Chapter 3

What is biodrainage, how does it work?
Issues related to its implementation

A range of issues is presented in this chapter associated with the design and management of biodrainage systems. In considering their long-term viability, biodrainage systems will have to be subjected to the same scrutiny as other plant-based biological systems with regards to nutrient and salt-balance, soil considerations, etc. Moreover, as large-scale adoption of biodrainage crops could include considerable tracts of land, socio-economic considerations will have to be taken into account when considering the adoption of this technique.

3.1 Scientific basis of biodrainage

In natural environments the components of the hydrological system, i.e. rainfall, evapotranspiration, change in soil-water storage and drainage, are (on average) in balance. Periods of high rainfall might temporarily result in increased drainage flows, a rise in the groundwater table and/or soil moisture storage, then over a period of about 5-10 years equilibrium is established. Vegetation plays a vital role in the evapotranspiration and soil-water storage components of this balance.

When natural vegetation is cleared and replaced by crops or tree plantations, the seepage losses to the groundwater table under the new land use system are either higher or lower than under the pre-clearing situation.

The increased seepage scenario prevails and the development of land for either rainfed or irrigated agriculture generally increases groundwater recharge rates; the new landscape systems “leak”!

Where this increased recharge results in shallow water tables, evaporation at the soil surface causes groundwater to move upwards through the soil, and consequently salts accumulate in the rootzone, limiting plant growth. Although this process has occurred gradually throughout history, it is currently adversely affecting extensive areas of the North American, Asian and Australian continents. For example in Australia, the area of shallow, saline water tables is expanding rapidly (Robertson, 1996; Western Australian Government, 1997) in response to widespread agricultural development over the past 50-100 years.

An example of increased recharge after clearing is presented by Allison and Hughes (1983). They showed that in a semi-arid region in southern Australia (average rainfall 250-300 mm/yr), the recharge rate beneath native Eucalyptus spp. was <0.1 mm/yr. Recharge was found to increase significantly to between 5 and 30 mm/yr following clearing and subsequent cropping. Management solutions to the problem of excessive recharge are being developed, based on improved water use efficiency of the agricultural systems.

The reduced seepage scenario, although less publicised, does also occur. Vertessy et al. (1996) studied the hydrology of mountain ash (Eucalyptus regnans) forest in a high-rainfall environment in southern Australia and analysed relationships between forest age and runoff volumes. Old-growth forest yielded up to twice as much annual runoff as younger re-growth forest. The same process was observed in a mixed-species forest in a drier catchment (www.catchment.crc.org.au). The driving mechanism behind this process is leaf area index, which was highest between the ages of 30 and 40 years. The findings have important consequences for the management of the catchments, which are used for water harvesting for urban water supplies. For these areas, long harvesting rotations are obviously preferred to obtain maximum runoff yields.

Plantations of fast growing tree species such as eucalyptus, when grown on previously cleared land, could also result in strongly reduced accessions to the groundwater and in the drying-up of wells and springs.

The driving force behind the biodrainage concept is the consumptive water use of plants. Early studies in Australia (e.g. Greenwood et al. 1985) suggested that the rates of transpiration and groundwater uptake by trees underlain by relatively shallow (5-8 m below surface) water tables, were very high, exceeding the annual evaporation from pasture (~400 mm) by a factor 3-6 (1 200-2 300 mm/yr). These results, coupled with a growing interest in timber production in Australia, led to the popularity of the tree-based water management strategy for agricultural areas. However, results obtained by the
measurement technique used by Greenwood (ventilated chambers) have been challenged and later work suggests more modest water use figures with potential stand water use approximating standard Class A pan evaporation. For example, Morris et al. (1998) found that *Eucalyptus camaldulensis* and *E. grandis* grown on a shallow saline water table both used approximately 300 mm per year. They also stated that the plantation’s ability to transpire groundwater is reduced where the groundwater table is drawn down in soils of low hydraulic conductivity.

Potential water use differences between species are also a topic of discussion. Hatton et al. (1998) recognized the need to generalize water use behaviour of Eucalypts to facilitate landscape management processes in a wide range of Australian environments. They concluded that the leaf efficiency of sympatric Eucalypt species in soil water-limited systems is similar, i.e. there was a strong linear relationship between tree leaf area and mean daily water use for a wide range of Eucalypt species grown under similar climatic conditions. Meyers et al. (1996) arrived at the same conclusion for non-water limited situations, stating that species (including *Pinus radiata*) with unrestricted access to water have similar rates of water use at similar stages of canopy development.

One of the major factors determining the sustainability of plant productivity (and thus plant water use) processes is salt balance. If the salts moving into the rootzone are not either (1) taken up by the vegetation and harvested or (2) removed from the rootzone by leaching, the vegetation is doomed to succumb to salinity. The general concept of salt balance is described in a large number of irrigation textbooks. These mostly focus on the water and salt balances and do not take into account nutrient balances and whatever salt uptake may take place with crops. Therefore, as salt balance considerations are crucial to the viability of biodrainage, a more detailed discussion of the issue as it relates to biodrainage will be presented in Section 3.4.

The deep-rooting characteristics of trees make them extremely efficient users of water. While shallow-rooted grasses and crops have limited access to underlying water tables, deep-rooted trees can access water tables down to several metres. The case studies in Chapter 5 present a number of scenarios. Also, in recharge situations with deep water tables, the deep root systems of trees greatly reduce the opportunity for rainfall/irrigation accessions to the water table.

An important consideration when discussing biodrainage issues is the definition of “water table”.

The water table can be defined as “the upper surface of a zone of saturation, where the body of groundwater is not confined by an overlying impermeable formation”. The depth of the water table is measured in observation wells. In contrast, piezometers record pressures at a specific depth in the soil profile; they are often installed in aquifers for faster response to changes in pressure. Where the water table, as measured in observation wells, is perched, leakage through an underlying slowly permeable layer can provide a means of salt export to deeper formations in the profile. Perched groundwaters are typically shallow, small in extent and often fresh (e.g. George et al., 1997). The distinction between water tables and piezometric pressures should be kept in mind when analysing soil water movement under vegetation.

### 3.2 Possible Biodrainage Scenarios

Biodrainage processes can be classified based on land use context. In this publication the authors have distinguished between dryland/rainfed and irrigated land use systems, considering the following biodrainage management mechanisms:

**Dryland/rainfed systems:**
- Recharge control
- Groundwater flow interception
- Discharge enhancement

**Irrigated systems:**
- Water table control
- Channel seepage interception
- Biodrainage cum conventional drainage systems

**Rainfed systems**

A major problem with biodrainage (as opposed to conventional drainage) in rainfed conditions is that plant water requirement is generally low during cooler winter periods with high rainfall. So there is a delayed drainage response to rainfall inputs with the soil reservoir filling over winter and being depleted by vegetation water use over summer, thus creating a storage buffer to accommodate the next rainfall season.

Non-irrigated biodrainage plantings can be designed for different purposes as described in the following sections (Figure 1).

**Recharge control (Figure 1a, Photo 1)**

The sustainability of natural environments relies on the balance between recharge and discharge or hydrological balance; water fluxes passing beneath
the rootzone of vegetation communities are laterally discharged through regional subsurface aquifer systems. Where vegetation is changed by agricultural ‘development’ (clearing) and crops with lower annual water use and/or shallower root systems are planted, recharge increases. As the conveyance capacity of the underground aquifer system is often not high enough to accommodate the increased recharge volumes, groundwater tables rise and cause waterlogging and salinization.

Often the clearing of vegetation in the higher areas of the landscape results in increased recharge, followed by the formation of shallow water tables in the lower areas of the landscape. Water tables in the recharge areas are too deep to be accessed by vegetation root systems, and plants in these areas rely on rainfall for their evaporative requirements. The process to minimize deep seepage losses in the higher parts of the landscape to minimize discharge problems down-slope is often referred to as recharge control. Re-vegetation of recharge areas is a major tool in the fight against dryland salinity in Australia. Often only relatively small proportions of the landscape have to be planted to achieve the objective of reducing localized salinity discharge problems in the lower part of the landscape (see Photo 1).

However, re-vegetation of recharge areas can also have negative effects. Where the evaporative capacity of the new vegetation exceeds the pre-clearing evaporative demand, the landscape ‘dries out’. This scenario is often encountered in catchments covered by newly established fast-growing plantations. It is an example of an over-designed recharge-control biodrainage system and could cause problems such as reduced river flows, the drying-up of wells and increasing groundwater salinity.
What is biodrainage, how does it work?

Groundwater flow interception (Figure 1b)
Break-of-slope, (where the slope ‘breaks’ from convex to concave) plantings have been promoted as flow interceptors for areas where groundwater flows through permeable layers overlying low-permeability strata. By tapping these layers at some point down the slope, where the quality is still relatively fresh, the trees are considered to intercept these flows and thus reduce discharge problems further down the slope. Location of the tree plantations, based on a thorough understanding of the underlying stratigraphy, is extremely important if this concept is to work. Photo 2 shows a break-of-slope planting of two-year-old blue gums (*Eucalyptus globulus*) in northern Victoria, Australia.

McJannet *et al.* (2000) discuss a trial planting site in northern Victoria, Australia. The local geography is dominated by acid igneous lavas, draped with thick colluvial deposits which under the plantation are about 10 m thick, with thinner deposits up-slope and thicker ones down-slope. A fresh shallow aquifer system flows through the colluvium. The water table under the plantation was deep (about 9 m below surface upstream of the site and increasingly shallow downstream from 6 to about 4 m below surface). The authors conclude that under the site’s deep water table condition, the break-of-slope tree plantation did not behave in the predicted manner. They highlight the need to design such systems carefully, taking into account factors such as up-slope catchment area, net recharge, profile stratigraphy, water table quality and depth to water table.

Discharge enhancement (Figure 1c)
Low-lying landscape units with shallow water tables often serve as local discharge areas. Where these areas have drainage outlets and seepage flows discharge into rivers, *salt balance* is provided.
Where the depressions are land-locked (closed basins) and percolation to deeper aquifers is inhibited, salinization of the landscape unit is inevitable.

The use of biodrainage in waterlogged discharge areas is based on the concept of enhanced evapotranspiration. The long-term sustainability of biodrainage in this environment is a topic of intense debate. Smedema (1997) highlights this in his short topic paper. He suggests that biodrainage could be considered for waterlogged landscape depressions and canal seepage interception, and could be applied in ‘parallel field drainage’ arrangements as an alternative to conventional field drainage systems. In Australia it is now widely accepted that in discharge situations, enhanced evapotranspiration biodrainage sites will eventually succumb to salinity, unless some form of conventional drainage is installed to control salt balance to the vegetation’s rootzone by removal of saline drainage effluent (Heuperman, 2000). Photo 3 shows a deforested hill in northern Victoria, Australia with salinity problems in the lower parts of the landscape.

Plants can use water both from the unsaturated part of the soil profile above the water table and from the saturated part below the water table. Plants in the latter category are called phreatophytes. They often (but not always) grow in (semi) arid climates where they tap deep water tables. Van Hylckama (1974) reports on mesquite (Prosopis) growing in desert washes in the southeastern United States where the groundwater is sufficiently shallow that seedlings can occasionally produce deep enough roots to reach the water table in wet years. In that same area the introduced phreatophyte Tamarix has lowered the water table to such a low level that other species with shallower rooting depths are being eliminated.

One special application of the biodrainage concept is the amelioration of waterlogged soils during the initial reclamation or ripening phase of ‘new’ land development. Vegetation with a vigorous, deep and extensive root system is used to dry out waterlogged soil profiles. For example, in the Netherlands land to be reclaimed from the sea is sown with reed while a few centimetres of water remain. This accelerates the ripening process. Another example of draining fully waterlogged land is quoted by Allender (1990) who states that Eucalypts were successfully used during the nineteenth century to drain the Pontine Swamps near Rome, a region that had been a malarial swamp since Roman times.

**Irrigated systems**

In landscapes with undulating topography, recharge and discharge areas are often relatively easy to delineate. Recharge occurs at the higher parts of the landscape and discharge lower down the slope. In irrigation areas, with their flat topography and (often) shallow water tables, the distinction between recharge and discharge is less clearly delineated and frequently areas that are discharging groundwater by evapotranspiration between irrigation events temporarily turn into recharge areas during and immediately after irrigation.

**Water table control**

Shallow water table levels pose a threat to agricultural crops as they often result in salinization of the plant rootzone. The management of irrigation areas often aims to keep water tables below the critical depth, which is defined as the depth at which capillary salinization is negligible.

Sustainability of irrigation is determined by the leaching capability of soils. To avoid salinity problems, the salts present in the irrigation water will have to be removed from the rootzone by leaching them either laterally to adjoining non-irrigated areas or streams or vertically down to levels below the vegetation rootzone.

Plants can remove water from the soil either (1) directly from the saturated zone below the water table, (2) from the unsaturated capillary fringe above the water table or (3) from unsaturated topsoil layers after rainfall or irrigation. Scenarios (1) and (2) result in water table control; scenario (3) recharge control. In scenario (3) leaching is unimpeded; when water application exceeds plant water demand, leaching will take place. In scenarios (1) and (2) leaching becomes restricted and salt accumulation processes begin to occur. This happens especially where water tables are shallow, as is often the case in irrigation areas. A final equilibrium salinity level will establish, depending on applied water salinity, soil hydraulic conductivity, hydraulic gradients (vertical and lateral) and vegetation type (salt tolerance).

In Chapter 5 there are a selection of biodrainage case studies that describe water table control in irrigation areas.

**Channel seepage interception**

Channel seepage can be a major contributor to water table accessions in irrigation areas. High seepage rates will result in groundwater mounds beneath
channels, causing waterlogging and salinity problems in the adjoining land. Water quality in supply channels is normally good and the seepage water, if not left to evaporate and increase in salinity, can be productively used by vegetation and commercial crops. The issue of salt balance, although less critical than for more saline groundwater situations, is still a matter of long-term concern. The issue is discussed in detail in some of the literature references in Chapter 4 and the case studies in Chapter 5 and in Section 3.4.

**Biodrainage cum conventional drainage systems**

Biodrainage crops are no exception to the basic rule that irrigation, or for that matter plant growth, is not sustainable without some form of rootzone salt balance. Where biodrainage results in salt accumulation, engineering assistance is needed to make the system sustainable. The issue of salt balance is discussed in detail in Chapter 3.4 and a number of biodrainage cum conventional drainage scenarios is presented in Section 3.3 and Chapter 5.

### 3.3 Principles of planning and design

The aim of biodrainage is to remove excess groundwater through the process of transpiration by vegetation. This is achieved by enhancing the transpiration capacity of the landscape by introducing high-water use vegetation types in large enough areas to balance recharge/discharge processes to maintain groundwater balances below the rootzone of the agriculture crops. The following issues should be considered in the development of biodrainage systems:

i. **Water balance:** Biodrainage plantations should be able to extract groundwater volumes equal to the net recharge. The water balance is to be maintained such that the water table is kept below the rootzone.

ii. **Plantation area:** The biodrainage plantation area should be kept as small as possible. Agriculture (particularly irrigated agriculture) is practised primarily to produce high-value crops. Conversion of high-value cropping land to relatively low-return forestry may be difficult. Often good quality water is in short supply while land is not a limited resource. Particularly in arid and semi-arid regions, dryland areas surrounded by irrigated land could be earmarked for tree plantations without loss of productive resources.

iii. **Salt tolerance:** Biodrainage crops need to be salt tolerant. Groundwater qualities can vary greatly spatially, normally they have a higher salinity than irrigation supplies. The water use capacity of trees and other crops decreases with increase in water salinity. In the case of Eucalypt species, it reduces to about one-half of potential when the water salinity increases to about 8 dS/m (Oster et al. 1999).

iv. **Drawdown of water table:** Crops, including trees, act as biopumps; they depress the water table directly underneath plantation areas and consequently lower the water table in the surrounding area. The drawdown effect under trees/crops depends on the tree/crop’s water use, the rate of recharge in the surrounding area, the hydraulic conductivity of substrata and the depth to deeper barrier layers. Biodrainage plantings should be established in blocks or strips and spaced to keep water table levels in the irrigated farmland in between the plantings below the rootzone. The harvesting of the biodrainage plantations would need to be planned in such a manner that the “drainage” function is not lost (thinning regimes).

v. **Salt balance:** The introduction of irrigation always upsets the salt balance. Although irrigation supplies often have relatively low salinities, the large volumes of water that are introduced in the landscape increase salt imports significantly. Drainage of effluent to export these salts is therefore generally considered a necessity. To achieve salt balance without conventional drainage, the irrigated crops, along with interspersed biodrainage plantings, would have to accumulate the salts introduced by irrigation, and would subsequently have to be harvested and removed from the region. This is only (potentially) achievable in situations where very low-salinity water is available to the plants.

vi. **Economic aspects:** The growing of biodrainage trees and crops requires a different operational management approach than the growing of agricultural crops. Up-front costs associated with planting and maintenance precedes the income from harvesting by many years. Some form of contract growing, based on annual payments might have to be considered to make the system acceptable to landholders.

vii. **Social acceptance:** The introduction of new crops such as tree plantations affects rural social societies. New markets might have to be developed, security arrangements differ from
those for normal crops (illegal pruning or cutting for fuelwood) and fires could destroy the results of many years of labour in a single day. Active participation of local communities in the development of tree plantation-based biodrainage systems is extremely important to overcome problems and ascertain that the benefits of the biodrainage systems are reaped to the maximum extent.

Some of the issues related to the design of biodrainage systems are discussed in more detail below.

**Design considerations for biodrainage**

**Comparison of drainage methods**

A range of issues has to be considered before an appropriate drainage technique can be selected. In Table 1 biodrainage is compared with conventional drainage techniques and various factors that should be considered in the selection of the appropriate technique are summarized.

**Tree water use**

Often fairly dependable data are available on the rate of evapotranspiration from standard crops (ET<sub>o</sub>) and the rate of evaporation from a free water surface in a pan of standard size such as a Class A pan which is generally 1.15 to 1.20 times of ET<sub>o</sub> (Allen et al., 1998).

Tree plantations often use water at higher rates than shorter vegetation types. This is for three reasons: (1) the high aerodynamic roughness of forests leads to greatly enhanced evaporation rates, which on an annual basis can be as much as twice that for grass; (2) this effect may be even more pronounced because of the so-called clothesline effect prevailing in rows of trees, substituting for a conventional drain pipe; (3) deep root system of trees with access to good-quality groundwater leads

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**Table 1: Comparison of drainage methods**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Horizontal drainage</th>
<th>Conventional Drainage method</th>
<th>Vertical drainage</th>
<th>Biodrainage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency and dependability</td>
<td>Well tested method</td>
<td>Water table control</td>
<td>Reclamation of waterlogged area</td>
<td>Tried and tested at many locations with success</td>
</tr>
<tr>
<td></td>
<td>Neatness of outfall</td>
<td>Local salinity control effective if disposal available</td>
<td>Water table control</td>
<td>Not presently adopted as large-scale drainage method on irrigation projects</td>
</tr>
<tr>
<td></td>
<td>Evaporation ponds have shown mixed results</td>
<td></td>
<td>Additional water available for conjunctive use</td>
<td>No outfall needed</td>
</tr>
<tr>
<td></td>
<td>Solar evaporators may be part of drainage system</td>
<td></td>
<td>Local salinity control effective if disposal available</td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>Medium cost</td>
<td>Medium cost</td>
<td></td>
<td>Low net cost (after returns)</td>
</tr>
<tr>
<td>Advantages/ disadvantages</td>
<td>Reclamation of waterlogged area</td>
<td>Periodic maintenance of pipe or open drains;</td>
<td>Reclamation of waterlogged area</td>
<td>Adverse; the drainage can contain high concentrations of salts, chemicals and/or nutrients;</td>
</tr>
<tr>
<td></td>
<td>Water table control</td>
<td>Evaporation ponds require periodical removal of salts</td>
<td>Water table control</td>
<td>Adverse; pumped water can be of inferior quality and cause deterioration in quality of stream or canal water on disposal</td>
</tr>
<tr>
<td></td>
<td>Local salinity control effective if disposal available</td>
<td></td>
<td>Additional water available</td>
<td>Water needed during establishment</td>
</tr>
<tr>
<td>Operation and maintenance</td>
<td>Periodic maintenance, including pipe lines, pumps, screens, etc.;</td>
<td>Power or fuel supply needed</td>
<td>Thinning, pruning, harvesting, Disease control</td>
<td></td>
</tr>
<tr>
<td>Requirements for:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Land</td>
<td>Nil for sub-surface drains</td>
<td>Only small areas needed</td>
<td>Relatively large areas of land needed; e.g. in IGNP India, land requirement is estimated at about 10 % of irrigated area</td>
<td></td>
</tr>
<tr>
<td>Good quality water</td>
<td>Open drains and evaporation ponds would require land</td>
<td>Small areas needed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy requirement</td>
<td>Pump-lifting from drainage outlets to final disposal sites may be necessary</td>
<td>Energy needed for pumping groundwater and possibly further removal.</td>
<td>Nil</td>
<td></td>
</tr>
<tr>
<td>Energy requirement</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environmental impact off-farm</td>
<td>Adverse; the drainage can contain high concentrations of salts, chemicals and/or nutrients;</td>
<td>Adverse; pumped water can be of inferior quality and cause deterioration in quality of stream or canal water on disposal</td>
<td>Positive; dewatering, transport and disposal combined in one system;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Evaporation ponds can pose environmental problems</td>
<td></td>
<td>For final salt balance control disposal system required</td>
<td></td>
</tr>
</tbody>
</table>
What is biodrainage, how does it work?

Figure 2: Flow towards depressed groundwater table under plantations

<table>
<thead>
<tr>
<th>Natural ground surface</th>
<th>Transpiration</th>
<th>Recharge</th>
<th>Plantation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impervious layer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Groundwater surface</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depressed groundwater table surface underneath plantations</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Donnan Equation

\[ L^2 = \frac{8KY_0h}{R} + \frac{4Kh^2}{R} \]

With \( R = 0.5 \text{ mm/day}, h = 10.0 \text{ m}, Y_0 = 10.0 \text{ m} \) and \( K = 100 \text{ mm/day} \), \( L \) works out to 500 m.

Water table drawdown by plantations

The water table under vegetation falls when discharge (evapotranspiration, surface runoff and groundwater outflow) exceeds recharge (infiltration and groundwater inflow) and stabilizes when they are equal. A depressed water table beneath a tree plantation induces groundwater flow from the surrounding areas (where the water table is higher) towards the plantation area, thus providing water table control to these areas. If tree plantations were planted in parallel strips, the water table profile would be similar to the profile found between parallel, open drainage ditches (Figure 2). The relationship between depression of the water table, rate of recharge, hydraulic conductivity, depth to barrier layer and distance between plantations can be described using equations developed by Hooghoudt (1940, in Dutch), and later applied by Donnan (1946, in English) as follows:

\[ L^2 = \frac{8KY_0h}{R} + \frac{4Kh^2}{R} \]

where:

- \( L \) = distance between parallel plantation strips (m)
- \( R \) = rate of recharge (m/day)
- \( Y_0 \) = height of water table above barrier layer under the tree plantations (m)
- \( K \) = hydraulic conductivity of substrata (m/day)
- \( h \) = head difference (m)

As an illustration, for \( R = 0.0005 \text{ m/day}, Y_0 = 10 \text{ m} \) and \( h = 10 \text{ m} \), the distance between tree plantations (\( L \)) would be 1 500, 500 and 150 m for \( K \)-values of respectively 1, 0.1 and 0.01 m/day. Low-hydraulic conductivity soils require closer-spaced plantation strips than soils with more permeable substrata. However, often higher intake rates occur in the high-permeability profiles and this would require larger larger areas to be covered by biodrainage crops to balance the increased accessions. The plantation strips in areas with high hydraulic conductivity could potentially cover large areas of the landscape. Site-specific field data should be collected to estimate the size of and spacing between plantation strips.

to high annual transpiration rates. The water use by tree plantations is not less than 1.5 times that of agriculture crops or about 1.25 times of Class A pan. A conservative tree water use figure of 1.0 Class A pan could therefore be assumed to estimate the potential biodraining capacity of tree plantations under conditions of good water quality. For design purposes this must be corrected for future estimated salinity levels.

Reported research data on tree water use under water-stressed conditions are not relevant to biodrainage scenarios under conditions of waterlogging where water is in ample supply. However, where trees are used to dry out soil strata to create a storage buffer for a subsequent rainfall season, water-stressed tree water use information can be highly relevant.
**Root depth and density**

The lateral extent of the impact of the water table depression beneath plantations on the surrounding land obviously depends on the vertical and lateral size of the trees’ root system. Root systems have a remarkable ability to expand to access water and nutrients. The selection of appropriate species is important in the design of efficient biodrainage plantations.

Zohar (1985) measured roots up to 20 m from the trunk of individual eucalyptus trees. Kolesnikov (1966) reports on root measurements on apple trees in the Crimea (Ukraine, formerly USSR). He found a total length of all tree scaffold and fibrous roots of 2.7 km under a 45 year-old ‘Sary Sinap’ apple tree, with the vertical roots accounting for 1.6 km and the horizontal roots 1.1 km. In the same orchard, on a site with a shallower water table, excavations under a 25 year-old ‘Reinette de Champagne’ apple tree revealed a root depth of only 1.3 m and a total root length of 523 m, the vertical roots accounting for 77 m and the horizontal roots for 456 m.

In the Indira Ghandi Nahar Project, Rajasthan, India, a perched water table along a seeping irrigation canal resulted in the development of pools in the borrow pits. Plantations of (mainly) *Eucalyptus camaldulensis* and *Acacia nilotica*, established around the waterlogged areas, transpired enough water to lower the water table by 15 m over a period of 6-7 years. Open pits excavated in the plantations down to a depth of 10 m, showed that tree roots were extending at least to that depth (see case study in Chapter 5.2).

Theiveyanathan and Benyon (2000) compared water use of Flooded Gum (*E. grandis*) and Spotted Gum (*Corymbia maculata*) on a shallow water table site in southeastern Australia. *E. grandis* used 300 mm groundwater per year while *C. maculata* used 675 mm over the same period at the same site. The researchers attribute the difference to the trees’ root systems. Both species showed dense root growth in the top half metre of the soil, Spotted Gum had a lot of roots in the capillary fringe just above the water table and seemed better equipped to tap water at depths of around 3 metres.

**Quality of groundwater**

In (semi-) arid regions, the groundwater table is normally quite deep before irrigation is introduced and groundwater is commonly saline and unsuitable for irrigation. After introduction of irrigation, with good quality water brought in from outside the region, the deep percolation losses increase and two things can happen:

- If there is a barrier layer above the groundwater table, most of the deep percolating water may collect over the barrier layer and form a perched water body. The perched water table will rise and will eventually cause waterlogging. Since the quality of water in the perched water body is generally good, the groundwater can be pumped out, either directly by conventional drainage or via biodrainage crops.

- Where the percolating water infiltrates down to the saline regional groundwater table, this water table then rises and causes waterlogging and salinization problems. The poor quality of the groundwater limits its use. Subsurface drainage presents problems for disposal. Biodrainage can be practised with certain limitations. The transpiring capacity of trees reduces progressively as the groundwater salinity increases. When the groundwater salinity is about 8 dS/m, eucalyptus trees may transpire only one-half as much water as they do under nonsaline conditions (Oster et al. 1999). However, this is true for many crops, not just trees.

**Water balance through biodrainage in irrigation areas**

When irrigation is introduced, the pre-existing water balance is disturbed; groundwater recharge increases and causes the water table to rise. The recharge to the groundwater occurs by way of (1) seepage losses from the water conveyance system, (2) irrigation water application and (3) rainfall events, the latter (especially) during cold seasons with limited crop growth.

Seepage losses from the conveyance system depend on construction techniques and materials used. Recharge accessions directly from irrigation can be small when appropriate efficient irrigation techniques are used. Winter rainfall events can be significant contributors to groundwater recharge as crops use little water during that time of the year and non-cultivated fields are often fallow.

If biodrainage is applied to obtain regional water balance, the total water use of the biodrainage plantations in a region should balance the recharge processes described above, minus the net regional subsurface drainage flows out of the region through underlying aquifer systems. The latter can be substantially different from the pre-irrigation situation when water tables were often much deeper.
What is biodrainage, how does it work?

Figure 3: Combined bio- and conventional drainage management options

(a) Pump area of influence

(b) Pump area of influence

(c) Crops; former tree site

'Old' tree plantation

'Young' tree plantation

Newly established plantation will 'drag' accumulated salts away from under the older plantation after harvest
Water balances and recharge volumes are inherently difficult to determine, especially at a regional level, as recharge processes are extremely variable, both spatially and over time. This makes it more difficult to plan regional level biodrainage activities. Planning should focus at local level implementation such as seepage interception or break-of-slope plantings.

**Sustainability and combined biodrainage and conventional drainage systems**

The long-term sustainability of non-irrigated biodrainage tree plantations growing in shallow saline water table areas may be questionable. At some stage in their commercial life their growth performance could be affected by increasing rootzone salinity. After the trees are harvested, in the absence of subsurface drainage to provide salt balance, the accumulated salts in the rootzone will move to the surface by capillarity and impact on successive land use. A number of management options could be considered to minimize, delay or even avoid this problem (Figure 3a-c).

**Trees adjacent to groundwater pump (Figures 3a and 3b)**

Groundwater pumps are used extensively for water table control. While trees lower water table levels, pumps actually lower piezometric pressure levels in the aquifers from which they pump. This way, a downward recharge gradient is created which allows salts to leach out of the rootzone from shallow-rooted irrigation crops and pastures.

Figure 3a presents a scenario where trees are planted in close vicinity to a groundwater pump. The trees are irrigated with groundwater and the planting acts as a biodisposal area. The pump provides protection to a larger area, which can be used to grow any salt sensitive crop if suitable quality irrigation supply is available. This way, a downward recharge gradient is created which allows salts to leach out of the rootzone from shallow-rooted irrigation crops and pastures.

Figure 3b shows where trees are planted at the periphery of a groundwater pump’s area of influence. The trees are not irrigated and live on rainfall and groundwater. As the piezometric drawdown impact of the pump at that location is only small (i.e. between 0.1 and 0.3 m), the trees would draw the water table down below the piezometric pressure level created by the pump and thus accumulate salts in their rootzone during their commercial lifespan of around 30 years. During this time the trees would (marginally) enlarge the water table-protection area, as the trees would provide water table control in a strip of about 50-100 m around the plantation. After the trees are harvested, the pump would subsequently leach the accumulated salts down the profile towards the aquifer, thus providing salinity protection for the successive shallow-rooted agricultural crop. Tree plantings could be moved progressively around the periphery of the area of influence.

**‘Walking’ plantations (Figure 3c)**

Where trees, after harvesting, are replaced by shallow-rooted irrigated crops, water table control could be provided by a new plantation established on an adjacent site. This second tree crop should be planted about five years before the planned harvesting date of the original plantation so that the new trees would be old enough to have an impact on the water table and protect the adjacent paddocks from shallow water table induced salinity problems. The tree plantation width would depend on its drawdown impact. Under this system tree plantations ‘walk’ through the landscape, each new planting providing water table and salinity protection to the preceding site.

It is important to note that neither of the three options described above is sustainable in the long term in the absence of some form of salt export, either from the tree rootzone (under the ‘walking plantation’ scenario) or from the groundwater body, tapped by the groundwater pump, after salinities have risen to unmanageably high levels (‘trees adjacent to groundwater pump’ scenario).

### 3.4 SALT BALANCE

No biological system is sustainable without salt balance. Salt balance is one of the most important issues to be addressed before biodrainage can be promoted as an appropriate drainage management technology.

As described in previous chapters, changing vegetation cover in a landscape is fraught with danger as it normally results in a redistribution of salts in the landscape, both vertically and/or laterally. This chapter sets out salt balance processes and their impact on the sustainability of biodrainage systems. Two salt balance mechanisms can be considered in plant systems: (1) salt balance through removal of salts from the vegetation rootzone by leaching and (2) salt applied to the plant is taken up and removed through grazing or harvesting of plant matter. The
What is biodrainage, how does it work?

former needs little discussion, as it is well understood and covered in many textbooks on irrigation technology. The latter mechanism however needs some elaboration as it is often mentioned in biodrainage related information.

There appears to be a general consensus that the salt uptake by plants is negligible compared to the total salt applied in irrigation supplies. Hoffman (1990) mentions that under most agricultural conditions where salinity is a concern, salt removal by crops can be ignored in the salt balance equation. The United States Salinity Laboratory (1954) suggests disregarding of salt removed from the soil in the harvested crop. Chhabra and Thakur (1998) of the Central Soil Salinity Research Institute in Karnal, India, mention that trees do not bio-harvest the salts and thus do not remove the salts from the soil. Heuperman (1999) mentions that the tree roots exclude salts during water uptake; the trees skim water off the top of the saturated part of the profile, causing the formation of a saltwater lens. The Nuclear Institute for Agriculture and Biology (1997) reports that when trees take up water, most of the dissolved salts remain in the soil.

Although in high-salinity environments plant salt uptake might be negligible in relation to the salts present in the system, under low-salinity scenarios this might not be the case and salt balance by plant uptake and removal might be achievable. This option needs to be critically reviewed. Important aspects to be considered in the salt balance analysis are (i) mineral content in supply (irrigation or ground) water and (ii) mineral content in plant biomass.

**Plant water supply**

James (1982) presents an overview of the average composition of river waters of the world as shown in Table 2.

Total dissolved solids (TDS) in irrigation supplies in IGNP in the Indus Valley in India is on average 125 mg/litre, more than three decades after the reservoirs were commissioned.

Salt loads in rivers generally increase in the lower reaches. This is true for natural river systems, even more so for river systems where irrigation is practised with discharge of drainage water from agricultural fields being one major source of contamination. Many examples are given in the literature. Safwat Abdel-Dayem (2000) reports that in Pakistan about nine million tonnes of salts are discharged annually with drainage water into the river Indus. The Amu Darya river in Uzbekistan receives an average of 6.5 billion m$^3$ per year of drainage water causing an increase of 1 000 mg/litre salt in downstream river water during normal flows and 2 000 mg/litre salt during the low flow season. Kitamura et al. (2000) report that in the lower river basin of the Syr Darya, drainage water from irrigated agriculture of rice-based cropping system has increased the salinity in river water from 400-600 mg/litre to 1 300-2 000 mg/litre during the last three decades. Xie et al. (1998) report that 1.1 billion m$^3$ of drainage water containing 1.2 million tonnes of salt is discharged annually from the Yinebi irrigated area in the Yellow River basin, China.

A distinction must therefore be made between irrigation systems using ‘natural’ river water from the upper part of the catchment and those using polluted water. Commonly ‘natural’ river water is stored in reservoirs and is used for irrigation through diversion canals. The quality of such water is not affected by drainage pollution. For example, irrigation water with a TDS load of 125 mg/litre used at an overall annual water application of 500 mm would add 625 kg of salt per hectare. Biomass harvesting could potentially evacuate this quantity of salt from the soil. However, the exported biomass salts will end up somewhere in the landscape, for example in the form of ash (after burning of crop residue or fuelwood), in animal or human excrements.

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**Table 2: Average compositions of river waters of the world**

<table>
<thead>
<tr>
<th>Region</th>
<th>EC at 25°C (dS/m)</th>
<th>Total Salts (mg/litre)</th>
<th>Ca</th>
<th>Mg</th>
<th>Na</th>
<th>K</th>
<th>Alkalinity $^a$</th>
<th>SO$_4$</th>
<th>Cl</th>
<th>NO$_3$</th>
<th>SAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>North America</td>
<td>.22</td>
<td>142</td>
<td>1.05</td>
<td>0.41</td>
<td>0.39</td>
<td>0.04</td>
<td>1.11</td>
<td>0.42</td>
<td>0.23</td>
<td>0.02</td>
<td>0.5</td>
</tr>
<tr>
<td>Europe</td>
<td>.27</td>
<td>182</td>
<td>1.55</td>
<td>0.46</td>
<td>0.23</td>
<td>0.04</td>
<td>1.56</td>
<td>0.50</td>
<td>0.19</td>
<td>0.06</td>
<td>0.2</td>
</tr>
<tr>
<td>Australia</td>
<td>.095</td>
<td>59</td>
<td>0.19</td>
<td>0.22</td>
<td>0.13</td>
<td>0.04</td>
<td>0.52</td>
<td>0.50</td>
<td>0.28</td>
<td>trace</td>
<td>0.3</td>
</tr>
<tr>
<td>World</td>
<td>.19</td>
<td>120</td>
<td>0.75</td>
<td>0.34</td>
<td>0.27</td>
<td>0.06</td>
<td>0.96</td>
<td>0.23</td>
<td>0.22</td>
<td>0.02</td>
<td>0.4</td>
</tr>
</tbody>
</table>

$^a$ Alkalinity is titrable bases made up mostly of HCO$_3^-$, with small amounts of CO$_3^{2-}$ and OH$^-$
(after grazing or from sewage treatment plants) or in food processing plant outlets as primary- or waste-products. The careful management of mineral transport flows through the landscape is important to avoid local accumulation areas.

Salinity mitigation drainage measures adopted in the upper reaches of catchments merely transfer the salinity problem from one region to another. In downstream reaches of river systems where irrigation is based on more saline river water, agricultural crops and tree plantations will be unable to bioharvest imported salts. Management of river systems should aim at minimizing the discharge of drainage effluent. Systems based on the use of good quality river water for irrigation and discharge of the saline drainage effluent back into the river are not sustainable. Biodrainage can play a role (although relatively minor) in the management of the salt-balance in river catchments.

**Salt uptake/exclusion processes in plants**

Water taken up by plants carries some soil solutes that, following transpiration, are eventually deposited in leaves so that salt in these leaves builds up gradually over time. For this reason older leaves generally have a higher mineral salt content than young leaves. The mineral content in plants largely depends on the species and (to a lesser extent) the mineral composition of the soil solution. The mineral content is maximum in leafy vegetables. The average dry weight content of minerals is around (1) leafy vegetables – 14 percent, (2) other vegetables – 8 percent, (3) roots and tubers – 6.5 percent, (4) pulses and legumes – 3.5 percent and (5) cereal grains – 2 percent. (ICMR-India, 1989).

Depending on prevailing climatic conditions, plants transpire from 30-70 times more water than they retain. Consequently any soil solutes not excluded by the roots, will end up in leaves in concentrations 30-70 times that of the water taken up at the root tips (Atwell et al. 1999, p 551).

For plants to achieve maximum growth rates, they should exclude most of the soil salts at their point of uptake. For example, if a plant is transpiring 40 times more water than it retains, it should admit only 1/40 or 2.5 percent of soil salt, and exclude the other 97.5 percent. If this was achieved, leaf salt concentration would stay comparable to soil salt concentration and the plant would survive indefinitely, provided salts remained compartmentalized. If salts were not excluded at all, shoot concentrations would soon be 40 times the external concentration (Atwell et al. 1999, p. 551).

All plants control Na and Cl uptake to some extent. Certain species excel and are able to maintain very low concentrations of Na and Cl ions in their sap flow from root to leaves. For example barley (a relatively salt tolerant plant) is a strong excluder, while lupin (salt sensitive legume) shows poor ability to regulate xylem salt concentration once the soil solution exceeds about 125 mM (7 250 mg/litre or EC of about 12 100 dS/m) (Atwell et al. 1999, p. 552).

Lambert and Turner (2000) present a good overview of tree crop physiology issues related to salinity. They describe the mechanisms behind the ability of plants to survive in saline environments by salt exclusion at the roots, transport prevention to the leaves, salt elimination by leaf shedding and salt excretion at the leaves. Plants take up inorganic chemicals from the soil solution and these include those essential for growth plus others, which are non-essential or even toxic, such as salts. At relatively low concentrations of salt ions in the soil solution, many plants can restrict their uptake. This is called the *single phase uptake*. At higher concentrations, there is more rapid, less restricted uptake, possibly related to mass flow. This uptake is equivalent to the quantity of nutrients in the water taken up in the transpiration stream and is less controlled. This is the *second phase in the dual mechanism* uptake process. With trees there is evidence that in the first phase they generally use exclusion, while in the second phase of rapid uptake they utilize compartmentation of elements through for example accumulation in bark. The concentration at which the Phase-2 mechanism occurs varies for each element. The authors quote an example of the uptake by *E. camaldulensis* where NaCl ions are excluded up to about 100 mM NaCl (5 800 mg/litre or EC of about 9.7 dS/m) soil solution; at about 200 mM NaCl there was a rapid uncontrolled uptake of salt by the tree roots.

*Atriplex* spp. (saltbush) are well known for their salt uptake capability. Schultz (1994) reports on salt uptake by halophytic *Atriplex* spp. as measured in field experiments under a range of saline conditions. Yields ranged from about 4 tonnes dry weight/ha (*A. lentiformis*) to nearly 10 tonnes dry weight/ha (*A. nummularia* and *A. undulata*) at a plant density of 10 000 bushes/ha, after one-year establishment with fresh water irrigation and two seasons of saline irrigation. The highest yield of 10 tonnes dry weight/yr/ha was achieved with the highest applied irrigation salinity of 10 000 mg/litre. All treatments showed reduced yields in the third year of saline irrigation. Higher irrigation salinities resulted in
higher Na and Cl concentrations in the leaf; K showed no trend with increased salinity and Mg and Ca leaf tissue concentrations actually decreased with increasing irrigation salinity. Data and salt balance calculations based on these figures are presented in Section 3.4.

Most trees and shrubs are classified as non-halophytes; they show growth reduction with increased salt concentrations. Some trees and shrubs are halophytic; they commonly require some salt to achieve maximal growth. Whilst they exclude salts to a certain extent, these plants are much better adapted to managing salt accumulation in their leaves.

Table 3 shows soil salinity versus leaf salinity ranges for halophytic and non-halophytic plants in NaCl-dominant environments. Concentration factors for the non-halophytes (about 3x) are higher than for the halophytes (about 2x). Clearly the halophytes (especially the dicotyledon species) accumulate much higher salt concentrations in their leaf tissues and are thus able to live in much higher salinity environments than non-halophytes.

Grattan (University of California, Davis; personal communication) states that for most agri-cultural crops the amount of salt accumulated is only a small fraction of the amount of salt applied to the system, at least under saline conditions. The latter part of this statement offers scope to consider the application of biodrainage technology in situations where plants have access to relatively fresh water supplies such as for example channel seepage.

Van Reuler (Applied Plant Research, Agricultural Research Department, Ministry of Agriculture, Nature Management and Fisheries, the Netherlands, personal communication) on the issue of salt uptake states that plants do not need Na and Cl, however, e.g. sugar beet reacts positive on some Na present in the soil. The amounts of Na and Cl taken up by plants are very low: the straw of wheat contains about 0.6 percent Cl and about 0.01 percent of Na. With a straw yield of 2 tonnes/ha the total amount taken up by the plants is 12 kg Cl and 0.2 kg Na per ha. For sugar beet this is 0.08 percent Na in the (root) beet; in the leaves this is even less.
More interestingly on grassland Cl content is about 1 percent and Na content about 0.3 percent, or 10 kg Cl and 3 kg Na per ha respectively. When several cuts of the grass take place every year, the total harvested grass may be several tonnes (dry weight), and then the salt removal somewhat increases.

**Salt storage in vegetation components**

Halophytes survive in saline environments by absorbing salts. Most halophytes accumulate (relatively) large amounts of salt in their leaves. For example, Atwell et al. (1999) report that Atriplex nummularia (Old Man Saltbush) grown near its optimum salinity of 200 mM NaCl (11 600 mg/litre or EC of about 19.5 dS/m) contains about 10 percent NaCl on a dry weight basis.

Schulz (1994) measured average yields of *A. nummularia* of 0.6 kg dry weight per plant per year across a range of applied irrigation salinities (100-10 000 mg/litre; NaCl-dominant water) over a three-year period. At planting densities of 10 000 bushes/ha this translated to 6 000 kg dry weight/ha/year. He also measured leaf ions for the range of applied water salinities for five *Atriplex* species, i.e. *A. ammenicola, A. cinerea, A. lentiformis, A. nummularia* and *A. undulata*. On average across the five species, leaf Na and Cl increased with increasing irrigation salinities, K showed no trend and Ca and Mg showed decreasing trends. Figure 4 (Schulz, 1994) shows the results. With the average leaf component of dry weight production being 43 percent (ranging between 38 and 51 percent for the five *Atriplex* spp.), the salt export in the leaves (considering the major ions in Figure 4) would be between 350 and 433 kg/ha/year for irrigation salinities of 100 mg/litre and 10 000 mg/litre respectively, if all leaf matter was harvested and removed from the site. The annual irrigation application of about 10 million litres/ha applied 1 tonne/ha/yr and 100 tonne/ha/yr for respectively the low and high salinity treatment. This suggests that with the low salinity irrigation water the plants made a significant contribution to salt removal, but with the higher salinity values, salt balance control by vegetation was not possible. In this experiment only the salt uptake in the leaves was considered, probably to simulate grazing; this only marginally affects the total salt uptake as the plants’ stems accumulate only minor quantities of salts.

Calculating salt balance based on total salts is risky. Plants take up ions from the soil solution selectively; different species take up different ions at different rates depending on climatic conditions and growth stage. Salt balance calculations based on plant material removal will have to be made on an individual ionic basis, rather than a total salt basis.

Salt content in irrigation water is generally assessed by measuring the EC of a sample and converting this to the gravimetric weight of all mineral compounds (chlorides, sulphates and (bi)carbonates of calcium, sodium, magnesium, etc.), using an empirically developed conversion factor. The ‘total salts’ (expressed in mg/litre) include the sulphate, (bi)carbonate and phosphate anions. Thus the carbon, hydrogen and oxygen components of the anions are included in the total salt measurement.

---

**Table 4: Mineral (cations: Na⁺, K⁺, Ca²⁺, Mg²⁺) content in tree and crop biomass¹**

<table>
<thead>
<tr>
<th>Tree species</th>
<th>Stem bark</th>
<th>Stem wood</th>
<th>Tree component (% dry weight)</th>
<th>Tree component (% dry weight)</th>
<th>Tree component (% dry weight)</th>
<th>Tree component (% dry weight)</th>
<th>Tree component (% dry weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Branch bark</td>
<td>Branch wood</td>
<td>Twig</td>
<td>Leaf</td>
<td>Fruit</td>
</tr>
<tr>
<td>Eucalyptus</td>
<td>5.8</td>
<td>1.8</td>
<td>6.6</td>
<td>2.4</td>
<td>2.7</td>
<td>2.2</td>
<td>3.2</td>
</tr>
<tr>
<td>Acacia nilotica</td>
<td>2.8</td>
<td>2.0</td>
<td>2.9</td>
<td>1.1</td>
<td>1.3</td>
<td>4.0</td>
<td>2.5</td>
</tr>
<tr>
<td>Ziziphus</td>
<td>3.8</td>
<td>2.1</td>
<td>3.5</td>
<td>2.6</td>
<td>4.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prosopis cineraria</td>
<td>6.0</td>
<td>2.0</td>
<td>4.6</td>
<td>2.5</td>
<td>4.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tecomella undulata</td>
<td>3.3</td>
<td>1.1</td>
<td>2.6</td>
<td>1.5</td>
<td>3.5</td>
<td>3.1</td>
<td>1.7</td>
</tr>
<tr>
<td>Delbergia sissoo</td>
<td>4.6</td>
<td>4.8</td>
<td>4.6</td>
<td>1.3</td>
<td>3.7</td>
<td>5.1</td>
<td>3.0</td>
</tr>
<tr>
<td>Azatirachta indica</td>
<td>1.5</td>
<td>1.7</td>
<td>2.3</td>
<td>0.9</td>
<td>3.3</td>
<td>3.3</td>
<td>3.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Crop</th>
<th>Stem</th>
<th>Leaves</th>
<th>Crop component (% dry weight)</th>
<th>Crop component (% dry weight)</th>
<th>Crop component (% dry weight)</th>
<th>Crop component (% dry weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>3.1</td>
<td>4.8</td>
<td>0.9</td>
<td>5.0</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Groundnut</td>
<td>5.0</td>
<td>4.8</td>
<td>1.5</td>
<td>1.5</td>
<td>7.7</td>
<td>7.7</td>
</tr>
<tr>
<td>Mustard</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cow pea (guar)</td>
<td>2.2</td>
<td>4.9</td>
<td>1.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gram</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cotton</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

¹ Data from IGNP project, India.
The mineral content in plants is determined by either ash analysis or by wet acid digestion methods. In the ashing method organic material is completely destroyed by burning in a crucible to a temperature of 600°C. Ashing techniques can cause vaporization and sublimation of some of the elements, resulting in mineral losses. Wet digestion methods determine individual element content; samples are washed with hydrochloric acid, treated and heated with nitric acid and then with perchloric acid. The method produces weight values of individual elements (calcium, sodium, magnesium, chloride, sulphur, nitrogen, phosphorus, etc.) in the plant as a percentage of the plant dry biomass weight. Anions such as \( \text{NO}_3^- \), \( \text{SO}_4^{2-} \) and \( \text{PO}_4^{3-} \) are not measured but their element components N, S, and P (sometimes) are. Chlorine when analysed using this method, would volatize and escape on heating and should be determined by, for example, titration. Both the ashing and the wet digestion method can result in an under-valuation of the mineral content in plants. Microwave assisted digestion, using closed containers, reduces these losses and gives more complete digestion.

Where salts are NaCl-dominant (as in the saltbush example above), the limited number of elements measured, including the chlorides, will be only slightly lower than the actual total mineral salt content of the plant samples.

The above suggests that calculations based on analysis of plant material often underestimate the total salts taken up by vegetation. The order of magnitude of the under-estimation depends on the ashing method used and on the composition of the salts. It seems that this aspect has often been overlooked by practising engineers and researchers.

Non-halophytic trees are salt excluders. The relatively small amounts of salts/nutrients that are taken up by trees are recycled by foliar drop. The only export of salts takes place through removal of timber during harvesting and through seepage losses where trees grow on deep water tables that can not be accessed by roots.

Eucalypt species are not known for their salt-uptake capability. Lambert (1981) discusses the results of a large number of bark and wood studies for Australian tree species grown in forest environments. She found very high variability between species and between the woody components in the same tree (sapwood-heartwood-bark). However, the mineral ash content of the heartwoods (the major bulk of the timber removed in logging operations) was quoted as generally being less than 0.1 percent, with some species showing higher levels, e.g. \( \text{E. maculata} \) (4 percent).

Mineral content in plants growing in the Indira Gandhi Nahar Project, Rajasthan, India, determined by the di-acid wet digestion method are presented in Table 4. Stem-wood percentages for the tree spp. are of the same order of magnitude as mentioned by Lambert (1981).

**Consequences for biodrainage systems**

Halophytes, with their high leaf salinities, on first sight seem to offer the best scope to achieve salt-balance through export of plant matter from sites. However, experimental field data do not support this. A yield of 1 500 kg dry matter per ha (Schulz, 1994; NaCl-dominant environment) would translate to 150 kg of salt per ha if the foliage was removed from the site. If water applied to the site contained about 5 000 mg salts/litre, and the saltbush would use around 5 million litres/yr (conservative), 25 tonnes of salt would be added to the site and only 150 kg (or 0.6 %) would be exported; hardly a salt-balance scenario.

A practical challenge would be the development of a technique to harvest the saltbush plants. Grazing would be the most convenient system although this would result in a return of most of the salts back to the site. Cut-and-carry systems that do not harm the productive capacity of the saltbush would have to be developed. The five species in the Schulz trial were harvested by cutting back at about 20 cm from ground level, using a flail mower. The bushes showed excellent re-growth during the first and second year. Yields declined in the third season and continuous heavy cutting back can be expected to result in dieback of the saltbush.

For Eucalypt plantations the prospects for salt balance in saline environments through harvesting and export are not much better. Following data from Lambert (1981) and using the highest recorded ash percent for the heartwood of 4 percent (for \( \text{E. rossii} \)), an annual growth increment of say 10 tonnes (high for saline environments) would result in an average salt removal through harvesting of 400 kg/ha per year. Following the same calculation as for saltbush above, with an assumed applied water quality of 3 000 mg salts/litre and annual water use of 10 million litres/yr, 30 tonnes of salt would be added to the site of which only 400 kg (or 1.3 percent) would be exported.

Lambert and Turner (2000) present data on sodium and chloride accumulation in different components of five and 22-year old \( \text{E. grandis} \)
plantations. For five-year old plantations, 35 kg/ha NaCl was stored in total wood plus 17 kg/ha in bark; for 27-year old plantations the figures were 186 kg/ha in total wood and 170 kg/ha in bark. This means that over the 22-year period the uptake in both the wood and the bark was about 7 kg/ha/yr or a total of 14 kg/ha/yr for the combined components. These quantities are small in relation to the salt inputs in the plantations, even under some rainfed scenarios where annual inputs of sodium and chloride in coastal areas can be as high as 65 kg/ha/yr (e.g. Coffs Harbour, 1 km from the coast in eastern Australia; Lambert and Turner, 2000). Leaching would still have to take care of considerable salt export from under tree plantations grown at these sites. It also has to be noted that bark and leaves and twigs are normally not exported from plantation sites at harvesting.

In conclusion, the potential for export of salt through plant harvesting does not look promising. Salt balance through the removal of vegetation has only been reported for situations with very low salt input/fresh water supplies such as channel seepage. More detailed information on this scenario is presented in a case study in Chapter 5.2. Other detailed examples of salt balance scenarios are included in Chapter 5.

3.5 Suitable Plant, Tree and Shrub Species

Selection of species for biodrainage purposes will depend on the environmental conditions for which they are planned. Salt tolerance will be an important criterion for (potentially) saline discharge environments, water use considerations will prevail in recharge control situations where salinity is of no concern and in channel seepage scenarios with low-salinity water supply.

Crop selection

Literature on salt tolerance for agricultural crops is commonly based on Maas and Hoffman (1977). For non-agricultural tree and bush species, reliable information is more difficult to obtain. Marcar et al. (1995) provide detailed information on the use of 30 tree species for use on salt affected land and less detailed summary descriptions for an additional 30 species. Schulz (1994) provides comparisons for five saltbush species grown on a range of saline irrigation regimes and other authors have investigated water use of different tree species under a range of saline conditions (Slavich et al., 1999; Cramer et al., 1999; Morris and Collopy, 1999; Benyon et al., 1999).

Shah et al. (2000) bring together salt tolerance information from research in Pakistan. They present data on crops, salt tolerant trees, grasses and saltbush (see Appendix I).

Khazaada et al. (1998) monitored the water use of Acacia nilotica, A. ampliceps and Prosopis pallida on 3-5 year old plantation sites with contrasting soil and groundwater salinity in the Indus Valley in Pakistan. Annual water use by A. nilotica was 1 248 mm on a severely saline site and 2 225 mm on a moderately saline site. This was considerably higher than the annual rainfall, indicating that much of the water was taken up from the saline water tables underlying the sites (20 dS/m at 1-1.5 m below surface at the saline site and 1.5 dS/m at 2 m below surface at the moderately saline site). The other species used less water, this was considered to be a result of a lower planting density. The authors concluded that trees can evaporate large volumes of saline groundwater but they warn against the dangers of salt accumulation as observed under the trial sites. Rootzone salt-balance might be achievable in the long term, but at a much reduced tree water use and thus shallower water table.

Photo 4 shows the heat-pulse method used to measure tree water use.
What is biodrainage, how does it work?

The Central Soil Salinity Research Institute (CSSRI) at Karnal, India, presents data on the tolerance of tree species to soil salinity as shown in Table 5 (Tomar and Gupta, 1999).

Reported salt tolerance data for the same tree species vary widely. Deep root systems make measurement of average rootzone-EC difficult and sometimes meaningless; the trees develop active roots in the least-saline part of the rootzone. For example ‘moderately tolerant’ is defined as ECe 4-8 dS/m by Marcar et al. (1995) but is reported as 15-25 dS/m by CSSRI Karnal (Table 5).

Eucalyptus species are generally considered to be effective for biodrainage purposes. Eucalyptus camaldulensis is a hardy tree that grows under a wide range of climatic conditions and soil types. Some provenances of the species tolerate saline conditions quite well. They grow fast when good quality water is available. In a study in IGNP, Rajasthan, India (Chapter 5.2), five-year old subirrigated plantations (channel seepage) produced dry biomass of 185 tonnes/ha. The utilizable biomass production was 29 tonnes/ha/year.

Acacia nilotica, Dalbergia sissoo, Tecomella undulata and Ziziphus mauritiana are other species that have performed quite well in plantations along leaking canals in arid conditions. Species suitable for non-irrigated conditions are Acacia tortilis, Prosopis cineraria, Prosopis juliflora and Parkinsonia. Poplar and tamarix trees are also reported to perform well for biodrainage (Bhutta and Chaudhry, 2000).

The tolerance of plants is governed by several factors such as the Na/K ratio of shoots and the capacity to take up K under strong Na competition, selective absorption or retention of cations (mainly Na in the foliage, roots and shoots), ability to excrete sodium through leaves, tolerance to oxygen stress in the rhizosphere and nutritional stresses.

Available research information on the soil alkalinity tolerance of important fuelwood/timber and fruit trees as compiled by Gill et al. (1990) and Singh and Gill (1990) is presented in Table 6.

Experiments at the Central Soil Salinity Research Institute, Karnal, India, (Gill and Abrol, 1985), have demonstrated that special tree establishment techniques in alkali soils require the planting of tree saplings (channel seepage) produced dry biomass of 185 tonnes/ha. The utilizable biomass production was 29 tonnes/ha/year.

<table>
<thead>
<tr>
<th>Tolerant</th>
<th>Tamarix troupi, T. articulata, Prosopis juliflora, Pithecellobium dulce, Parkinsonia aculeata, Acacia farnesiana</th>
</tr>
</thead>
<tbody>
<tr>
<td>(ECe 25-35 dS/m)*</td>
<td>Callistemon lanceolatus, Acacia nilotica, A. pennatula, A. tortilis, Casuarina glauca 13144, C. gauca 13897, C. obessa 27, G. glauca (FRI), C. equisetifolia (FRI), Eucalyptus camaldulensis, Leucaena leucocephala, Erescintia alata</td>
</tr>
<tr>
<td>Moderately tolerant</td>
<td>Casuarina cunninghamiana (FRI), C. cunninghamiana (Aust.), Eucalyptus tereticornis, Acacia auriculiformis, Guazuma ulmifolia, Leucaena shannonii, Samanea saman, Albizzia carieba, Senna atromeria, Terminalia arjuna, Pongamia pinnata</td>
</tr>
<tr>
<td>(ECe 15-25 dS/m)</td>
<td>Eucalyptus camaldulensis, Zizyphus mauritiana</td>
</tr>
<tr>
<td>Moderately sensitive</td>
<td>Syzygium cumini, S. fruticosum, Tamarindus indica, Salix spp., Acacia deanei, Albizia quachepela, A. herbertsmithi, C. erieostachya, C. velutina, Halmatoxylon brasiliensis</td>
</tr>
<tr>
<td>(ECe 10-15 dS/m)</td>
<td>Acacia nilotica, A. pennatula, A. tortilis, Casuarina glauca 13144, C. glauca 13897, C. obessa 27, G. glauca (FRI), C. equisetifolia (FRI), Eucalyptus camaldulensis, Leucaena leucocephala, Erescintia alata</td>
</tr>
<tr>
<td>Sensitive</td>
<td>Tamarix troupi, T. articulata, Prosopis juliflora, Pithecellobium dulce, Parkinsonia aculeata, Acacia farnesiana</td>
</tr>
<tr>
<td>(ECe 7-10 dS/m)</td>
<td>Callistemon lanceolatus, Acacia nilotica, A. pennatula, A. tortilis, Casuarina glauca 13144, C. gauca 13897, C. obessa 27, G. glauca (FRI), C. equisetifolia (FRI), Eucalyptus camaldulensis, Leucaena leucocephala, Erescintia alata</td>
</tr>
</tbody>
</table>

* ECe is the average rootzone salinity as measured in a saturation extract

<table>
<thead>
<tr>
<th>Average soil pH in 1:2 soil water suspension</th>
<th>Fuelwood/timber tree species</th>
<th>Fruit tree species</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;10.0</td>
<td>Prosopis juliflora, Acacia nilotica, Casuarina equisetifolía</td>
<td>Acchras japota</td>
</tr>
<tr>
<td>9.0-10.0</td>
<td>Tamarix articulata, Terminalia arjuna, Albizzia lebbeck, Pongamia pinnata, Sesbania sesban, Eucalyptus tereticornis</td>
<td>Zizyphus mauritiana, Sapindus laurifolius, Emblica officinalis, Carissa carandas, Psidium guajava, Phoenix dactylifera, Aegle marmelos</td>
</tr>
<tr>
<td>8.2-9.0</td>
<td>Dalbergia sissoo, Morus alba, Grevillea robusta, Azadirachta indica, Tectona grandis, Populus deltoides</td>
<td>Punica granatum, Pyrus persica, Pyrus communis, Vitis vinifera, mangifera indica, Syzygium cumini</td>
</tr>
</tbody>
</table>

Improvement of alkali soils by tree plantations

Alkali soils are characterized by high pH (8.2-10.5) and high exchangeable sodium percentage (ESP >15). High pH and ESP primarily occur as a result of the presence of measurable amounts of soluble sodium carbonates and bicarbonates in these soils.
ment (commercial survival rates) and boosting early growth of trees in the inhospitable alkali soil environments. Tree growth by itself initiates biological amelioration once a good canopy cover is developed. Significant decrease in soil pH, electrical conductivity, and increase in organic carbon and other nutrients (N, P, K, etc.) was observed to result in recycling of nutrients through litter production, Gill et al. (1987). Nitrogen-fixing trees do exceptionally well in this respect. Irrigation promotes root development and decreases soil sodicity. Pruning and lopping help tree growth. Close spacing of trees (1 x 1 or 2 x 2 m) produces less biomass yield per tree but more biomass per ha. Growing of trees has been reported to ameliorate alkali soils by improving physical, chemical and biological properties, Tyagi (1999).

Tree cropping systems management
Selection of species for biodrainage purposes will have to be based on currently prevailing and expected future environmental and economic conditions, rather than natural conditions as they existed before agricultural clearing and development. For example, in regions where water tables were deep before agricultural development, clearing and the introduction of irrigation have often resulted in the formation of shallow water tables. Under this scenario tree species selected for biodrainage should be able to survive and grow in shallow-water table environments, rather than in the pre-clearing deep-water table environment.

The management of forest plantations in saline waterlogged environments is described in detail in Lambert and Turner (2000), Chapter 8, and Marcar et al. (1995). Issues such as site preparation (deep ripping, liming, gypsum application, weed control), soil mounding, mulching and fertilizer application all need to be considered if tree vegetation is to be established successfully at sites with unfavourable characteristics. On sites with high soil salinities, (temporary) remedial drainage might have to be applied before biodrainage plantings can be established.

On-going management issues, such as pruning and pest control are dependent on the purpose of the final product (e.g. timber or fuelwood) and local economic considerations. Generally selection of a mix of species rather than a monoculture tree plantation minimizes the risk of severe insect or disease attack.

Animals and young trees do not mix well. Young seedlings might have to be protected from small native wildlife species such as rodents or rabbits. Individual tree guards might be required to avoid major losses. When animals are introduced for grazing/weed control at a later stage, close supervision is initially needed to prevent damage to bark.

The planting of crops between widely spaced tree rows can be considered, especially at an early stage before competition for light becomes an issue. Crops such as wheat, mustard, lentil, berseem and gram or pasture species can be grown. However, the main objective of biodrainage plantations is the prevention of waterlogging and salinity management. The use of plantation plots for the growing of inter-crops may divert landholders’ attention from the trees in favour of the crops and for this reason inter-cropping is not recommended until the water table and salinity conditions are fully and finally stabilized. In general it is recommended to assign a certain function to a certain area to avoid conflict of interests negatively affecting the biodrainage function.

Monitoring of plant health and soil salinities at biodrainage sites is extremely important to be able to adjust management of perennial (tree) crops (e.g. by occasional irrigation, pruning or thinning to reduce water use) and avoid tree crop losses.

3.6 Biodiversity values

Landscape biodiversity is currently in the spotlight in many agricultural areas of the developed world. In the past, biodiversity was often a neglected issue, especially in irrigation areas. Lack of awareness and short-sightedness of previous generations of policy makers, regional resource managers and landholders has often resulted in landscapes with very little left of the original native vegetation and fauna. Conditions in agricultural environments often vary considerably from those of the original landscape. For example water table regimes are changed, there are higher water and/or nutrient inputs and intensive cropping practices impact on native flora and fauna. The “monopolizing” of the landscape by the agricultural sector alone is increasingly challenged by other landscape users, including promoters of more natural environment development. However, farming and landscaping may compatibly coexist.

Adoption of biodrainage practices rather than conventional drainage can contribute to diversification in the agricultural landscape. However, often the tree crops selected for biodrainage will not be the same as the indigenous species for that locality as the agricultural practices will have changed the environmental conditions at the site.
Monoculture blocks of land have an inherently poor biodiversity and if biodrainage plantings are designed for dual-purpose drainage/biodiversity purposes, they should incorporate a mixture of tree, shrub and grass species. An example of the biodiversity value of a small biodrainage block attracting large numbers of bird species is presented in a case study in Section 5.1.

Biodrainage plantings will often incorporate (or even be fully composed of) Eucalypt species. The ecological effects of Eucalypts are reviewed by Poore and Fries (1985). Eucalypts are often perceived as environmental ‘bandits’ because they are alleged to have adverse impacts on soil (nutrient status and encouraging erosion), on hydrology (drying up aquifers) and on the ecosystem (poor habitat for fauna). In their discussion on the impact of Eucalypts on the water cycle, Poore and Fries consider Eucalypts as another ‘crop’ and outside their natural ecological region, Eucalypts probably have little value as habitat providers. However, eucalyptus trees provide wildlife habitat in California and especially when, apart from trees, other salt-tolerant crops are introduced, the ecological value increases remarkably.

3.7 Marketability of Produce

The adoption of new production systems, such as biodrainage plantations, by private landholders is to some extent linked to the market value of its end products, which in turn, depends on local conditions. In fact, the biodrainage plantation is needed to sustain high yields of the main commercial crops.

Studies carried out in different parts of the world indicate that an increase in income is always associated with an increase in commercial and industrial wood consumption. In rural areas in developing countries such as India, fuelwood is a basic need. In India, during the past decades the rate of rise in price of fuelwood, timber and charcoal has been much greater than that of agriculture commodities. The trend is continuing (Dwivedi, 1992).

In several parts of India farm forestry has shown phenomenal growth rates in the past and good economic returns. Recently, however, market prices have collapsed because of the lack of marketing facilities. Obviously market research should form the basis of any large-scale move towards the production of new crops, including trees. However, the situation might be completely different for rural communities in developing countries where other economic drivers apply and where fuelwood production can be a very profitable activity.

Economic evaluation studies were carried out on watershed management projects in India having important forestry components. In a World Bank survey (1981-1988) near Kandi, Punjab, the internal rate of return for different components was: forestry 18.2 percent, animal husbandry 15.6 percent, soil conservation 10.8 percent, horticulture 25.3 percent and irrigation minus 1.22 percent. In another study by the Indian Agriculture Finance Corporation (1988) in the catchment of the Matatila reservoir, the benefit/cost ratios for different investment sectors were assessed as: soil conservation 1.68:1, water storage structure 1.84:1 and forest/tree plantations (of Eucalyptus, Acacia catechu and Dalbergia sissoo) 4.48:1. Similar results were obtained on several research farms in India.

Over time conditions may change considerably. For instance a tree-growing project in California looked at the market value of Eucalypt wood for fuelwood production. Based on a net value of US$30-50 per cord (2.3 m$^3$), the annual sustainable yields of 0.2-0.8 cords per acre (0.5 -1.8 m$^3$/ha) were not considered high enough to generate the level of annual income that would exceed the annual operating costs of US$40/ha and a fair share of the development cost of about US$3 000/ha. However, it is reported that there would currently be a large profitable market for eucalyptus chips used in landscaping.

Timber yields of trees grown under saline conditions can be reasonably high, e.g. *E. occidentalis* grown with 9 dS/m irrigation water on a saline site in northern Victoria, Australia, showed annual growth increments of nearly 17 m$^3$ during its fourth year of saline irrigation. However, because of poor tree shape, the timber was not suitable for anything except fuelwood. Breeding efforts to improve form and timber quality have traditionally focused on high yielding species in more benign environments. There is scope for improvement in this area.

Pasture and other perennial forage species such as lucerne are generally easier to incorporate in existing agricultural systems than tree plantations. They can be either grazed directly or harvested. As with trees, breeding efforts have traditionally focused on more productive non-saline environments. More salt tolerant species are being developed and production systems are presently being tested in the USA (Oster et al., 1999b).
3.8 **Biodrainage and Wetlands**

Wetlands are areas that are covered with water for at least part of the year to a depth of less than two metres. The values of wetlands are now widely recognized as reserves of native plants and wildlife, water quality improvers (nutrient filters) and flood-protection buffers. In their natural environments, the evapotranspiration of the vegetation of the wetland system is in balance with the through-flow and seepage fluxes. Where either the vegetation or the watering regime is changed, these finely tuned balances are disturbed and habitat changes are inevitable.

Water balance changes in wetlands are mentioned by Poore and Fries (1985) who state that tree plantations, especially Eucalypts, have been used to lower water tables in swampy areas, either to dry out the soil or to control mosquitoes. Obviously this practice clashes with the management of wetlands for ecological values.

3.9 **Biodrainage and Urban Landscapes**

Urban salinity is an issue associated with rising water table levels. Water use in arid urban environments can be high and leakage from water pipes substantial. Urban areas often have relatively good surface drainage but subsurface drainage is rarely considered. Only in places where groundwater is pumped for water supplies is subsurface drainage provided. This practice is not feasible in urban landscapes overlying saline water tables. In some cases, old and leaking sewage pipe systems might have been providing some form of salt-balance by intercepting shallow saline groundwater, however, where these old systems are being upgraded and leaks fixed, serious waterlogging and/or salinity problems can be expected to develop.

In Australia, urban salinity has been identified as a serious problem. The city of Wagga Wagga in eastern Australia suffers from extensive damage to old brick structures (Spennemann, 1998). The strategies involved in managing this problem include biodrainage through planting of deep-rooted vegetation species adapted to the local arid climatic conditions, rather than the commonly used imported exotic species requiring irrigation to survive.

3.10 **Socio-economic Considerations**

Commercial tree plantations are grown to yield economic returns. Plantations developed for biodrainage potentially offer an extra protection benefit, free of cost, and improve the regional economy. However, looking at the level of the individual landholder who needs annual returns to survive, the aim should be to produce economic returns comparable at least to those from agriculture.

The planting of large areas of new crops, especially tree crops, will have a significant impact on regional economies and social structures. Casson (1997) discusses these issues in a working paper based on two case studies in South India and Thailand. During the 1980s, social protests developed in Asia (and elsewhere in the world) over alleged adverse effects of Eucalypts on soil nutrient status, soil water depletion, soil erosion and wildlife. Casson argues that the criticism against Eucalypts often conceals the real reasons for anxieties, i.e. the lack of consideration of community needs.

In the Indian case study timber production was the main driver for the forestry project. Issues such as (1) loss of grazing opportunities for the local farmers, (2) the use of ‘public’, ‘communal’ land for tree growing, and (3) insufficient involvement of local communities in the planning, establishment and management of the plantations, all complicated the implementation of the project.

In the Thailand example the two main objectives of the project were to (1) improve the standard of living of the rural population; and (2) improve resource management through tree planting in recharge areas to protect down-slope salt-affected agricultural land. The main problems encountered were that (1) village wells dried up as a result of the Eucalypts lowering the water table, (2) communal grazing land in recharge areas was replaced by close-canopy plantations without under-storey and (3) ownership of the new trees was not clearly identified. Therefore, by focusing on solving the salinity problem, the community inadvertently suffered from fuelwood, fodder and water shortages.

The lessons learned from the two dryland case studies could have relevance to irrigation scenarios elsewhere. For example, in rural communities with small-scale landholdings, the development of small-scale biodrainage plantations targets communal lands that, even when salt affected, have some community value for grazing and fuelwood production. The benefits of biodrainage systems in these areas must be carefully weighed against the existing value of such land. The involvement of local village representatives at the start of project development is extremely important.

The biodrainage system can have significant advantages in the rural environment of many
developing countries, especially when there are new projects and the choice is between (1) biodrainage, (2) installation of a conventional subsurface drainage system using a closed horizontal pipe drainage system, by open drains, or by vertical drainage, and (3) a combined system of biodrainage and conventional drainage. Often the rural livelihood benefits because biodrainage provides for fuelwood, fruits, timber, fodder, windbreak, flora and fauna, biodiversity, pollutant removal.

### 3.11 On-farm versus regional biodrainage systems

The most important factor to consider when deciding where to establish biodrainage plantings is the hydrological process underlying the catchment water balance. Accurate identification of recharge (intake) and discharge (seepage) areas in the landscape is a major requirement for the proper planning of biodrainage activities.

In non-irrigated, undulating areas the identification of recharge-discharge relationships is often relatively easy with the lower areas of the landscape generally serving as discharge land units. Exceptions do occur where impermeable layers in the soil profile can cause discharge to occur higher up the slope. Biodrainage plantings in dryland areas where salts are stored in the soil profile should focus on recharge areas and thus prevent the development of saline seeps further down the slope. In non-saline areas, recharge plantings could result in the drying-up of springs or wells further down the slope and thus have negative social impacts.

In relatively flat irrigation areas, recharge-discharge interactions are often less clear. On the same land unit a recharge scenario immediately after irrigation can turn into a discharge situation at the end of the irrigation cycle when vegetation starts to tap the shallow water table.

The planning scale of biodrainage plantings depends on a large number of factors. Where farm holdings are small, obviously landholders are unable to set part of their farm aside for biodrainage activities. Therefore any application of this technique will have to focus on public land. Where farms are large, landholders might be able to integrate biodrainage plantings in their farm layout.

Where large-scale recharge plantings are planned, cost-sharing arrangements might have to be developed to assure that (part of) the implementation costs of the works are carried by the beneficiaries. In Australia, where regional tree-planting activities are widely supported by volunteer community groups, there have been examples of salt-affected irrigation farmers in the bottom-end of catchments actively participating in tree planting activities in the top-end of the catchment, 50 or more kilometres away.

In Australia, large-scale commercial plantations are now being considered in irrigation areas, especially to use poor-quality drainage water. Similar to the small-scale scenario described above, the socio-economic impact of the introduction of large-scale plantations can be either positive (new industry, offering employment) or negative (regional restructuring with industry buying out small farmers and causing social change).