2. SOURCES AND CONTROLLING FACTORS OF HYROSALINITY

High levels of dissolved salts make some of South Africa's rivers unsuitable as a supply source for growing crops. Major sources of saline water are municipal, mining and industrial effluents and seepage from waste disposal sites (DEAT, 1996). In the semi-arid parts of the country low precipitation, coupled with high evaporation, further increase the salt concentrations of both surface and groundwater resources. Identification of the various sources of salinity, the factors controlling it and knowledge on the interrelationships between sources and factors are most important for the development of a hydrosalinity model. This chapter, therefore, reviews the main sources and controlling factors of hydrosalinity.

2.1 Sources of Hydrosalinity

The main sources of hydrosalinity may differ from one area to another depending on governing environmental and social factors in that particular area. However, an assessment made by different researchers to identify the various sources has revealed the main sources of hydrosalinity to be rock and soil weathering, wet and dry atmospheric inputs, irrigation return flows as well as urban and industrial effluents. These sources can broadly be categorised into natural and anthropogenic sources.

2.1.1 Natural sources

Soil and rock weathering, as well as atmospheric inputs, are natural sources for most of the salts added to the soil solution and open water bodies. The weathering of parent material of soil or rocks, which includes hydrolysis, hydration, solution, oxidation and carbonation is reported to be the primary source of salinity in irrigation water (Michael, 1997a). Most rocks consist of an assemblage of minerals. The mechanism and rate of reaction of these minerals in the presence of water depends on how the minerals themselves react (Spears, 1986). Interactions between water and surrounding rocks involves reactions which generally include chemical weathering of rock forming minerals, dissolution-precipitation of secondary minerals and ion exchange between water and secondary minerals (Njitchoua *et al.*, 1997).

Atmospheric inputs can be of marine or continental origin and can be deposited as wet or dry inputs. Atmospheric inputs can vary according to the relative influence of major sources such as oceanic aerosols, continental dust, living and decaying vegetation and active volcanoes (Meybeck, 1983). Oceanic aerosols are the main contributors of atmospheric inputs, particularly in coastal areas (Walling and Webb, 1986). The common constituents of atmospheric inputs derived from continental sources include Ca^{2+}, NH_4, SO_4^{2-}, HCO_3^- and NO_3^-, while marine sources contribute Na^+, Cl^-, Mg^{2+} and K^+ (Raymond, 2001). Atmospheric inputs can greatly influence water salinity, especially when the rate of weathering is very low (Meybeck, 1983).

Different studies have reported the complexity of predicting atmospheric inputs based on atmospheric processes. First, it is difficult to trace the origin of most atmospheric salts, because they may be carried hundreds of kilometres from their sources (Johnston, 1993). Moreover, according to Walling and Webb (1986), the relative importance of atmospheric material removal mechanisms varies in response to change in droplet size distribution, atmospheric conditions, droplet life times and precipitation duration and intensity. Thus the complexity and variability of atmospheric input mechanisms make any attempt to model wet deposition from a knowledge of its component processes difficult. For above reasons it is common practice to use relatively simple empirical analysis of collected wet deposition samples mainly because of the easy measurement techniques which are available, compared to the more complex mechanistic approach which has proved less valuable in a predictive sense because of difficulties of obtaining all the input variables (Walling and Webb, 1986).

2.1.2 Anthropogenic sources

Return flows from irrigated lands as well as urban and industrial effluents are the main sources of hydrosalinity from anthropogenic influences. According to Johnston (1993), drainage effluent, especially from arid or semi-arid agricultural land, almost always contains some amount of dissolved mineral salts. These salts either originate in the irrigation water or the soil, or are present as a result of fertiliser application. The concentration of these salts increase as water is lost from soil and plants in the form of evaporation and transpiration. Water applied in excess of plant requirement dissolves and leaches the salts through either natural or artificial drainage systems.

Most irrigation water contains certain amounts of salt that generally range from 70 to 3500 mg/l (Luthin, 1997) and water uptake by plants and evaporation from the soil surface further concentrates the salt. Thus the salinity level of drainage water is usually higher than that of the applied irrigation water. The salt content of mountain streams increases as the streams pass through alluvial areas which receive water from upstream irrigation activities. Hence drainage water from agricultural lands always contains some amount of dissolved mineral salts and, according to Ayers and Westcot (1985), drainage systems are usually constructed without consideration of the adverse impacts on receiving surface waters. Therefore irrigated agriculture, especially in arid and semi-arid regions, is the primary diverter of water and donor of salts to water resources (Johnston, 1993).

Salinity problems in irrigation areas and in rivers can be exacerbated by poor management systems. For example, they can get worse by downstream irrigators having to use water already containing high salt concentrations, drawn from rivers which drain salt-affected dry land areas (NSW, 2000). The same applies to pumping from saline groundwaters.. Other major causes of irrigation salinity include over-irrigation of farmlands, inefficient water use, poor sub-surface drainage, irrigating on unsuitable or "leaky" soil, allowing water to pond for long periods and allowing seepage from irrigation channels, drains and storage (NSW, 2000). Thus the type of irrigation and leaching practices are likely to affect the salt contribution through subsurface return flows. For example, basin and border types of irrigation practices are reported to result in soluble salts moving through the soil with the irrigation water because of their relatively poorer efficiencies, and thereby increasing subsurface salt concentrations. Most subsurface return flow problems, however, result from unlined water delivery and drainage ditches (Seelig *et al.*, 2001).

Urban sewage and industrial waste effluents can also be significant sources of water salinity. Some industrial processes concentrate salts in the water they use. For example, in coal fired power stations water used for cooling is partly evaporated and concentrates the salt in the water discharged from coolers (NSW, 2000). Similarly, sulphate emissions from energy and industrial facilities cause an "acid rain" effect (Pegram and Görgens, 2001). Abandoned mines are also reported as major sources of salinity in some areas. Wiechers *et al.* (1996), from their research on Nigel Dam in South Africa, noted high concentrations of salts dominated by sulphate concentrations of up to 780 mg/l attributed to seepage from gold mines. Similarly, in more densely populated urban areas, the annual levels of stream chemistry are reported to reflect the varying effect of sewage inputs (Walling and Webb, 1986). An increase in sodium and chloride ion concentrations by 40 and 45 mg/l respectively, was reported by Wiechers *et al.* (1996) when direct discharge into Nigel Dam from sewage treatment works was commenced. Studies in the Vaal River Catchment in South Africa have also shown a similar rise of total dissolved solid concentrations from 125 to 700 mg/l in the period 1935-1980 (Furness, 1989). The increased salinisation of this river was mainly attributed to increased urbanisation and industrialisation. Industries and sewage works alone contribute about 35% of the total load entering the Vaal River (Cowan and Skivington, 1993).

2.2 Factors Controlling Hydrosalinity

The factors involved in hydrosalinity are highly inter-linked. The basic factors reported by various studies can, however, be broadly grouped into soil and geologic formations, hydrological and climatic factors, land use and land cover as well as topographic characteristics and time.

2.2.1 Soil and geologic formations

Certain soils and rock types are more likely to contribute to land and stream salinity problems than others because of their composition, texture, structure, location or other physical and chemical characteristics. For example, there is a high degree of association of salinity with certain classes of sedimentary rocks compared with that from other rock formations (Blackmorea *et al.*, 1999). A frequency distribution analysis of specific conductance level in relation to major rock types by Walling and Webb (1986) has shown a clear contrast of the distributions between most rock types. This was related to the varying susceptibility of the major rock types to chemical weathering. Weatherablity of a mineral depends on the basicity of the mineral, the degree of linkage of tetrahedrons, as well as structure and the degree of crystallinity and purity of the mineral (Michael, 1997a). The differences in major rock types not only affects the variation in the magnitude of total solute concentrations, as expressed by specific conductance, but also the balance between the concentrations of individual cations in receiving streams, as shown in Table 2.1.

Table 2.1 Influence of rock type on the average composition of world river waters (Meybeck, 1981)

Constituents	Average concentration (mg/l)		
	Plutonic and highly metamorphosed rocks	Volcanic rocks	Sedimentary rocks
SiO_2	1.5x	3.5x	x
Ca^{2+}	4	8	30
Mg^{2+}	1	3	8
K^-	1	1.5	1
Na^-	Oceanic influences dominant		
Cl^-	Oceanic influences dominant		
SO_4^{2-}	2	6	25
HCO_3^-	15	45	100

NB. x denotes average SiO_2 content of water from rivers draining sedimentary rocks at a given temperature.

Furthermore, even small-scale changes in bedrock geology can have a large impact on stream water chemistry. For example, according to Billett *et al.* (1996) and Raymond (2001), parent material such as evaporites or carbonates, which on a catchment scale may be spatially insignificant, will have a disproportionally large effect on stream water chemistry (Table 2.2).

Table 2.2 The influence of rock type on dissolved river loads (Raymond, 2001)

Rock Type	World Outcrop Area (%)	Dissolved River Load (%)
Crystalline igneous and metamorphic	34.0	12.0
Evaporites	1.3	15.0
Carbonates	16.0	50.0

The physical characteristics of geological formations also affect the movement of water and dissolved solids to receiving streams. Frequently, discharge points will first appear where there is a change in rock type or along a fracture (NSW, 2000). Moreover, according to Blackmorea *et al.* (1999), groundwater movement is usually independent of local landforms, being determined more by the regional rock structures. Thus, in the presence of saline groundwater, these factors can make important contributions to the processes involved in water salinisation. Similarly the chemical and physical properties of a soil can also influence water salinity both in terms of composition and movement of draining water. For example, Rhoades *et al.* (1997) have observed greater increases in salt concentration of irrigation water as it flowed across heavy textured soils with large cracks and fractures than across non-cracking soils. However, in order to simplify calculations of water losses below the root zone, some researchers assume that the amount of water that flows directly below the root zone through the cracks (by pass flow) in cracking soils does not contribute to leaching (for example, Crescimanno *et al.*, 2002).

2.2.2 Hydrologic and climatic factors

Hydrologic and climatic factors are the major factors that control water salinisation. The following sections review some of the factors grouped under these categories, on how they influence water salinisation.

2.2.2.1 Rainfall

Rainfall is the fundamental driving force and pulsar input to most hydrological processes (Schulze *et al.*, 1995c), resulting also in water quality impacts from non-point sources (Pegram and Görgens, 2001). Rainfall plays a major role during wet atmospheric deposition. Flügel (1987) has suggested that rainfall salt input could account for about 10 to 20% of the total salt output measured in the Sandspruit River, South Africa. Similarly, Michael (1997b) has reported a positive correlation between rainfall depth and chloride content in coastal stations of the UK. According to Gibbs (1992), the chemical composition of low-salinity waters is controlled by the amount of dissolved salts furnished by precipitation. This principle has been observed in moorland areas, where there are low solute inputs from weathered local material. In these areas seasonal variation in stream solute concentrations are strongly related to annual variations in the chemistry of incoming precipitation (Walling and Webb, 1986).

Under certain circumstance rainwater composition can play a substantial role in rain-derived flood and mineral chemical interaction. Generally, according to Nativ *et al.* (1997), in rainwater the concentrations of sodium are higher than those of potassium. Sodium ion is more electronegative than potassium and thus there is a higher affinity of this ion to be absorbed by the soil particle surfaces as compared to potassium. It was suggested, therefore, that sodium could be sorbed from the rain-derived floodwater on to mineral surfaces releasing sorbed potassium to the floodwater and thereby affecting the composition of receiving streams.

2.2.2.2 Irrigation water

The volume of irrigation water is also a key management issue for proper salinity control in irrigated areas. According to Tedeschi *et al.* (2001), over-irrigation is the main cause of two alternative negative scenarios: (1) areas with limited drainage experience rising water tables, "evapoconcentration" of water and soil salinisation, and (2) areas with unlimited drainage result in deep percolation of surplus water, mineral dissolution, mobilisation of salts and salinisation of the receiving subsurface and surface water bodies.

2.2.2.3 Total evaporation

A reduction in water content of the soil in the field at water contents below drained upper limit (DUL) and consequent increase in salt concentration would normally arise from evaporative drying, either as a result of evaporation from the soil surface, or due to water uptake by plant roots in response to transpiration by the leaves (Johnston, 1994). Different studies have shown the presence of some chemical constituents in irrigation and rainwater and the loss of this water through evaporation from the soil and vegetation tends to increase salt concentration. Irrigation water drawn from surface or groundwater sources can typically contain 200 to 2000 mg/l of salts (Aswathanarayana, 2001). Dissolved solids are added to agricultural land by way of irrigation and rainwater. However, neither surface water evaporation nor absorption by plants appreciably reduces the amount of these salts added to the soil (Kay, 1986). Rather, the continuous upward movement of water from a subsurface system results in salt accumulation near the soil surface as water is lost by evaporation (Hoffman *et al.*, 1990). An increase in evaporation can also cause a lowering of the water table during the day time hours. This, in turn, can result in a daily cycle of accumulation and re-dissolution of soluble materials (Walling and Webb, 1986).

2.2.2.4 Runoff volume and flow components

Different researchers have noted the rise of salt concentrations during periods of low flows and a corresponding decrease during high flow periods. Kelbe and Germishuyse (1999), for example, have noted a drop in electrical conductivity of runoff immediately as discharge rates started to increase. The conductivity of runoff reached a minimum value at almost the same time as the peak flow occurred. However, according to Datta (1983), there may be a lag or lead effect in the drop of TDS concentration after or before a rise in discharge. Usually the trough in solute concentration in water progressively lags behind the peak of water discharge as the flood hydrograph moves downstream.

Several natural and anthropogenic factors can influence hydrosalinity through their effect on reducing the levels of flow. Increasing regulation of river flows and the abstraction of water for consumptive uses are some of the aggravating anthropogenic factors resulting in a decrease in natural flushing of salts out of a particular catchment. Irrigation practices reduce the diluting flows of natural runoff. The use of water for irrigation not only reduces dilution flows, but also speeds up the rise in groundwater levels, bringing salts to the surface and increasing salt flushes to rivers (Blackmorea *et al.,* 1999).

Unlike the relationship between TDS concentration and runoff volume, a positive correlation exists between salt load and annual runoff. According to Crabtree (1986) this can be partly explained by the increased rate of salinity related chemical reactions with increased water availability. High runoff volumes result in increased moisture availability, this in turn provides an increase in the total quantity of dissolved material released or available for transport. Moreover, the erosive power of high runoff volumes may also cause an exposure of saline subsoil and consequent washing away of solutes to watercourses (NSW, 2000).

One of the main reasons for the difference in solute concentrations of high and low flows, with a mainly inverse relationship between flow volume and salinity, are the different sources of runoff components contributing to the total flow. During low flows runoff is generated from the lower soil profile and the groundwater reservoir and has a relatively high concentration of dissolved solids (Walling and Webb, 1986). Ferguson *et al.* (1994) suggest that the pathways are slow through soil and rock in low flow conditions and faster near or over the land surface during rainfall events and floods. Thus the longer residence time of slow–moving groundwater allows solute enrichment. On the other hand, during high flow much of the runoff is translated rapidly to the channel and has little opportunity for solute pickup. It is this variable mixture in the stream of enriched "old" water and more diluted "young" surface water that leads generally to an inverse relationship between solute concentration and water discharge.

As a rule runoff components reflect the pathway of water. Thus, variation of solute concentrations in runoff water occur as a result of the changing contributions of the different pathways. Although, the soil chemistry of deeper mineral soils is strongly influenced by the underlying geology, this influence becomes less evident on receiving streams at high flows as water flow paths become increasingly dominated by surface and subsurface flow passing through organic top soils (Billet *et al.* 1996).

2.2.3 Land use and land cover

Land use and development in a catchment can have a significant impact on the quantity and quality of the surface and groundwater resources (Pegram *et al.*, 1998). In most areas of Australia, for example, increased salinity was found to result from a particular land use practice such as deforestation, urban development, river regulation, irrigation or cultivation of crops and pasture (NSW, 2000). The effect of land use on salinisation is mainly associated with intensive use and re-use of water as a result of increasing urbanisation, industrialisation, mining and irrigation (Furness, 1989). Some researchers have also reported the role of land use on hydrosalinity through its effect on dry and wet atmospheric deposition, weathering and other sources of salinity (for example, Walling and Webb, 1986).

Any land use practice which allows excess moisture to migrate downward through the soil profile beneath the root zone, can contribute to the rise of the groundwater table and consequent formation and growth of dry land salinity (Johnston, 1993). Trees and shrubs consume more water than annual crops and grasses. Moreover, because of their deep rooting system, they usually extract water from greater depths. Research in high rainfall areas (more than 600 mm per annum) of the Murray-Darling basin in Australia has shown that land use change from native vegetation to grazing land has increased the amount of water entering the groundwater system by 10 mm per annum (Blackmorea *et al.*, 1999). The same authors have also reported that the "leakage" rate for grazing areas in medium rainfall areas is two to three times greater than under woodland vegetation. Similarly, an increase in amount of water entering the groundwater system as a result of removal of vegetation for urban development has been reported by NSW (2000). The entrance of this additional water into the groundwater system leads to an accumulation of soluble salts at or near the surface along with the rising water table (Johnston, 1993). As to the effect of fallow land, Miller *et al.* (1981) suggest that most soils store limited amounts of water in the root zone during a fallow period. Thus, once recharged by precipitation, any additional water entering the soil moves to the water table and may appear downslope as a saline seep. Generally the basic cause of dryland salinity in Australia is clearing of natural vegetation for agricultural land use (Hillman, 1981). Once dry land salinity is developed, leaching of salts stored in the landscape causes serious problem on the quality of water resources.

Management practices associated with certain land use types can also influence hydrosalinity, depending on whether the particular land use or management practice has soil disturbing or stabilising effect. According to Collins and Jenkins (1996), higher weathering rates as a result of soil tillage practices in agricultural lands can promote high concentrations of base cations. Some studies have indicated the existence of a strong contrast in solute level of streams draining from agricultural land and other land uses, which are less disturbed by agricultural practices. For example, Walling and Webb (1986) noted a progressive decline in total solute level with increase in percentage of moorland cover from 50% to 90% (Figure 2.1 a), with a subsequent shift in the composition of water from Ca^{2+} and Mg^{2+} (mainly as a result of weathering) to Na^{+} and K^{+} (mainly as a result of atmospheric input) as major constituents (Figure 2.1 b). This phenomenon is associated with the lower soil disturbing effects of moorland compared to those of agricultural lands. The addition of mineral fertilizers on drainage basins can also result in an elevated concentration of some solutes on the receiving streams draining agricultural lands.

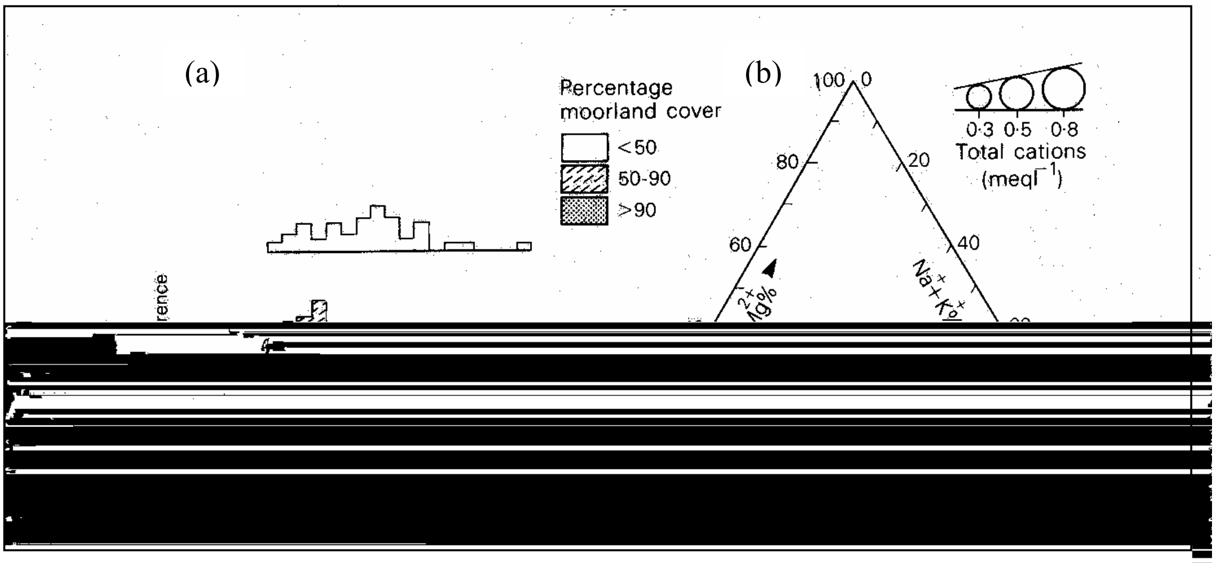

Figure 2.1 The influence of land use on (a) specific conductance levels and (b) cation composition of streams (Walling and Webb, 1986)

Depending on their type and size, plants can play a significant role in the solute balance of soil water and receiving streams through their uptake, storage and release mechanisms. Thus, according to Meybeck (1983), not all the solute inputs from weathering or other sources necessarily reach the watercourse. In some ecosystems and for some elements, the stream output may be less than these inputs from the atmosphere alone, or from atmospheric and weathering sources together. For example, Froehlich (1983) has observed a difference in calcium concentration from 3.6 μeq/l in rainwater to 1.9 μeq/l in stream water mainly as a result of plant accumulation. Solutes may accumulate either as surface deposits on vegetation surfaces or as labile ions within plant bodies. The passage of rainfall through a vegetation canopy thus considerably modifies the solute concentration of receiving streams by washing off surface deposits from vegetation surfaces or by the leaching of labile ions and compounds from within as a result of mineralisation (Foster *et al.,* 1983).

The type and nature of land cover also have a significant influence on dry and wet atmospheric deposition. For example, the capture of hill cloud by forests is observed to be an important deposition pathway for marine ions (Reynolds *et al.*, 1997). The nature of the surface is very important in dry atmospheric deposition. Its configuration, roughness, wetness and chemical characteristics have all been reported as affecting dry deposition rates. Thus the rough surface presented by a forest associated with high wind speed and frequent wet surface conditions increases the capture efficiency of the vegetation for particles and small droplets

(Cryer, 1986). According to Kinross (2001), this is one of the main factors in the apparent change in chemistry of lakes and streams in some afforested upland areas.

2.2.4 Topographic characteristics

Various reports have indicated that topographic characteristics of a drainage basin, including slope, size and elevation can influence the release, transportation and deposition of solutes, thereby influencing land and stream salinity. Meybeck (1983) has reported a ten-fold decrease in chloride concentrations of streams at similar distances from the sea but which vary between 100 and 150m in mean altitude. This observation was attributed to the combined effects of variation in both the water budget and concentration of chloride in precipitation at higher and lower altitudes. Similarly, Walling and Webb (1986) have identified a positive correlation between catchment slope and stream salinity. Both stormflow and baseflow salt concentrations are dependent on basin area. Dissolved solutes in surface runoff increase proportionally with increase in basin area (Froehlich, 1983). Similarly, the conductance levels of baseflow was reported to rise with increasing catchment area until a threshold size of approximately 2 km^2 is attained. However, solute levels are observed to be independent of basin scale beyond this threshold catchment size (Walling and Webb, 1986). High stream density is also noted to increase delivery ratios for eroded material as well as creating opportunities for stream bank erosion and consequent increases in concentrations of some solutes (Archeimer *et al.*, 1996).

2.2.5 The effect of time

The release, transportation and deposition of solutes are also subject to temporal influences and are reflected in annual, seasonal and even storm period cyclic variation of dissolved solid concentrations. Kelbe and Germishuyse (1999) have noted solute concentrations showing an initial rise with increasing flow for a rainstorm following prolonged dry conditions. On the other hand, a series of closely spaced and similar high discharges exhibit progressively lower total dissolved solute concentrations (Figure 2.2). Similarly, Loah and Stoikes (1981) observed major salinity fluctuations as a result of different sequences of flood and drought years on partially cleared catchments, which far outweighed the long term increases caused by clearing. This reflects a temporary exhaustion in the supply of soluble salts from the same sources during the sequence of events (Froehlich, 1983).

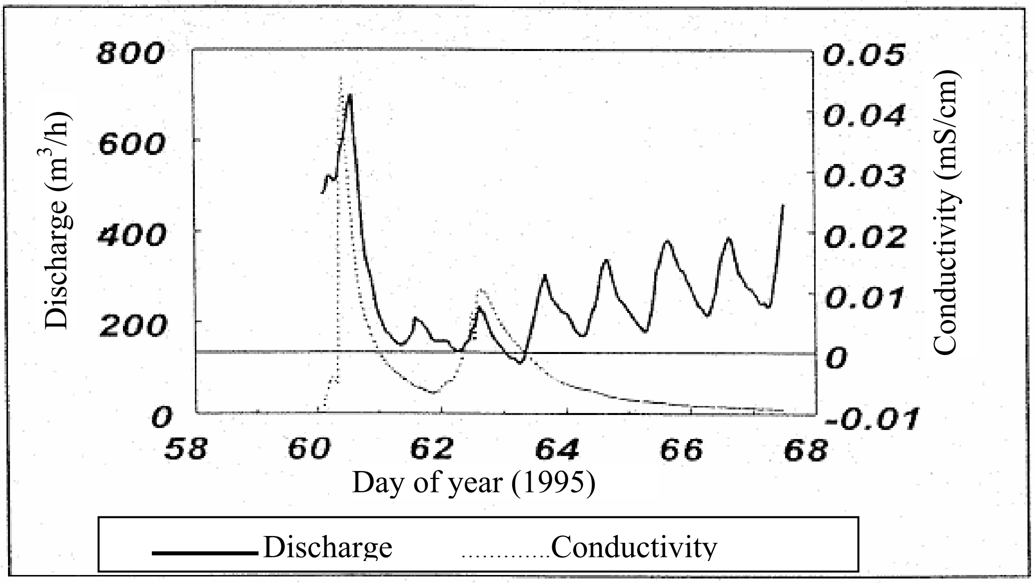

Figure 2.2 Changes in conductivity following prolonged drought conditions (after Kelbe and Germishuyse, 1999)

Temporal variation of water salinity can occur as a result of the various sources of flows contributing in different seasons of the year. According to Davis and Keller (1983), in some areas this temporal variation may reveal underlying seasonal influence on the varying contribution of water from rain, snowmelt and groundwater during the course of the year. Since each of these sources has a markedly different range of solute concentrations, it may be considered a logical consequence that cyclic behavior will also characterise the concentration of most solutes found in stream water. For example, Walling and Webb (1986) have reported that, rivers characterised by very low solute concentrations and dominated by atmospheric solute sources occasionally show a positive salinity–flow relationship, since in this situation maximum dissolved solute concentrations may occur during storm events.

This chapter has reviewed the major sources and factors that control the release, transport and deposition of salts from various sources. Despite the fact that most of these sources and processes of hydrosalinity are highly interrelated, knowledge about the main sources and how the dominating processes influence water salinity is vitally important for the development of hydrosalinity models. The next chapter deals with the basic approaches used to describe salt movement from the soil surface through the subsoil to groundwater and stream flows as well as reservoirs as conceptualised in different hydrosalinity models.