the unsaturated soil water storage is filled and the watertable rises. The period during which the soil water storage becomes saturated provides the lead time that occurs between the initial hydrologic change and the subsequent development of discharge areas. This lead time can range from a few years to up to 50 years.

Table 3 shows generalised figures for a salted catchment of 1 000 ha (that is, 10 x 10^6 m^2) with, say, 10% of the catchment having a high recharge rate of 20 mm/d (0.02 m/d), 20% of the catchment having a lower recharge rate of 10 mm/d (0.01 m/d), and the remaining 70% having a low recharge rate of 3 mm/d (0.003 m/d), averaging over the recharge area to 0.006-m/d. In this illustration, subsurface outflow is likely to occur every day of the year, but recharge will only occur when the soil is saturated down to the watertable—perhaps only two days each year.

The difference between recharge and subsurface outflow (here, between 120 and 18.2 ML/yr) is the volume of water that the system must remove in other ways.

In this situation, the system will compensate and discharge will be increased via:

- increased surface seepage
- increased evaporation from a discharge area with a watertable near the soil surface (At an evaporation rate of 2 mm/d, 73 ML/yr of water will be removed from 10 ha of bare discharge area.)
- increased evapotranspiration from vegetated areas in a low salinity discharge area (due to increased vigour of growth in response to increased water availability).