Best-practice surface drainage for low-lying sugarcane lands Herbert District : a manual for extensionists and practitioners

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Best-practice Surface Drainage for Low-lying Sugarcane Lands Herbert District

John R. Reghenzani and Christian H. Roth
Edited by Robert E. Reid
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Herbert District

A manual for extensionists and practitioners

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Edited by Robert E. Reid
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1 INTRODUCTION

Cane growers in all districts often have to deal with excess water on or near the soil surface. However, the problem occurs most frequently in the high rainfall Mackay, Herbert and Wet Tropics districts. Wetness problems in the Herbert River area are aggravated because:

- topography is extremely flat;
- slowly permeable, heavy textured soils occupy large areas; and
- regional drainage mostly flows away from the major river systems where the river levees form the highest points in the landscape.

In addition, some areas on the fans of colluvial material beneath the hills surrounding the Herbert cane area are affected by springs and seeps.

High rainfall, slow runoff and low soil permeability result in long periods of inundation or waterlogging, causing poor crop performance and difficulties in timely access to land for field operations. The immediate response by many growers is to initiate some form of drainage management to increase overall productivity and improve flexibility of farm operations.

Growers have made much progress in managing drainage problems such as inundation and waterlogging effectively. However, poor crop performance and disruption to farm operations due to inadequate drainage are still significant issues in some districts. Thus, there is a high demand for more information and new approaches to drainage management to deliver best-practice outcomes. Figure 1 summarises the outcomes required and the techniques available to achieve them.

1.1 Best-practice surface-drainage management outcomes

The overall objective of surface-drainage management is to increase whole-farm sugarcane productivity. However, this must be achieved within the current legislative framework and with minimum environmental impacts. Potential environmental impacts include increased:
Figure 1: Required outcomes and some available techniques for best-practice surface drainage management.
- erosion and sediment movement that may damage crops, change on-farm levels and choke streams;
- peak water discharge rates that may increase downstream flooding;
- movement of suspended sediments, nutrients and other contaminants into freshwater streams and wetlands where habitat damage may occur; and
- movement of suspended sediments, nutrients and other contaminants into estuarine and marine environments where ecosystem processes may be altered.

Integration is needed to ensure that a whole-farm approach to drainage and water quality management does not impact on downstream landholders sub-catchments or catchments.

1.2 Techniques available

Best-practice surface-drainage and crop-management techniques relate to managing surface water in the field, managing the sugarcane crop to reduce the impacts of excess water, and managing runoff water to minimise erosion and maintain water quality.

Surface water within the cropped area may be managed by:
- levelling blocks using laser technology to reduce the incidence of shallow depressions or hollows and to provide even slopes on sections within blocks;
- establishing water furrows to remove water from depressions or hollows where laser levelling has not been carried out;
- providing headland drainage to improve surface and near-surface flow from the cropped area; and
- mounding to reduce waterlogging by raising the cane stool above the average level of the block.

Crop-management strategies that will reduce the impacts of wet conditions include:
- planting or ratooning as early as possible so that the crop will be at an advanced growth stage, more resistant to waterlogging and capable of extracting larger amounts of water during the wet season;
- selecting varieties that are more tolerant of wet conditions; and
- maintaining healthy, vigorous crops that will best withstand wet conditions and extract large amounts of water.
Drainage practices have an appreciable effect on water quality. The concentration of flow in the landscape invariably leads to higher erosive power of runoff, increasing the sediment and nutrient load leaving farms in drains. Acidification of discharge water can result from the drainage of acid-sulphate or potential acid-sulphate soil materials.

Techniques available to minimise erosion and manage water quality include:

- maintaining a blanket of cane trash on the soil surface to prevent raindrop impacts on bare soil and to slow runoff;
- reducing tillage to maintain soil structure and give a rougher, clodder surface between rows to increase infiltration and reduce flow velocity;
- spraying out old ratoons at the end of the crop cycle to reduce soil disturbance;
- maintaining soil cover by using cover crops during fallows;
- managing headlands to minimise erosion and maximise trapping of sediment;
- using flat, grass-covered drains wherever possible to minimise erosion, maximise trapping of sediment and avoid disturbance of acid-sulphate or potential acid-sulphate materials;
- designing drain banks so they can be grassed to provide erosion protection;
- designing drain drop structures, where required, to minimise erosion and provide aeration of water;
- maintaining drains in ways that minimise soil disturbance and maximise retention of protective vegetation cover; and
- establishing trees along larger drains to form dense, protective root mats.

Public concern about water quality and the potential impact of farm runoff on waterways, wetlands, and ultimately, the near-shore ecosystems of the Great Barrier Reef Lagoon has increased significantly in recent years. As a result, growers need to ensure that drainage practices are put in place with the least possible impact on the environment. Many cane growers are very aware of these issues, and there are many examples of where best-practice drainage has been established in harmony with the environment. However, there are opportunities for improvements in drainage management.

1.3 Purpose of manual

The concept of integrated drainage and water quality management requires that a whole-of-farm approach be embedded within the needs of landscape management at a
sub-catchment scale. There is no single effective technique to deal with inundation or waterlogging. However, improving drainage management for better productivity within a farm requires a package of techniques as well as optimisation of drainage networks across farm boundaries. The latter avoids flooding of neighbouring and downstream farms and minimises environmental impacts.

The Sugar Research and Development Corporation and the former Cooperative Research Centre for Sustainable Sugar Production, in partnership with BSES and CSIRO Land and Water, have supported several linked projects in the Herbert district over the past ten years. Given the nature of the soils and topography, the research undertaken primarily addressed surface drainage. Projects have addressed the issues of:

- improving surface drainage design;
- improving drainage management;
- integrating drainage at the sub-catchment scale; and
- reducing soil loss from cane lands.

The results of the individual projects have already been documented and made available to the industry.

This manual brings available information together in one document to provide a framework for integrated surface drainage management. It does not cover sub-surface drainage issues in depth, but it addresses drainage management by:

- defining the issues and impacts of flooding, inundation and waterlogging;
- setting out details of the techniques available to achieve best-practice drainage outcomes;
- considering strategies to achieve the required integration both on and off the farm;
- identifying major Queensland legislation relevant to drainage; and
- setting out some suggested approaches.
2 ISSUES, IMPACTS AND SUSCEPTIBILITY

The terms flooding, inundation and waterlogging are not always used consistently when considering surface-water management. They are different processes requiring different management approaches. Definitions are required to avoid confusion when assessing drainage needs and developing implementation strategies. In addition, landforms and their associated soils differ in their susceptibility to inundation and waterlogging.

2.1 Flooding and inundation

Though flooding and inundation both involve partial or complete submergence of the soil surface and often the cane crop by water, it is useful to distinguish between them. Flooding involves flowing water usually coming from off-farm. Inundation involves water that is essentially still although some slow drainage may be occurring (see Figures 2 and 3).

Flooding is usually widespread and triggered by stream overflow following major rainfall events such as severe storms or cyclones. It is often associated with high flow depths in low-lying areas, but is usually of short duration (hours to days).

The main direct effects of flooding on cane productivity are:

- lodged cane due to the force of flowing floodwater and associated debris including cane trash;
- reduced photosynthesis (the plant’s ability to absorb light to produce biomass) because of silt and debris deposited on cane leaves;
- scoured out cane blocks, particularly of young plant cane; and
- reduced CCS due to cane deterioration and introduction of additional foreign matter into the paddock (trash, debris).

Indirect effects include changed surface levels due to scouring and deposition of silt and sand and inundation of low-lying areas.
Figure 2: Cane stand damaged by flooding. Cane die-off caused by submerged crop.

Figure 3: Large depression showing widespread, shallow inundation following heavy local rainfall affecting a plant-cane block.
Management of flooding is generally beyond the scope of surface-drainage management, although drainage may affect the speed with which residual floodwaters recede.

Inundation is usually more localised. It can occur following storms or prolonged rainfall events of lesser intensity, when water is generated on-farm or as an aftermath of flooding. Areas inundated include both depressions within paddocks and lower-lying areas of cane land that may cover several paddocks.

Inundated areas usually have shallower water depths than flooded areas and water is still or almost so. Inundating water remains for longer periods (days to weeks) than floodwater. The shallowness of inundation allows high temperatures to develop in the water and these conditions together with low oxygen levels are the primary causes of adverse impacts on cane plants.

It is generally accepted that cane land can remain inundated for periods of 3 to 5 days without suffering appreciable damage. The main effects of localised and prolonged inundation beyond this period are:

- damaged cane growing points due to high water temperatures and low oxygen levels, resulting in severe losses of plant cane, particularly at early crop-canopy development stages;
- depleted oxygen levels in the root zone inhibiting root growth;
- reduced soil nitrate levels due to denitrification (the breakdown of nitrate in the soil or from fertilizer to nitrogen gas or oxides of nitrogen that are released to the atmosphere – it occurs when oxygen levels in the soil are depleted);
- increased manganese and/or iron availability, resulting in toxicity due to changed redox potential (a measure of the soil’s ability to affect the solubility of certain minerals).

### 2.2 Waterlogging

Waterlogging occurs when soil remains saturated near the surface for prolonged periods, usually in the order of weeks to months. Pore spaces in the soil are filled with water so that plant roots and soil organisms have no access to oxygen.

Interrelated factors that may cause waterlogging are:
- high and continuous rainfall;
- inadequate irrigation practices – either excessive water applications or inadequate provisions for runoff;
- presence of shallow or perched water tables, including those on hardpans resulting from cultivation;
- poor surface drainage on poorly draining soils; and
- flooding or inundation when soils remain saturated after surface water recedes.

The main direct effects of waterlogging are similar to those of localised inundation, with the exception of the water temperature effect.

The economic impacts of waterlogging and inundation are difficult to separate, but the yield and rainfall data in Figure 4 show that production losses can be substantial.

![Graph showing average cane yields and annual rainfall in the Herbert district over 11 years.](image)

**Figure 4:** Average cane yields and annual rainfall in the Herbert district over 11 years. Contrasting the highest productive year (1996) with the lowest (2000) indicates that productivity has fallen by 50 t cane per hectare over the five-year period due to wet weather. Gross returns to growers have fallen by $1 861 per hectare. This fall in productivity means that returns in 2000 were worth $94.6m less to the farming community and $141.9m less to the total sugar industry (millers and farmers) in the Herbert district. The cumulative effect of four successive wet years with widespread inundation and waterlogging has been a tremendous strain on the financial resources of this district.

Research conducted in the Herbert by BSES and CSR Limited (CSR) in the late 1970s estimated the yield losses caused by waterlogging and high water tables. Using
regression analysis, it was predicted that yields are reduced by 0.5 t cane per hectare for every day that the water table is less than 0.5 m from the soil surface (Rudd and Chardon, 1977; Chardon and Rudd, 1978; Wood, Maclean and Stewart, 1984). Soil oxygen becomes limiting when water tables are higher than this.

A major indirect effect of waterlogging is reduced trafficability for machinery. Wet soils tend to smear, compact and form ruts when traversed, causing damage to the soil structure and, if too wet, machines will bog (see Figure 5).

![Figure 5: Waterlogging not only reduces productivity, but can also cause indirect problems such as reduced field trafficability.](image)

The lack of accessibility for timely operations reduces productivity by:

- delaying or preventing crop husbandry operations (fertilisation, pest and weed control); and
- delaying or preventing harvest.

Weeds or pests can flourish uncontrolled and reduce crop growth. Crops yellow and grow poorly because of losses of nitrogen and lack of fertilizer. In the worst cases, cane has to be left standing because of the inability to harvest on waterlogged soils.
These indirect effects on productivity can often be more significant than the direct effects of inundation or waterlogging. In addition, compaction caused by traffic on wet soils reduces pore space increasing the potential for waterlogging, so that a cycle of decreasing productivity can become established.

2.3 Identifying susceptible areas

Inundation and waterlogging are most frequent in low-lying former swamp or floodplain country. Natural surface drainage outlets are limited because of the very gentle land slopes. In addition, levees along present-day and relict creeks and streams are usually slightly elevated, so drainage lines meander over large distances before reaching an outlet.

Large areas of floodplain and swamp are dominated by soils with heavy clay subsoils or uniform clay soils formed on alluvium. Clay subsoils in these situations usually have very low permeability, so such areas typically suffer from temporary perched water tables or general waterlogging during the wet season. Good surface drainage is critical to maintain productivity.

The low intensity (1:100 000 scale) soil mapping of Wilson and Baker (1990) can be used to estimate the extent of potential inundation and waterlogging problems across the Herbert River area. Wilson and Baker (1990) grouped soil and landscape factors related to inundation and waterlogging under the concept wetness subclasses when assessing suitability for sugarcane. Table 1 sets out the soils in the wetness subclasses for sugarcane and the total areas involved considering only the dominant soils in each map unit.

The data in Table 1 confirm that inundation and waterlogging are serious problems in the Herbert River district and suggest that about:

- 2 100 ha are unsuitable for sugarcane because of inundation and/or waterlogging;
- 5 280 ha have severe inundation and/or waterlogging problems and require intensive drainage measures before sugarcane production should be considered;
- 83 590 ha have moderate inundation and/or waterlogging problems and require drainage; and
- 13 710 ha have minor inundation and/or waterlogging problems such that some form of drainage is required for maximum productivity.
Table 1: Wetness suitability subclasses for sugarcane for the dominant soils of the Herbert River area mapping units and the total areas of each group (Wilson and Baker, 1990).

<table>
<thead>
<tr>
<th>Wetness suitability subclass 1,2</th>
<th>Soils</th>
<th>Area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Negligible wetness limitation – highly productive land requiring only simple management practices to maintain economic production.</td>
<td>Abergowrie, Bluewater, Cadillah, Canoe, Cassidy, Elliot, Fox, Hawkins, Herbert, Hillview, Lucy, Macknade, Palm, Thorpe, Tinkle, Yellarai</td>
<td>55 590</td>
</tr>
<tr>
<td>2. Minor wetness limitations that either reduce production or require more than simple management practices to maintain production.</td>
<td>Ashton, Lee, Midway, Trebonne</td>
<td>13 710</td>
</tr>
<tr>
<td>3. Moderate wetness limitations that either further lower production or require more than those management practices for subclass 2 above to maintain economic production.</td>
<td>Althaus, Arnot, Byabra, Catherine, Cudmore, Hamleigh, Ingham, Lannercost, Lugger, Manor, Molonga, Porter, Ripple, Rungoo, Stone, Toobanna, Yuruga</td>
<td>83 590</td>
</tr>
<tr>
<td>4. Severe wetness limitations – marginal land presently (1990) considered unsuitable due to severe limitations with use dependent upon either undertaking additional studies to determine suitability of sustained production or reducing the effect of the limitation to achieve production.</td>
<td>Leach, Mandam, Orient, Ripple</td>
<td>5 280</td>
</tr>
<tr>
<td>5. Extreme wetness limitations that preclude use for sugarcane.</td>
<td>Brae</td>
<td>2 100</td>
</tr>
</tbody>
</table>

Notes:
1. Note that this allocation to suitability subclasses considers only the wetness limitation.
2. Where Wilson and Baker (1990) have allocated a soil to more than one category, apparently on the basis of local factors in different individual areas mapped, the highest (most severe) limitation subclass has been used.

The high intensity (1:5 000 scale) soil mapping conducted by CSR (Wood and Bramley, 1996; Wood, Schroeder and Stewart, 2003) can be used to assist in identifying areas that are likely to benefit from drainage at the block level. This information can be accessed through Herbert Cane Productivity Services Ltd (HCPSL). Table 2 sets out the soils this study identified where some form of drainage is likely to improve productivity and a summary of their drainage requirements.
Table 2: Soils with wetness problems described by Wood, Schroeder and Stewart (2003) at levels of detail applicable to blocks and a summary of their characteristics and drainage requirements.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Wetness characteristics</th>
<th>Drainage requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Soils on terraces above the Herbert and Stone Rivers</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Terrace Silty Loam</td>
<td>Imperfect to good drainage with seasonally high water tables.</td>
<td>Laser levelling beneficial for improving surface drainage.</td>
</tr>
<tr>
<td><strong>Clay soils in the lowest parts of the landscape</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Black Organic Clay</td>
<td>Poor drainage and high water tables.</td>
<td>Difficult to drain and wetland areas with these soils should not be developed unless an obvious drainage outlet exists. Laser levelling essential to improve surface drainage. Cross drains may be beneficial for long drill lengths. Mounding of cane will help reduce denitrification.</td>
</tr>
<tr>
<td>(1% of cane area)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td>Poor drainage and seasonally high water tables.</td>
<td>Laser levelling essential to improve surface drainage and reduce waterlogging. Cross drains may be beneficial for long drill lengths. Mounding of cane will help reduce denitrification.</td>
</tr>
<tr>
<td>(12% of cane area)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay Loam</td>
<td>Poor drainage and seasonally high water tables.</td>
<td>Laser levelling essential to improve surface drainage and reduce waterlogging. Cross drains may be beneficial for long drill lengths. Mounding of cane will help reduce denitrification. Headland compaction may need to be alleviated for better infield drainage.</td>
</tr>
<tr>
<td>(5% of cane area)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heavy Clay</td>
<td>Poor drainage and high water tables.</td>
<td>Difficult to drain and areas with these soils should not be developed unless an obvious drainage outlet exists. Laser levelling essential to improve surface drainage and reduce ponding and inundation. Cross drains may be beneficial for long drill lengths. Mounding of cane will help reduce denitrification.</td>
</tr>
<tr>
<td>(1% of cane area)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silty Clay</td>
<td>Poor drainage and seasonally high water tables.</td>
<td>Laser levelling essential to improve surface drainage and reduce waterlogging. Cross drains may be beneficial for long drill lengths. Mounding of cane will help reduce denitrification.</td>
</tr>
<tr>
<td>(15 % of cane area)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil</td>
<td>Wetness characteristics</td>
<td>Drainage requirements</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td>----------------------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>Sandy soils formed on raised deposits following old stream channels</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fine Sandy Loam (5% of cane area)</td>
<td>Imperfect drainage with seasonally high water tables with areas that may remain wet due to seepage.</td>
<td>Laser levelling essential to improve surface drainage and slotted underground pipes useful for draining seeps and springs.</td>
</tr>
<tr>
<td>Sandy Clay (4% of cane area)</td>
<td>Imperfect drainage with seasonally high water tables and parts may remain wet due to seepage.</td>
<td>Laser levelling essential to improve surface drainage and slotted underground pipes useful for draining seeps and springs.</td>
</tr>
<tr>
<td><strong>Hillslope soils</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grey Sand (2% of cane area)</td>
<td>Profiles often remain wet well into the dry season due to seepage from the surrounding hills.</td>
<td>Springs and seeps can be drained using slotted underground pipes if there is a suitable outfall.</td>
</tr>
<tr>
<td><strong>Seymour soils on acid volcanic parent materials</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fine Black Sand (&lt;1% of cane area)</td>
<td>Profiles often remain wet well into the dry season due to seepage from surrounding hills.</td>
<td>Springs and seeps can be drained using slotted underground pipes if there is a suitable outfall.</td>
</tr>
<tr>
<td>Fine Grey Sand (&lt;1% of cane area)</td>
<td>Profiles often remain wet well into the dry season due to seepage from surrounding hills.</td>
<td>Springs and seeps can be drained using slotted underground pipes if there is a suitable outfall. Laser levelling would improve surface drainage and reduce waterlogging.</td>
</tr>
<tr>
<td>Coarse Sandy Clay (&lt;1% of cane area)</td>
<td>Imperfect to poor drainage and seasonally high water tables.</td>
<td>Laser levelling recommended to improve surface drainage and reduce waterlogging.</td>
</tr>
<tr>
<td>Grey Brown Loam (&lt;1% of cane area)</td>
<td>Imperfect to poor drainage due to seasonally high water tables.</td>
<td>Laser levelling beneficial to improve surface drainage and reduce impact of waterlogging. Headland compaction may need to be alleviated for better infield drainage.</td>
</tr>
<tr>
<td>Pale Brown Sandy Loam (&lt;1% of cane area)</td>
<td>Profiles often remain wet well into the dry season due to seepage from surrounding hills.</td>
<td>Springs and seeps can be drained using slotted underground pipes if there is a suitable outfall.</td>
</tr>
</tbody>
</table>

Table 2 shows that 14 of the 24 soils identified by Wood, Schroeder and Stewart (2003) have wetness and/or seepage problems. However, the Fine Black Sand, Pale Brown Sandy Loam and Grey Sand soils are identified as having seepage problems requiring underground drainage. This is beyond the scope of this manual, but there are at least 11 of the soils occupying around 40% of the area likely to benefit from surface drainage.
Areas with soils likely to benefit from surface drainage can be identified from the CSR soil mapping combined with local knowledge of the distribution of low permeability soils.

Inundation maps can be developed from detailed topographic data, drainage data and satellite imagery. Data are available from the Herbert Resource Information Centre and can be supplemented with local knowledge of the location of depressions and the extent of low-lying lands.

Soils, topographic and drainage information can be combined to map areas likely to benefit from surface drainage. Such maps provide a means of:

- targeting key areas;
- identifying drainage opportunities including possible outfalls for water;
- guiding and integrating drainage works; and
- avoiding development of land where drainage is environmentally and/or economically impractical.
3 SURFACE WATER MANAGEMENT

3.1 Introduction

Inundation of cane land for periods beyond about three days can severely damage crops so on-farm drainage works should be designed to remove residual surface water within this period.

Removal of surface water allows soils to commence drying through evaporation from the surface, downward drainage and water use by the crop. In addition, drainage of the inter-rows in mounded cane improves drainage of the mounds and helps minimise the impacts of waterlogging.

The main techniques available to manage surface water are laser levelling, water furrows, mounding of rows and headland drainage. These may be used alone or in combination.

3.2 Laser levelling

Laser levelling is a widespread technique that has been recognised by growers as an effective means of reducing the incidence of shallow inundation in small depressions or hollows within individual blocks (see Figure 6). Table 2 shows that it is likely to be of benefit on soils occupying more than 40% of Herbert River sugarcane lands.

Field research at Macknade has shown that laser levelling can give yield advantages of up to 13 t cane per hectare in wet years compared to non laser-levelled areas. Even in dry years, there is a trend for laser-levelled blocks to slightly outperform conventional blocks.

Cross drains may be needed to enhance the effectiveness of laser levelling on blocks with very low grades (<0.5%) and/or long runs. As the name implies, these are drains across the row direction, so that runoff does not have to flow the full length of the row before it leaves the cropped area. Cross drains need to be flat to shallow spoon-shaped and vegetated to avoid problems for harvesters and to minimise sediment export (see Figure 7).
Figure 6: A laser-levelled plant block showing the complete removal of inundation water shortly after a storm.

Figure 7: Laser levelling a block in Ingham.

Laser levelling involves:
- surveying blocks using laser technology and high-resolution Global Positioning Systems (GPS);
- developing an optimum design based on the survey data and any other constraints such as minimising the amount of soil to be moved, adjacent land use, the position of established drains and drainage and any other drainage opportunities; and
- levelling using laser controlled machinery with GPS to cut and fill to implement the optimum design.
HCPSL and BSES Ingham offer a service to growers for optimised design of laser levelling works. The service includes carrying out the field surveys required to prepare computer-aided designs.

Cane blocks need to be dry enough for the survey vehicle and levelling machinery to operate without the wheels sinking to uneven depths to give false level readings.

A number of criteria need to be adhered to optimise laser-levelling designs and their performance. Experience in the Herbert, backed by modelling results, suggests that the following issues need to be considered:

- **Integration across the whole farm and with adjacent farms:**
  - Impacts of changed flow volumes or discharge points on the rest of the farm or on neighbours may make some otherwise good designs unacceptable.
  - Changes in row direction may give a better overall farm layout.
  - Deep cuts where topsoil is shallow may reduce yields or expose highly erodible or acid-sulphate materials with consequent environmental risks. Topsoil may require stockpiling and redistributing after levelling the subsoil.

- **Number and size of sections per block:**
  - Generally one section per hectare is required on big blocks with uniform slope. More sections are required on blocks with varying slope. These sections are areas that are graded to a uniform slope and would usually be levelled as a single entity.

- **Maximum and minimum slope of each section:**
  - A suitable compromise between ensuring sufficiently rapid flow of water off paddocks without causing excessive erosion in fields is 0.125% (one inch in a chain). Higher slopes (i.e. larger than 0.5%) also come at the expense of shorter flow residence times leading to inundation of downstream farms. The lower limit below which flow is too slow to ensure adequate drainage on sections longer than 100 m is 0.01%.

- **Row length of sections and blocks:**
  - Row lengths in excess of 300 m are suboptimal for slopes of less than 0.5% and should be avoided. Where this row length is exceeded, it is necessary to establish cross drains.
Volume of cut and fill:
- A cost-efficient compromise between matching the lay of the land and meeting the above criteria is considered to be 350 m$^3$ of cut per hectare.

Fall to headland:
- About 200 mm fall is needed to the headland at the lower end to allow runoff.

Maintenance:
- Practices such as cultivation or raking should not move soil around creating mounds or depressions or blocking drains or headlands.

Laser levelling should be considered on all the soils of Wood, Schroeder and Stewart (2003) where it is identified as appropriate in Table 2. It may be beneficial in some other situations as well but careful investigation would be needed to make sure it is the best option.

3.3 Water furrows

Water furrows are shallow depressions running parallel with the cane rows that separate the block into a number of slightly raised beds (see Figure 8). These furrows increase drainage density within blocks. Thus, they enhance drainage of flood and inundation water, in particular when combined with laser levelling.

Many cane farmers are convinced that water furrows also reduce waterlogging. This has been confirmed by work conducted in the Ripple Creek catchment, where it was demonstrated that water furrows contributed to a reduction of waterlogging by reducing that part of the total water balance retained on-site by 9%. This represented a reduction in the average probability of a perched water table being less that 500 mm below the soil surface from a frequency of about 83% to a frequency of about 75% for absence or presence of water furrows, respectively. This frequency difference of about 8% is represented by the horizontal distance between the two curves in Figure 9 at a depth of −0.5 m. Whilst this is only a small difference, it does affect yields quite significantly.
Figure 8: A traditional cane block, showing how water furrows enable the drainage of a water-filled depression within a plant block. Note flow concentration and erosion.

Figure 9: Frequency diagram of water table depth at the Palmas site (Ripple Creek) modelled with and without water furrows. Water furrows are not as effective in reducing waterlogging as they are in reducing inundation (Mitchell, 2003).

Figure 10 shows water table fluctuations adjacent to a water furrow, between the furrow and the centre of the bed, and in the centre of the bed in a water-furrowed
block. Adjacent to the furrow is the driest environment with the centre of the bed the wettest. The data give no indication of how wet the site would have been without water furrows.

Figure 10: Water table fluctuations on a poorly drained waterlogged site in Ripple Creek. Row 1 is located next to the water furrow and row 7 on the middle of the bed between furrows. During most of the waterlogged periods, the perched watertable is highest in row 7 indicating that lateral drainage decreases with distance from the furrow. The perched water table rises quickly after rain, but once a healthy crop has established, draw down by root water uptake can rapidly lower the water table and dry out the soil during dry periods, reducing the duration of waterlogging (Mitchell, 2003).

Water furrows come at the cost of lost area for production, as they take the space of a crop row. Typically, every twelfth row is lost and furrow construction and maintenance incur additional recurrent costs. There is some evidence of lower yields immediately adjacent to the furrows, possibly as a result of competition from weeds in the furrow or loss of nutrients by leaching into the furrow, and higher yields on the slightly higher ground in the centre of the beds.

Water furrows constitute a very significant source of sediments in districts where they are used, such as the Lower Herbert floodplain (see Section 5.2). They concentrate field runoff into deeper channels resulting higher velocity, more erosive flow (e.g Figure 8). This leads to scouring of the furrow and a high ability to transport any sediment received from the adjacent field area. Water furrows in sandier soils such as the hillslope soils around the margins of the floodplain erode more than furrows established on the heavier alluvial floodplain soils.
Visual examination of the sequence of sections across a water furrow shown in Figure 11, where erosion was monitored on three occasions, indicates that there has been a net soil loss. The area between the 14 December and 3 May section lines where the 14 December surface is higher than the 3 May surface (soil erosion) is greater than the area between the lines where the 3 May surface is higher (soil deposition).

![Graph showing erosion and deposition](image)

**Figure 11**: Example of three consecutive profilometer readings across a water furrow, showing portions the have eroded, remained unchanged, or where deposition has occurred. Net erosion or deposition is calculated from the average of all points (taken from Visser, 2003).

Field observations indicate that the amount of soil lost through water furrows depends on the frequency of maintenance. Some growers grade or reshape the furrows on an annual basis to retain their effectiveness in removing surface water. However, this increases erosion by removing protective ground cover and it usually provides a source of readily erodible, loose soil material within the furrow itself and along its edges.

The benefits of water furrows for reducing waterlogging can be offset by early planting and/or combinations of laser levelling, headland drainage and mounding. Because of the problems water furrows present with respect of water quality, this is a reasonable compromise between productivity and environmental safeguards.
Water furrows should be phased out wherever practical as growers progressively laser level their blocks and include some form of headland drainage. Laser levelling will remove existing furrows and should provide for adequate drainage in most situations where there is good provision for runoff to headlands.

The other measures identified may not provide adequate surface and near-surface drainage in some low-lying areas subject to frequent and prolonged inundation. Where water furrows are required, it is recommended that they be used in conjunction with laser levelling. The frequency of grading of the furrows should be minimised and vegetative ground cover up to levels of at least 65% should be maintained. This level of ground cover will slightly reduce the drainage efficiency of the furrows. However, it will result in a very substantial reduction in soil loss.

3.4 Mounding

Mounding involves raising the row profile so that the cane plant and some of the roots are above the mean level of the field (see Figure 12). This practice reduces soil moisture in upper parts of the root zone by 4 to 6%. Thus, the cane stool is more likely to be in aerated soil when wet conditions prevail with a resultant increase in production.

Mounding reduces water movement through the fertilizer band and nitrogen losses in drainage water. In addition, the reduction in waterlogging around the fertilizer band should reduce denitrification.

Possible mounding techniques include:

- conventional furrow planting and subsequent mound formation at filling in; or
- placing the billet on the surface of the tilled block and covering the billet and mounding up in one pass using following tynes or discs.
Figure 12: Mounding is particularly beneficial where in-field slope is small and cane is advanced at the onset of waterlogging. Note the height by which the stalks are raised above the inundation water. Other advantages of mounding are improved uptake efficiency and less leaching of nitrogen.

However, with the latter option germination can be poor in dry years due to lack of moisture around the setts. This can be offset by supplementary irrigation where available.

Another risk with mounding generally is the increased likelihood of erosion on the steep edges of the mound. This risk can be reduced by:

- seeding the mounds and inter-rows with low-growing cover plants such as pinto peanuts or soybeans; or
- establishing permanent mound beds on which trash is maintained and not disturbed by subsequent minimum-tillage planting, possibly with controlled-traffic regimes.

Mounding is currently the most cost-effective means of reducing the effects of waterlogging, particularly in combination with laser levelling and headland drainage. It has a particular yield advantage for cane grown on poorly drained lands, where limited outfall does not permit adequate slope from laser grading in the field. However, outlets from the inter-rows to lowered headlands are required.
The greatest trend of yield response to mounding was measured where cane was well advanced at the onset of waterlogging and surface drainage was poor due to inadequate slope. In one situation, mounding showed an increase of 3 t cane per hectare in the plant crop and an additional 1.8 CCS units in the first-ratoon crop. However, in very dry years, mounding can result in a yield decrease (Palmas, personal communication).

The soils information of Wood, Schroeder and Stewart (2003) provides guidance on soils where mounding should be considered, although there may be other circumstances where it would reduce the impacts of waterlogging.

### 3.5 Headland drainage

Drainage strategies designed to remove surface water from the cropped area can only be effective if adjacent drainage is adequate to handle the flows. Headlands can be a major impediment to surface and interflow (sub-surface flow) from the cropped area to field drains. Some of the options available to overcome this impediment include the following, alone or in combination:

- lowered headlands of spoon-drain shape;
- slotted pipes; and
- sand-filled mole drains.

Care must be taken when lowering headlands to avoid erosion due to excessive slopes between the cane row, or inter-row after filling in or mounding, and the headland. The key to minimising erosion of lowered headlands is the profile of this interface. Prior to planting, the profile should be a sharp rise from the headland to the field. After planting, the base of the row or inter-row should be only slightly above the headland. Thus, water does not pond in the crop area just above the headland as is frequently the case, nor does it cause excessive erosion as it flows to the base of the lowered headland (see Figure 13).

If laser levelling is not sufficient to keep headlands dry enough to allow the required degree of trafficability, a narrow trench with agricultural drainage pipe surrounded by gravel may be needed. This should be placed in the lowest part of the headland and drainage of the lower parts of the cropped block can be improved if sand-filled moles are linked to it as illustrated in Figure 14. Headland gravel-filled drains or drainage
pipes can discharge to an open drain if there is a deep enough one adjacent. Otherwise, they can discharge to a sump that is pumped. Further design details are provided in Appendix A.

Figure 13: Left picture – Poorly designed headlands that are too elevated in relation to the inter-row space impede drainage of boc-k-ends and limit accessibility for timely field operations. Right picture – Appropriately designed headland showing a lowered headland showing the slight but consistent fall from the field to the base of the headland allowing surface flow across the headland.

Figure 14: Possible headland drainage layouts. In controlled traffic, it is possible to establish mole drains in each inter-row. Where position of inter-rows change in uncontrolled traffic systems, moles should be placed at an angle to ensure they drain effectively. Mole drains feed into pipe in a gravel-filled trench.
Results of field trials conducted in the Herbert district have demonstrated the effectiveness of headland drainage in reducing localised waterlogging at the lower ends of fields.

Planning of a lowered headland system should proceed with as much care as planning of the remainder of the farm drains because lowered headland systems that act as waterways during flooding have potential to direct substantial water in new directions. In addition, headlands need to be trafficable.
4 CROP MANAGEMENT

4.1 Introduction

Crop management strategies to reduce the impacts of inundation and waterlogging involve:

- having cane crops at stages that tolerate wet conditions when they are most likely to occur;
- selecting varieties tolerant of wet conditions; and
- maintaining healthy crops by minimising other constraints to crop growth.

These strategies are aimed at minimising the damage that wet conditions cause to crops and maximising the ability to remove water from wet soils by evapotranspiration.

4.2 Early planting

The results of trials in the Macknade area and modelling outputs consistently show that the more advanced cane plants are in their growth stage, the less prone they are to the effects of waterlogging at the onset of the wet season. The modelling results indicate that early planting or harvest has a greater positive effect on subsequent yield than the negative effect of elimination of water furrows from blocks.

Yield advantages of early over late planting and harvesting have been measured at 50 t cane per hectare and 7.6 t sugar per hectare. There is an additional carry-over effect the subsequent crop of 15 t cane per hectare and 2.5 t sugar per hectare (see Table 3).

The sediment budget set out in Section 5.2 shows that plant cane is the major source of sediments in cane lands after water furrows. The problem is particularly exacerbated when early wet season thunderstorms in November coincide with late planting. Early planting allows consolidation of surface soil and the development of closed crop-canopy cover before the onset of summer storms and the wet season. The canopy cover reduces erosion by:

- protecting the soil surface;
- reducing surface crusting;
- maintaining higher infiltration;
lowering runoff; and
reducing soil detachment and transport.

In addition, early planting allows for timely fertilisation operations, reducing the likelihood of nutrient loss in runoff. It ensures the establishment of a healthier crop stand, because the possibility of the stand being affected by early inundation or flooding is reduced. Thus, early planting is the single most effective measure in reducing sediment loss from plant cane as well as an important strategy to reduce the impact of wet conditions.

**Table 3:** Yield data obtained from the Macknade trial shows that early planting combined with mounding and laser levelling will deliver significantly higher yields in wet years.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Increase in yield above control treatment [t/ha]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cane</td>
</tr>
<tr>
<td>Year 1 (Normal year)</td>
<td></td>
</tr>
<tr>
<td>Laser levelling</td>
<td>7</td>
</tr>
<tr>
<td>Mounding</td>
<td>3</td>
</tr>
<tr>
<td>Year 2 (Wet year)</td>
<td></td>
</tr>
<tr>
<td>Early planting</td>
<td>50*</td>
</tr>
<tr>
<td>Laser levelling</td>
<td>11*</td>
</tr>
<tr>
<td>Year 3 (Wet year)</td>
<td></td>
</tr>
<tr>
<td>Early planting carry-over</td>
<td>15</td>
</tr>
<tr>
<td>Laser levelling</td>
<td>13*</td>
</tr>
<tr>
<td>Year 4 (Dry year)</td>
<td></td>
</tr>
<tr>
<td>Laser levelling</td>
<td>7</td>
</tr>
</tbody>
</table>

* Denotes statistically significant difference compared to untreated control

If planting is likely to be late, or during fallow periods, it is highly recommended that cover crops are planted to protect the soil surface. A dense canopy cover from legumes, such as soybeans, ensures that the soil surface remains well protected from rainfall impact throughout the fallow period. This measure is effective in:

- reducing soil loss;
- providing a break from long-term sugarcane monoculture and improving subsequent cane yields; and
- producing additional benefits in terms of nitrogen accumulation and yield increases.
Growers recognise the value of early planting but prolonged waterlogging often impedes timely planting. However, given the other benefits outlined above, it is recommended that this measure together with laser levelling and mounding provide the basis for managing both waterlogging and runoff water quality on cane blocks.

4.3 Tolerant varieties

Some cane varieties tolerate wet conditions better than others. However, no current variety can produce high yields under very wet conditions so that the varieties listed in Table 4 are likely to only out-perform relative to others recommended for the Herbert district.

Table 4: Cane varieties showing some ability to tolerate a range of wet conditions.

<table>
<thead>
<tr>
<th>Conditions tolerated</th>
<th>Varieties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flooding and waterlogging</td>
<td>Q120, Q204&lt;sup&gt;b&lt;/sup&gt;, Q183&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Flooding</td>
<td>Q135, Q174&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Waterlogging</td>
<td>Q138, Q194&lt;sup&gt;b&lt;/sup&gt;, Q215&lt;sup&gt;b&lt;/sup&gt;, Q216&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

As with all varieties, these will perform best when other management strategies are in place to minimise the impacts of wet conditions. Thus, any varieties selected for their tolerance characteristics will give best yields when the crop is planted early and the rows are mounded.

4.4 Healthy crops

Healthy, well-grown crops of cane are known to resist the effects of flooding and waterlogging better than poorly grown crops (see Figure 15). Thus, minimisation of crop growth constraints will result in a crop more capable of withstanding the effects of wet conditions.

Additional benefits of healthy, well-developed crops include:

- **Faster drying of wet fields:**
  - Actively growing crops assist in drying out fields through water extraction by evapotranspiration. A well-developed stand of cane can lower the perched water
table present in many low permeability Herbert soils by 0.5 m within two weeks, depending on weather conditions.

- **Reduced erosion:**
  - Quicker development of full canopy cover by healthy crops gives greater soil protection from raindrop impact.

- **Greater nutrient uptake and reduced nutrient loss to the environment:**
  - Healthy crops take up a greater proportion of applied nutrients, more rapid water extraction reduces denitrification and possibly leaching, and reduced erosion can decrease losses in runoff.

- **Increased yields.**

![Figure 15: A healthy stand of cane grown on a poorly drained, heavy alluvial soil in the Herbert district. Ensuring that all growth constraints have been addressed through good crop husbandry is a critical measure in strengthening the crop’s ability to withstand periods of waterlogging.](image)

Many factors contribute to healthy crop growth and attention to all of them is required. Items that should be considered are:

- removing growth constraints (e.g. poor drainage by land levelling, mounding and infield drains, excess acidity by the application of lime);
- developing a balanced fertilizer program based on soil and leaf assays;
- using varieties that are suited to the district and soil types;
- planting disease- and insect-free setts;
- aiding good germination and establishment by preparing the seedbed well and ensuring adequate moisture;
- ensuring that planting equipment is cleaned with fresh steriliser solution and set up for correct fertiliser placement, as well as adequate soil and fungicide coverage;
- developing a pest management plan before weeds, diseases or insects cause problems;
- placing fertilizer close to the root system during main growth to encourage better nutrient uptake;
- reducing factors that stress the crop and limit growth (e.g. providing supplementary irrigation with proper irrigation scheduling); and
- monitoring the crop so that any problems that arise can be dealt with in a timely manner.

Wood, Schroeder and Stewart (2003) give soil specific guidelines that cover a wide range of the above factors such as nutrient management, needs for levelling and likely benefits of supplementary irrigation. Their publication also gives guidelines for interpreting soil analysis results. This information should be extremely useful when used in conjunction with a soil map for each cane block obtained through HCPSL, and with local knowledge.
5 SEDIMENT MANAGEMENT

5.1 Introduction

Increased rates of soil erosion are usually associated with intensification of agricultural practices and the cane lands of the Hebert district are no exception. For example, maps showing estimates of contributions of fine sediments to the coast before European settlement show the most common contribution rate across floodplain areas now developed for cane was 0.00 t/ha/yr to 0.05 t/ha/yr (Bartley et al., 2003). There were moderate areas estimated to contribute 0.05 t/ha/yr to 0.2 t/ha/yr and small areas contributing 0.2 t/ha/yr to 0.3 t/ha/yr. Estimates by the above authors show that contribution rates have increased under current conditions. Estimated rates of 0.05 t/ha/yr to 0.2 t/ha/yr are now most common, with moderate areas contributing 0.2 t/ha/yr to 0.5 t/ha/yr and small areas contributing 0.5 t/ha/yr to 2 t/ha/yr.

Engineering works, including the establishment of drains, also increase erosion rates. Establishment of drainage systems usually involves:

- reducing protective vegetation cover;
- straightening natural drainage pathways, thus increasing gradient; and
- accelerating bank erosion, as flows tend to re-establish more natural meandering stream patterns.

Sediment management must be an integral part of surface-water management because of the role of sediment in nutrient loss from cane land and because of the damage sediments can do to receiving waters.

5.2 Soil loss from cane lands

The loss of sediment and nutrients from the land reduces productivity of farming systems and can degrade downstream freshwater and marine ecosystems. It can reduce water quality and degrades aquatic habitats by:

- changing the bed morphology of water bodies;
- reducing water clarity, light penetration and photosynthesis;
- inhibiting respiration and feeding of biota; and
- changing ecological balances by increasing nutrient supply.
One practical approach to reducing erosion from the cane farming landscape involves targeting the important parts of the system. The development of a sediment budget is a method of identifying ‘sources’ and ‘sinks’ for sediments. Sources are those parts of the cane-land system that contribute sediment, while sinks are the areas where sediment is deposited or filtered. The sediment budget gives guidance to which parts of cane-land landscape we need to focus on to manage soil loss.

A sediment budget is like a bank account where:

- sediments moved from their original position represent cash flow into the account;
- sediments moved but deposited within the landscape represent cash being stored in the account; and
- sediments leaving the landscape represent cash leaving the account.

Three years of research in low-lying cane land representative of extensive areas of the Hebert district have enabled such a sediment budget to be developed for the Ripple Creek sub-catchment (Roth and Visser, 2003). The estimates of soil lost as suspended sediment from the components of the system produced by the budget are shown in Table 5.

The Ripple Creek suspended sediment budget shows that water furrows, followed by plant blocks, are the main sediment sources. Conversely, headlands and spoon drains can act as sinks, trapping a significant amount of the sediment being lost from source areas before it leaves the cane lands. The per hectare soil loss from ratoon blocks is comparatively small, but total loss from ratooned land is an appreciable component of the net sediment export because ratooned blocks occupy the largest area.

The Ripple Creek soil loss data is backed up by water quality samples collected in the Herbert district. Water samples show that suspended sediments in runoff from different components of cane land can vary significantly. The highest values were found in water from recently planted cane blocks. The results show also that runoff from cane land always has higher suspended sediment concentrations than samples taken from adjacent upland forested streams where sediment losses are about 1 t/ha (Roth and Visser, 2003).
Table 5: Average sediment budget for low-lying cane lands, based on data obtained for Ripple Creek sub-catchment in the Lower Herbert (adapted from Visser, 2003). Soil loss comprises suspended sediment load only.

The key issue in using a sediment budget approach is not the absolute sediment loss rate. It is the recognition that the principal sources of soil loss may well be components of the system other than actual cane paddocks. Other components act as sediment sinks. Identifying and effectively managing key components of the system may reduce net sediment export.

Erosion control measures can be targeted at identified sediment sources rather than focussing merely on the cane fields themselves. For example, eliminating water furrows from blocks following laser levelling could reduce net soil erosion significantly. Conversely, inappropriate drain design and management of headlands or spoon drains could eliminate their filter function, increasing net soil loss (see Figures 16 and 17). Loss of ground cover and accelerated erosion in these elements can be caused by:

- removing ground cover by grading;
- exposing dispersive subsoils;
- slashing too frequently; and
- planting inappropriate cover species.
Figure 16: Incidence of drain erosion for different farm drain designs (data obtained from a drain survey of more than 900 drains in the Ripple Creek area of the Herbert district). Conventional, steep-walled drains have a higher frequency of moderate and high erosion due to bank collapse and bank erosion, while well-covered spoon drains show no or little erosion (Roth and Visser, 2003).

Figure 17: Plant-cane field leaking sediment-laden runoff into a drain. Wider headlands and better cover in the drain than as shown here could act as a filter.

It is often important to focus on assessing suspended sediment load rather than total sediment load, because nutrients are associated with the fine sediments. Most of the phosphorus and potassium leaving the landscape in runoff water is bound to fine particles. Thus, any fine sediments that leave the farm take a substantial amount of
nutrients with them. Nitrogen can also be bound to fine soil particles, but more is in the form of nitrate dissolved in the water that may or may not be associated with fine sediments.

Control of sediment loss from cane lands is likely to significantly reduce phosphorus losses. However, measures to control sediment loss need to be complemented by other measures such as control of waterlogging to ensure nitrogen loss from cane lands is minimised.

5.3 Trash-blanket harvesting

The sugar industry has successfully promoted the adoption of green-cane trash-blanket harvesting as an effective means of reducing sediment and nutrient export from cane paddocks (see Figures 18, 19 and 20). The current industry-wide adoption rate is about 70% with close to 100% adoption in districts such as the Herbert. Indeed, protecting the soil surface with trash is critical to maintain soil loss at the relatively low levels shown in Table 5 for ratooned blocks. Cover crops can provide similar protection when it is not practical to maintain trash blankets to maintain trash blankets.

Trash-blanketed ratooned fields still act as a net source of sediments, but there is little scope for further reducing soil loss because values are already close to background. However, the following strategies are recommended to avoid increased soil loss from ratooned paddocks:

- maintaining the trash blanket and avoiding burning, as burning the trash will leave the soil unprotected and more prone to erosion;
- ensuring the trash is evenly spread by the harvester during harvesting operations; and
- avoiding or minimising ripping and cultivation of ratooned blocks at the onset of the wet season as any disturbance of the trash blanket due to tillage provides an additional source of sediments.
**Figure 18:** Concentration of sediments in runoff samples taken at various points in cane land during a 150 mm storm in November 1999, Herbert district. Low concentrations for ratoon crop indicate the benefit of trash retention. Bars in columns show the level of variation as the standard deviation (adapted from Visser, 2003).

**Figure 19:** Trash blankets ensure the soils is covered and protected against rainfall impact, significantly reducing soil erosion (left). Trash also enhances soil biological activity, which further enhances rainfall infiltration and runoff reduction. In the absence of trash, cover crops can protect plant cane fields, as shown by an excellent cover crop of soybeans during fallow on the right.
Figure 20: An even blanket of trash provides protection for the soil surface right across the cropped area.

Trash blanket harvesting has additional benefits including:

- improving air quality because cane is not burnt;
- retaining soil water in dry periods;
- reducing nitrogen loss, with one study suggesting a reduction from 3.8 kg/ha to 0.8 kg/ha;
- improving soil structure and general fertility; and
- reducing weed populations.

Preliminary studies have not been able to directly link fish kills to organically loaded runoff from cane fields. However, studies conducted in the Burdekin show that, under certain conditions immediately after harvest, runoff from trash can contain a high amount of oxygen-demanding organic compounds. These could potentially lead to fish kills in small drains or watercourses. Consequently, it is recommended that trash-blanket harvesting be combined with techniques such as grassed drains and grassed filter strips adjacent to water courses that minimise movement of trash from paddocks to waterways.
5.4 Minimum tillage

Reduction of tillage intensity by restricting high-impact operations such as rotary hoeing to the immediate row space leaves a rougher, cloddy surface between plant rows. This greater cloddiness and surface roughness enhances infiltration of rainfall and reduces flow velocity of runoff, thereby decreasing sediment transport capacity.

There is little agronomic justification for intensive tillage between rows and a reduction in tillage intensity would have additional benefits in terms of reduced fuel and operational costs. This measure may require alterations to existing tillage equipment such as removal of rotary hoe blades normally operating in the inter-row space.

In the longer term, the introduction of a controlled traffic, minimum tillage, legume based farming system is a feasible alternative (Garside, Bell and Robotham, 2006). This proposed new farming system is based on:

- providing legume breaks between crops resulting in a better balanced soil biota, fewer root pathogens and considerable biologically fixed nitrogen;
- separating cane grown in the paddock from vehicular traffic in the paddock by matching wheel and row spacing with guided harvester and haul-out tracking to reduce the impact of compaction to a small area;
- widening row spacing to reduce the distance machinery travels in carrying out operations;
- reducing tillage under minimum- or zero-tillage systems to conserve soil organic matter, improve soil structure and maintain beneficial soil biota;
- improving weed control through the presence of trash blankets or cover crops; and
- reducing waterlogging by using permanent raised beds.

In this system, which results in higher cane productivity, cane is direct-drilled into the stubble of a previous cover crop [e.g. soybeans] that was planted into raised, permanent beds [see Figures 21 and 22]. This means that the field is covered by cane trash, cover crop or cover crop stubble throughout the cropping cycle. This and the fact that soil is no longer loosened appreciably during any tillage are likely to significantly reduce soil loss.
Figure 21: Directly planting of cane into beds with maintained soybean residue - permanent traffic lanes (Photo: Alan Garside and the SYDJV).

Figure 22: Well-established controlled-traffic cane on dual rows (Photo: Alan Garside and the SYDJV).

The long-term effect on runoff generation from highly compacted controlled-traffic lanes has yet to be quantified to ensure that, on balance, this system reduces the net soil loss from plant-cane blocks. However, protection of the lanes by cover crops and trash blankets should minimise erosion and the associated increase in soil organic matter should improve soil structure. This would lessen traffic impacts.
As yet, no monitoring data are available to confirm that overall soil loss is reduced but this is a reasonable assumption based on understanding of soil erosion processes. Further details regarding this system that should not only minimise soil loss, but also result in a more productive and sustainable cane farming system may be found in reports on the work carried out as part of the Sugar Yield Decline Joint Venture.

5.5 Headland management

Results from the sediment budget (Table 5) indicate that headlands usually act as sediment sinks. Sediment trapping efficiency is greatly enhanced if headlands have a healthy and intact grass sward. A threshold of 80% ground cover is recommended to ensure headlands act as sediment traps and not as sediment sources. At cover levels below 65%, headlands will start actively eroding. Frequent grading following harvest and slashing with the implement set to cut close to the soil surface will reduce grass cover below this level with resultant erosion (see Figure 23).

Smoothing out of wheel ruts following harvest is best carried out by tractor pulled levelling bars and slashing height is best controlled using slashers with adjustable height wheels.

It may be necessary to rehabilitate headlands by planting with common couch grass (Cynodon dactylon), water couch grass (Paspalum distichum), pangola grass (Digitaria decumbens) or another suitable species where they have been damaged to the point of active erosion. The grass species chosen should provide good ground cover but not provide harbourage for rats. Pangola grass may have some advantages because it sets little if any viable seed. This may reduce its invasiveness and decrease its attractiveness to rats.

A light top-dressing of fertilizer based on a soil test is recommended to ensure successful establishment of the cover plants. Grass establishment should take place before the onset of wet-season storms.
Figure 23: Actively eroding headland (left) that requires remediation to re-establish cover, contrasting with a well covered headland acting as a trap for sediments (right). Cover levels of 80% are desirable to ensure headlands act as efficient sediment traps. Minimum width of headlands to be effective is 2 m, and they should be wider if land slope is greater than 5%.

Apart from managing ground cover, the actual design of the headland is also important. Headlands need to have a minimum width to be effective as sediment traps. Width is dependant on slope, and recommended widths are:

- 2 m wide for headland slopes of less than 5%;
- 3 m wide for slopes 6 to 7%; and
- 4 m wide for slopes greater than 7%.

As noted in Section 3.5, poorly designed headlands act as a barrier to drainage from the field, leading to waterlogging in the rows immediately upslope of the headland and the headland itself. This also affects accessibility of the headlands and the block. Traffic on headlands that are too wet results in ruts and damage to soil cover, increasing the need for maintenance and the likelihood of headland erosion.

5.6 Drain shape

Analysis of the drain survey data shown in Figure 16 shows clear trends of increasing drain erosion associated with older, traditional steep walled drains. Conversely, flat, grass-covered spoon drains erode less, are easier to maintain and usually function as
sediment sinks. Farm drains are now established mostly as shallow spoon drains [see Figure 24].

![Figure 24: Revegetation of a spoon drain and adjacent headlands using couch grass and lamendra strips. Note application of gypsum to assist establishment on dispersive soils. As for headlands, cover levels should be at least 80% in spoon drains to make them effective sediment filters. A light top-dressing of nitrogen fertilizer is recommended on poor soils, but care has to be taken to apply fertilizers before the onset of the wet season.

Where possible, minor farm drains need to be flat and well covered with grass [more than 80% cover is desirable] to enhance their ability to act as sediment traps, much like extended filter strips.

Flat, spoon-shaped drains have the additional benefit of increasing oxygen levels in runoff water because of the large exposed surface area relative to the volume of flow. This can help compensate for any reductions in oxygen levels as a result of water moving through trash blankets in the cropped area.

There are instances where farmers have already taken the initiative by installing grass filter strips along drains and have found that these strips protect drains from erosion as well as filtering sediments leaving cane blocks. Pangola grass has proved particularly suitable for this task. It is easy to establish and does not impede water flow.

Grass establishment may be improved by:

- applying nitrogen fertilizer at planting;
- stockpiling and redistributing topsoil after the drain is shaped; and
- applying gypsum where dispersive subsoils are exposed in the drain bed.

The grass cover should not be slashed or removed during drain cleaning.
5.7 Appropriate drain maintenance

Water furrows and minor (farm) drains, including headland drains, require maintenance. These drains act as sediment sinks, so the bed level will rise. Thus, occasional grading or scraping will be required to maintain the relative elevations of fields and adjacent drains. Repeated grading or scraping of water furrows and minor drains decreases the level of vegetative cover, greatly increasing erosion.

Reducing the frequency of grading or scraping so that it is only done half as often would greatly increase sediment-trapping efficiency of furrows and drains at minimal reduction of drainage efficiency and is recommended as a minimum requirement. Slashing with machines with adjustable height wheels should be a satisfactory alternative to scraping or grading on many occasions. This should be possible as farm drains are now mostly established as shallow spoon drains.

Where spoon drains are not an option, grass should not be slashed or removed during drain cleaning in order to retain protection against drain bank erosion. Cleaning operations should be limited to the base of the drain and solely to remove sediment deposits, preferably leaving the grassed drain banks untouched.

Reducing the frequency of drain maintenance is often in conflict with the need to control aquatic and semi-aquatic weeds in drains and waterways that contain water for long periods. If land is productive and looked after by growers, undesirable plants, such as para grass (Brachiaria mutica), hymenachne (Hymenachne amplexicaulis), Guinea grass (Panicum maximum) and water hyacinth (Eichhornia crassipes), are usually kept under control.

Water hyacinth is a serious weed that causes significant water quality deterioration, loss of fishery production, reduction in aquatic habitat value, loss of performance of road culverts and increased need for drainage improvements. Para grass is a well-established semi-aquatic weed throughout the catchment, seriously affecting drains and aquatic habitats. Hymenachne, a more recent exotic arrival in the catchment, has rapidly come to dominate many aquatic habitats and low-lying lands, and can grow in deeper water (more than 2 m deep) than para grass.
Unless controlled, these plants will clog drains, waterways and wetlands and severely reduce their effectiveness for drainage purposes. They also damage aquatic habitats by crowding out desirable species and reducing oxygen levels and provide harbour for rats and other vermin.

Weed management should be pro-active and strategic with efforts being directed towards minimising herbicide use and the costs of ongoing maintenance by implementing long-term solutions. Options which should be employed include, but are not limited to:

- planting trees that produce shade and mulch (especially those with allelopathic properties that suppress the growth of nearby plants) along banks of major drains;
- establishing non-invasive native aquatic plants;
- planting non-invasive native grasses and ground cover plants on exposed banks;
- grazing livestock seasonally or periodically, where feasible, and with appropriate fencing, to consume exotic grass weeds;
- removing weeds manually; and
- poisoning selectively, on a limited scale timed to ensure no large weed build-ups.

Extensive herbicide applications should be considered only as a last resort and should be used only when terrestrial or fully exposed semi-aquatic weed species are out of control.

Dense assemblages of aquatic weeds such as water hyacinth should not be poisoned unless few plants are being treated. Large-scale poisoning introduces substantial quantities of bioavailable organic matter and nutrients (in the form of dead plants) into the water, causing deoxygenation and rotting, followed by eutrophication and very rapid regrowth. In such cases, mechanical removal and mulching appears to be the only environmentally acceptable alternative.

The costs and logistical difficulties of mechanical removal can be considerable if the weeds are allowed to proliferate. However, many of these difficulties can be minimised by taking full advantage of wet season flushes and implementing ongoing pre-emptive clearing in areas that are known to be seasonally invaded.
5.8 Drain design

Analysis of the drain survey results shown in Figure 16 indicates that the highest incidence of drain erosion occurs on main drains with steep, bare drain walls. Measurements of drain bank erosion corroborate these findings.

Both constructed drains and incised natural streams flowing in unconsolidated materials, such as soils, tend to meander by eroding one bank and laying down sediment on the opposite bank as point-bar deposits. The simultaneous deposition and erosion shown in Figure 25 suggests that this phenomenon is occurring. One way to minimise meandering is to mimic overland flow by using broad flat or spoon-shaped, vegetated, drains.

![Deposition and Erosion](image)

**Figure 25:** Example of simultaneous erosion and deposition in a major drain. Right: steep-walled drain bank actively eroding. Left: flatter and better vegetated relatively stable bank. Significant amounts of bed deposition are taking place in the drain itself and on the left bank.

In those cases where spoon drains are not an option, it is essential that drain banks be shaped to an angle of about 45° or less and protected with vegetation. Drain banks steeper than 45° are subject to collapse and accelerated erosion due to difficulties in establishing ground cover on the drain wall (see Figure 25). Ground cover is difficult to establish because:

- seeds or runners fall down the slope or wash off;
- runoff is very rapid so the soil takes in most water from flows in the drain;
- subsoils exposed are often dispersive and/or infertile; and
- very steep slopes on the northern side of east-west drains can be shaded in mid-year.

Pangola grass has proved particularly suitable for protecting drain banks where the slope is 45° or less. It is easy to establish, low maintenance and does not impede water flow. The grass should not be slashed or removed during drain cleaning in order to retain protection against drain bank erosion.

Good grass cover on the banks of deeper drains will provide erosion protection during high flows (see Figure 26). However, erosion and deposition can occur if velocity is sufficient during lower flows that persist for some days or weeks because protective vegetation can be killed off.

![Figure 26: Example of a well-grassed drain bank with pangola grass (right hand). Once established, the grass sward on banks should not be removed. Maintenance should be restricted to the bed of the drain.](image)

Responsibility for revegetation or reshaping the banks of major drains may reside with drainage or water boards. However, smaller farm drains which exhibit bank erosion need to be reshaped and/or revegetated by growers.

### 5.9 Drain drop structures

Constructed flow drop structures can overcome problems of significant erosion of drains in sections that are too steep. Cases where drop structures are warranted include:

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_BSES Limited Technical Publication TE06004_
- shallow farm drains entering deep main drains where the bed of the shallow drain will erode down until it reaches the bed level of the main drain; and
- gully erosion in main drains where the terrain is too steep, such as on steeper colluvial soils on foot slopes of hills and mountains, in particular on the more erodible sodic duplex soils with dispersive subsoils in the headwaters of Cattle Creek and Stone River.

Gullies in natural situations usually form a series of overfalls into plunge pools, creating a stepped drainage profile. The lower ends of the plunge pools silt up as the overfalls erode, so the steps migrate up the drainage line, gradually lowering the drainage profile.

Artificial drop structures and lining of the drain bed with rocks are effective control measures to stop erosion and head-ward migration of the overfalls (see Figure 27). The drop structures break the drain into shorter reaches with lower slopes. This gives a more stable system, provided that there is sufficient roughness in the bed to dissipate the flow energy immediately below the overfalls and adjacent banks are protected.

![Image](image_url)

**Figure 27:** An example of a successful series of drop structures established on a farm drain that was too steep and cutting into dispersive soils. Rock piling and concreting at regular intervals were sufficient to slow flow and stabilise the drain, with re-vegetation occurring spontaneously once the gullying had been stopped.

Drop structures can be constructed with loose rocks, rock-filled mesh mattresses or concrete. Concrete overfalls and downstream aprons with protruding rocks to dissipate flow energy may be required in more dispersive soils vulnerable to erosion. In all cases, fringes around the drop structures need to be well grassed to avoid new incision at the edges of the structures.
It is critical that designs for drop structures ensure that low flows go over the centre of the structure and are confined to the centre of downstream rock or concrete aprons. If low flows are able to bypass the structures, they will form small channels where erosion during high flows quickly cause major bypass gullies. Specialist design input may be required (see Figure 28).

![Figure 28: Schematic diagram of a site where a drop structure may be required to prevent bed erosion of the shallow farm drain entering a deep main drain.](image)

An environmental benefit of drop structures such as those suggested above is that they enhance aeration of drain waters through their riffle effect. Water in cane-land drains is frequently oxygen deficient and lack of oxygen has been recognised as a major problem for fish and other aquatic species.

### 5.10 Revegetating main drains

Main drains are those drains that link major farm drains and provide the main conduit of drain waters out of a particular drainage network or sub-catchment. They are usually managed by drainage or water boards. They can vary significantly in their propensity to act as net sink of sediments, depending on the magnitude and balance of bank erosion and drain-bed deposition.

The same management principles set out for farm drains in the preceding sections generally apply. However, main drains, because of their larger size, offer an additional
opportunity to improve water quality and aquatic habitat conditions by establishing riparian tree vegetation (see Figure 29).

![Image of riparian tree vegetation](image)

**Figure 29:** Examples of effective control of drain erosion through re-vegetation. Left example: right bank protected by a dense cover of grass and growing trees that will eventually shade out the grass and reduce rat harbourage problems; left bank sprayed and with little cover – not recommended. Right example: showing a reshaped drain bank prior to revegetation with species selected to maximise future shade and of moderate height to avoid branching and interference with harvester operations.

These drains are larger, so flow energy is usually greater. Thus, using trees for stabilising bank erosion provides a better alternative than grass cover provided the correct tree species are selected and they are planted at sufficiently high density. High tree density is required to form a dense root mat along the entirety of the drain bank to avoid preferential scouring of the drain bank. A high tree density provides a high level of shade that inhibits grass and minimises rat harbourage.

Shading of the drain can also significantly decrease the incidence of light dependant aquatic weeds such as para grass and hymenachne. Elimination of such weeds by shade reduces drain maintenance costs, but more importantly, improves the oxygen status of the drain water. In addition, shade reduces water temperature further improving oxygen status.

The establishment of trees in the riparian zone of main drains provides a more attractive fish habitat by:

- lowering water temperatures;
- improving the oxygen status of the water;
• eliminating weeds; and
• providing shelter amongst the root mats.

No scientifically tested recommendations on appropriate tree species for vegetating drain banks are available but species selected should have:
• quick canopy growth to shade-out weeds;
• potential value as timber species;
• high survival rate of seedlings; and
• reduced propensity for low lateral branches that would interfere with farm-machinery operations.

Vegetating drain banks with trees will require earthworks to reshape the drain wall in many cases, so it is a costly measure. Establishing trees along all main farm drains requires funds beyond the means of individual farmers or even drainage boards. Thus, vegetation needs to be highly targeted and a drain survey to identify the hotspot drain sections most in need of rehabilitation is recommended. Details on how to conduct drain surveys are provided in Section 6.2 and Appendix B.

Other opportunities to enhance the environmental performance of large drains include the formation of artificial wetlands and the introduction of silt traps. Artificial wetlands can be beneficial by:
• intercepting water with low dissolved oxygen levels;
• acting as silt traps and nutrient sinks by reducing the movement of nutrients and soil into natural waterways;
• helping to recharge underground water aquifers; and
• serving as a breeding habitat for fish, birds and water plants.

Opportunities for establishing wetlands and improving drains in the Ripple Creek area are identified by Butler and Burrows in Roth et al. (2001) and some design principles are provided.
6 INTEGRATED DRAINAGE MANAGEMENT

6.1 Introduction

An important principle of any drainage management system is that there are two levels of integration. Firstly, the strategies adopted on-farm must be integrated with each other and with ongoing farm- and crop-management practices (see previous Sections and Section 8). Secondly, on-farm drainage management strategies must integrate with the sub-catchment and then the catchment. This requires the active involvement of all growers.

Once drainage water leaves the farm, it does not disappear. It merely moves elsewhere. This may be into natural streams or remnant wetlands, but it could also be to a downstream neighbour, who now has to cope with additional runoff possibly entering their property at a different point.

Design of drainage works has often been uncoordinated across farm boundaries, or undertaken without taking account of catchment flow and drainage conditions. Lack of coordination has often given rise to disputes between growers and resulted in sub-optimal drainage design and wasted resources. This is particularly the case where it was not recognised that, to achieve effective drainage at the field level, there needs to be effective drainage at the sub-catchment level.

The main benefit of integrating drainage across farm boundaries is that it allows for better performance of drainage measures across a whole district. It also means achieving greater equity amongst growers. Often upstream growers enjoy excellent drainage at the expense of downstream growers who experience increased inundation because of the additional run-on water they have to drain. This can lead to lower overall productivity from a whole-of-district perspective, because average production will be significantly less if a large proportion of growers are suffering lower yields.

If the drainage system is optimised such that upstream farms drain only as fast as is necessary and not as rapidly as possible, downstream growers are likely to achieve appreciably higher productivity while upstream growers maintain similar or marginally
reduced productivity. Under this scenario, the district would be better off, as overall productivity would be higher.

Planning drainage systems for a sub-catchment provides more opportunities to augment drains to deliver environmental benefits by means such as:

- protecting key natural areas and/or cultural heritage sites;
- incorporating appropriately designed fish habitats;
- developing artificial wetlands in areas that otherwise would remain marginal if in production or are unused; and
- incorporating sediment-trapping structures.

Thus, integrated drainage management is not only about implementing the best suite of drainage options on a farm, but also about optimising the drainage network to meet the requirements of all growers in the sub-catchment. Environmental benefits can be delivered at the same time. Sections 6.2, 6.3 and 6.4 provide some guidelines how to plan and develop better drainage systems within the landscape through optimisation of the drainage network.

6.2 Data and information required

Optimisation of an existing surface drainage network requires information on the length, dimensions, slope and flow direction of individual drain segments and natural watercourses as well as information on topography and land boundaries. Flow efficiency through the network is also affected by the location and characteristics of culverts, weirs, settling ponds and other drain structures.

Most of the required drainage information is not readily available and has to be obtained by on-ground survey. To be useful, such a survey requires a systematic and standardised approach. Appendix B provides an example of a drain-survey template successfully used in the Ripple Creek case study. Such a survey can also be used to assess the condition of drains and adjacent headlands with respect to:

- weed infestation;
- ground cover;
- drain-bank erosion or collapse; and
- sediment deposits in the drain bed.
Once the drain-survey data have been collected, it is recommended that they be compiled into a Geographic Information System (GIS). The GIS provides an efficient means of producing maps and/or querying the data. Maps are useful planning tools and are particularly helpful in identifying drain erosion hotspots requiring targeted management intervention. Isolated problem areas may require repair, while clusters may indicate that redesign is needed.

The information stored in the GIS is also critical input data for modelling tools used to optimise drainage networks (see Section 6.3). The survey data obtained in the Ripple Creek case study is accessible through the Herbert Resource Information Centre, which can produce a variety of map products for drainage planning purposes at block, farm and sub-catchment level.

### 6.3 Tools to optimise drainage networks

Determining the optimal design of a drainage network is a very complex task. The specific dimensions required for individual drains within it and the impact of the inclusion of features to enhance environmental performance must be considered. Computer-simulation tools called models are used to solve these optimisation problems.

Drainage network models calculate the amount of runoff flowing through the various components of the drainage systems for different rainfall events. They are able to match the flow generated by a specified rainfall event against the drain network’s capacity to handling the runoff volume. This allows identification of locations where the system may fail because it is unable to cope with the flow. Such failures will result in drains overtopping, spilling into adjacent cane land and causing inundation. Both the failure points and the areas likely to be inundated can be represented in maps produced by the models.

By successively changing the drainage network’s parameters and changing the design specifications of individual drain sections in the model before re-running it, failure points can be eliminated until the system is optimal for the specified conditions. The optimisation could mean that no major inundation would occur in a given sub-catchment for a specified event because runoff is evenly drained from all parts of the network. For example, successive runs of the model could be used to determine changes to
parameters such as drain cross-sections and culvert dimensions to allow a system to cope with runoff from a 125 mm rainfall event over 24 hours.

There are many commercially available drainage models that can be applied to the above type of exercise. The main differences between the various models relate to:

- speed and efficiency with which they can be run;
- ease of use; and most importantly,
- type and amount of input data required.

The more sophisticated and realistic models are, the higher their computational demands and the greater their data requirements. Most of these modelling tools are too complex to be readily used by individual growers, so drainage optimisation exercises invariably require specialist input. This expertise can be provided by engineers and hydrologists employed by research agencies, relevant government agencies such as the Department of Natural Resources and Water, water boards or private consulting firms.

The application of a model called MIKE 11 coupled to a GIS that contained detailed terrain information to solve inundation problems in the Ripple Creek area of the Herbert district is a recent example. This is a very sophisticated approach. It was possible because of the good data available and because initially this was part of an SRDC integrated-drainage research project involving BSES and CSIRO. Procedures and brief descriptions of how the model was applied in the Ripple Creek case study can be obtained in a number of separate publications (see references and further reading list, Section 9).

Examples of two types of output generated by the model are provided in Figures 30 and 31. To enable growers to relate the model output to their farm, the drainage network shown in both screen captures is underlain by a satellite image showing actual vegetation and cane blocks.
Figure 30: Example of MIKE 11 output, showing the Ripple Creek drainage system in the Herbert district. Different colours in the drains denote flow depth. Most of the drains are showing shallow flow of less than 0.5 m, but Ripple Creek in the north and the two main drains have flow depths ranging from about 1.5 to 3 m. In the top of the screen the corresponding hydrograph of a selected drain is shown (Roth et al., 2001).

Figure 31: An inundation map for Ripple Creek in the Herbert district generated by MIKE 11 coupled to a digital terrain model. During the model run, the inundation dynamics can be observed. The main inundation in the top right corner remained for an extended period, while the other inundated areas were readily drained after the rainfall event simulated by the model ended (Roth et al., 2001).
In one case, as the model simulates the flow of water through the drain systems, it is possible to visualize the flow through the drainage network. Figure 29 shows a computer screen capture of the flow visualisation, with the drainage network in different colours according to depth of flow. Any individual drain can be queried, generating a drain hydrograph as depicted in the top section of Figure 30.

The ability to examine individual drains is important because it allows growers to query drains on their farm that they know well so they can ‘reality check’ the model. Thus, the model’s performance can be tested to ensure it is in line with local knowledge.

Figure 31 illustrates the second type of output. Linking the flow depth in Figure 30 with the digital terrain model that captures elevation and landscape depressions enables the determination of areas that will be inundated when flow exceeds drain capacity. The inundated areas are clearly visible, and during the model run the dynamics of inundation can be realistically captured. Because the drainage model was coupled to an accurate representation of topography, it was possible to visualise the location and duration of inundation that would occur with different drainage-systems management options.

Adequate visualisation of model outputs is a key prerequisite for models to be useful tools in assisting growers understand the drainage system responses to changes made on a specific farm within the drainage network. Initial set-up costs can be high, depending on the amount of data acquisition required and the complexity of the modelling software. However, once the model is set up, re-running it with different management scenarios or to test the implications of changes to particular drains is a cost-effective operation.

Development of such a tool may be a worthwhile initial investment for a water board, given that it can be an essential management tool to optimise drainage networks. It functions on a rational basis and is transparent, so it can support the negotiation of more equitable drainage network configurations among growers.

6.4 Developing and testing drainage network scenarios

The modelling tools discussed in the previous section require specialist input to set up and run. However, they should be tools that growers can use collectively to determine the drainage design and network features they would like to implement to achieve a
suite of agreed objectives. A number of key steps have to be observed for this to work effectively.

Growers need to develop trust and ownership of the model results in order to accept recommendations resulting from model outputs. They need to understand:

- how the model works;
- the data it uses; and
- the assumptions on which it is based.

If the model output is not credible or does not give a reasonable representation of the systems in which growers are accustomed to operate, it is unlikely that its results will be accepted. This is particularly relevant if the modelling outputs are to form the basis of dispute resolution between individual growers in relation to more equitable drainage arrangement across farm boundaries.

Based on the Ripple Creek case study, it is suggested that users adhere to the following steps:

- **Placing the problems and issues on the table:**
  - All growers within a drainage board or water board area (which ideally should be delineated on catchment boundaries) should agree which problems they need to solve, and what common outcomes they want to achieve.

- **Getting agreement on the process and selecting the appropriate modelling or decision support tools to assist this process:**
  - The selection of appropriate modelling tools should be determined in the planning process participating growers want to use. Process definition should include the types of data that will be collected and who will collect it, as data type and availability will define which tools are applicable.
  - This step also needs to spell out how the information and the modelling results will be shared between participants, and to set up agreed methods of evaluation and conflict resolution.
➢ Acquiring and collating data and setting up the model:
  • Growers should actively participate in some of the aspects of data collection, such as carrying out the drain survey, determining the drain dimensions and monitoring erosion and water quality.
  • The collation of the data into appropriate formats and the subsequent setting up of the model is then typically undertaken by specialists from research institutions, in collaboration with government technical officers, or by consultants.

➢ Demonstrating the model and ensuring that it reflects reality:
  • This is probably the most important step. It entails a demonstration and explanation of how the model works, how it uses the data and how the model results relate to local experience. This is both an informal model validation and a method to allow the integration of grower knowledge. It is an essential step that increases grower knowledge and ownership and acceptance of the model.
  • It may have to be carried out in a number of iterations with subsequent periods of further model refinement and presentations to growers until a sufficient level of acceptance is achieved.

➢ Defining the management options and scenarios to be tested:
  • The model can be used to test the merits or deficiencies of different management scenarios once it is generally accepted as reflecting reality well enough to design and optimise drainage networks.
  • Suggestions on how to change the system; which drains to alter, what changes are needed and where, what flow control structures to include etc. can be determined interactively in workshops with growers, water board members and agency technical officers.
  • Once the scenarios have been agreed upon, the modelling team will set up the model accordingly and re-run it with the new parameters.

➢ Analysis of modelling results, options selection and implementation:
  • The results of the scenario analysis are presented and discussed with growers.
  • Growers need to agree then on which are the most equitable and preferred options for implementation. In some instances this step may need to be complemented by an economic analysis of the various options to assist in the selection process.
  • Implementation is undertaken according to an agreed schedule. Generally, working up the catchment is best.
Monitoring, evaluation and review:

- It is important to establish a monitoring and evaluation process to ensure that the agreed objectives of the drainage network optimisation are being achieved once works have been completed.
- A formal review process should be included from the onset to allow for dispute resolution and to assess any necessary modifications to the original drainage plan.
7 LEGAL ASPECTS OF DRAINAGE

7.1 Introduction

Many Acts of Parliament and associated Regulations cover drainage of lands, so the legislative aspects of drainage are complex. In addition, some of the requirements of these Acts and Regulations are open to interpretation.

Expert advice should be obtained in relation to the provisions of the various Acts and the requirements they place on proposed drainage works. Advice from the contact people listed in Table 6 may be sufficient in many cases. However, legal advice should be sought where there are any doubts about compliance requirements or where disputes may arise.

The legal aspects of drainage may be considered under the following three categories which are not mutually exclusive:

- **Disputes between neighbours:**
  - These often rely on common law precedents for settlement.

- **Legislation designed to ensure the orderly management of water in the landscape and development and management the necessary infrastructure.**

- **Legislation designed to protect the common good:**
  - Legislation in this category is designed to protect society through planning and to protect natural resources and the natural environment.

7.2 Common law precedents

Drainage and the effects of water redirected by drainage works are responsible for many disputes between landholders and these can end in litigation often based on common law precedent. Disputes are most frequent where one party working in isolation has been responsible for the works. Thus, integrated catchment drainage plans, preferably developed within the framework of a Water Authority, go a long way towards preventing such disputes.
The following legal precedents have been established in Queensland:

- upstream proprietors cannot be held liable merely because surface water flows naturally from their land onto the lower land of their neighbour;
- upstream proprietors may be liable if they cause water to flow in a more concentrated form than it would do naturally;
- upstream proprietors may be liable if they cause water to flow in a place where it would not do naturally;
- downstream neighbours are obliged to receive natural (i.e. unaltered) flow from higher in the catchment but can take reasonable steps to protect their land without diverting water to a third person; and
- downstream neighbours can claim damages as a result of concentrated or altered natural flow.

### 7.3 Queensland legislation

There are a number of Queensland Acts that may relate to drainage activities and frequently there will be requirements to comply with the provisions of more than one. The main acts applying directly to drainage works are:

- **Water Act 2000 (replaces the Water Resources Act 1989)**
  - This is described as “An Act to provide for the sustainable management of water and other resources, a regulatory framework for providing water and sewerage services and the establishment and operation of water authorities, and for other purposes”.
  - It specifies that the bed and banks of all watercourses and lakes forming all or part of property boundaries are the property of the State.
  - It covers establishment of Water Authorities that can deal with drainage issues and delineation of the areas in which they will operate.
  - It covers a number of other activities that may be related to drainage, such as granting permits for destroying vegetation, excavating or placing fill in a watercourse or placing barriers in watercourses.
  - It does not apply to tidal watercourses.

- **River Improvement Trust Act 1940**
  This Act provides for the protection and improvement of rivers, the repair and prevention of damage to rivers, the prevention of flooding, the prevention or mitigation of inundation and the management and administration of Trusts.
Integrated Planning Act 1997
- This Act seeks to achieve ecological sustainability by coordinating and integrating planning and managing the processes of development with provisions that consider drainage works as development infrastructure in some cases.

Environmental Protection Act 1994 and the associated Environmental Protection (Water) Policy 1997
- Relevant sections of this Act deal with environmental protection and the maintenance of ecosystem processes.
- The Regulation deals with identifying and protecting the environmental values of Queensland Waters, including protection from acidity released by the disturbance of acid-sulphate soils.
- Farm drains are considered to be first order streams requiring management practices that minimise environmental harm.

Fisheries Act 1994
- This Act covers the management, use and development of fisheries resources and fish habitats.
- It provides for the issue of permits to destroy marine plants and/or to carry out works in declared fish habitat areas.

Native Title (Queensland) Act 1993
- This Act covers the existence of Native Title over some land tenures established by Europeans, subject to defined conditions.

All of the above Acts may be downloaded from http://www.legislation.qld.gov.au/.

Legislation that applies to drainage is primarily drafted to manage extraction of water from watercourses and to manage the watercourses themselves. Thus, it is not well suited to managing situations involving excess water such as:
- flooding;
- drainage;
- constructed drains; and
- impacts of drainage on natural watercourses.

The approvals required for drainage works generally relate to outfalls and to the disposal of drainage water.
7.4 Queensland approval agencies and processes

Landholders require a development permit under the *Water Act 2000* if drainage works will interfere with the bed or banks of a watercourse. Additional permits may be required for destroying vegetation, excavating, or placing fill in a watercourse, lake or spring. The Department of Natural Resources, Mines and Water administers this Act.

Other permits and licences may be necessary as shown in Table 6 for the Herbert district.

**Table 6**: Overview of agencies’ responsibilities in relation to licences and permits for drainage work and relevant contacts for the Herbert district.

<table>
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<tr>
<th>Agency</th>
<th>Responsibility</th>
<th>Contact for Herbert</th>
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</table>
| Department of Natural Resources and Water | o Licensing works in all non-tidal watercourses, lakes and swamps.  
 o Vegetation management. | Ian Baker  
 4777 2822  
 Dennis Schy  
 4799 7507  
 Peter Shilton  
 3224 8392 |
| Environmental Protection Agency | o Maintaining and monitoring quality of all discharge waters.  
 o Issuing discharge licences if necessary.  
 o Permits for works in tidal areas.  
 o Permits for certain dredging within watercourses. | Murray Whitehead  
 4722 5211 |
| Department of Primary Industries and Fisheries | o Permits for destruction of marine vegetation.  
 o Permits for fish barriers.  
 o Permits for works in declared fish habitat areas. | Rebecca Shephard  
 4722 2656 |
| Department of Transport (Main Roads, Queensland Rail) | o *Transport Infrastructure Act 1994*  
 o Integrated drainage with Main Roads and Queensland Rail. | Gary Poul sen  
 132380 |
| Local Authorities | o Urban areas and road drainage, ensuring drainage conforms to Development Control Plans.  
 o Increasing responsibility under the Integrated Planning Act. | Andrew Brown  
 Department of Local Government  
 3234 1870  
 Hinchinbrook Shire  
 Engineer  
 4776 4607 |
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<tbody>
<tr>
<td>Water Authorities</td>
<td>○ Approvals for works within a proclaimed Water Management or Drainage Areas.</td>
<td>Chairman: Sam Girgenti (Ripple) 4777 2785 Leno Cantoni (Forrest Home) 4777 2734 John Marsh (Loder) 4777 1619 Tim Kemp (Mandam) 4777 1603</td>
</tr>
<tr>
<td>River Improvement</td>
<td>○ Approvals for and responsibility for works within watercourses for which they are responsible.</td>
<td>Chairman: Bill Pickering 4776 1718 Ross Hogan 4776 4607</td>
</tr>
<tr>
<td>Trusts</td>
<td></td>
<td>Graheme Dickson 4776 4229</td>
</tr>
<tr>
<td>CSR</td>
<td>○ Drainage works within cane tramway easement areas</td>
<td></td>
</tr>
</tbody>
</table>

The preparation and submission of a sub-catchment drainage plan would enhance the licensing process regardless of which Acts pertain to the approval.

Tenure has to be considered for all affected land. Works on State Land, including some leasehold land, may involve Native Title. In addition, Native Title can apply to some freehold lands.

An acceptable acid-sulphate management plan will be required before approval of a permit for works below 5 m AHD (Australian Height Datum). An example is listed in the references and further reading list. The management plan will have to demonstrate that acid-sulphate materials will not be disturbed or show the volume of material and concentration of acid sulphate. If acid-sulphate material is to be disturbed, suitable ways of containing or treating the excavated material will have to be set out. Verification assays and monitoring for up to 2 years after construction may be necessary.

General planning for drainage works within the Herbert district are covered by a Master Land and Water Management Plan, which has been prepared for Hinchinbrook Shire Council, CANEGROWERS Herbert River District, Department of Natural Resources and Water, and Thuringowa City Council.
7.5 Establishment of a Water Authority

As noted in Section 7.2, integrated catchment drainage plans can be developed within the framework of a Water Authority. There are at least two advantages to this approach.

Firstly, integrated drainage works designed for larger catchments generally function better and cause less off-site damage than works planned for small areas within a catchment. Integration occurs across a larger area and more options are available to overcome problems. Thus, they usually have less adverse impacts on individual landholders.

Secondly, larger schemes such, as those within a catchment Water Authority Area, have access to greater funding. This may allow payment of compensation to individuals or minority groups who may be disadvantaged by drainage works developed for the general good.

The formation of a Water Authority under the Water Act 2000 with drainage as its main activity is one option for establishing sub catchment drainage plans and for provision for ongoing drainage works and maintenance. A Water Authority Area for drainage purposes may be constituted by the Governor-in-Council where a sufficient number of landholders in a locality support the proposal.

Formation of a Water Authority requires a formal proposal that includes:

- a description of the purposes for which it is proposed to constitute the Water Authority;
- a description of the boundaries of the Water Authority Area;
- a plan and description of works already constructed that it is intended the proposed Authority will acquire;
- a plan and description of works that it is intended the proposed Authority will construct;
- a plan and description of land that it is intended the proposed Authority will acquire for its purposes;
- estimated costs together with a statement of the proposed means of defraying those costs; and
- the number of members and the constitution of the proposed Authority.
The proposal is lodged with the Queensland Department of Natural Resources and Water and, if acceptable, is recommended by the Minister for Natural Resources and Water to the Governor-in-Council.

Water Authorities are Statutory Bodies and as such they are bodies corporate and can:
- borrow money and levy rates; and
- enter into contracts and agreements;

Water Authorities also have the powers to plan and undertake drainage works. After giving notice to the affected landholder, Water Authorities can:
- make surveys and take levels;
- set out works and break up the soil;
- open up drains;
- construct and carry out all necessary drainage works;
- erect fences;
- remove or use any quarry material, trees, timber, or other material considered necessary; and
- carry out blasting operations.

In relation to administration, Water Authorities must:
- elect a chair, a secretary and have nominated members;
- meet annually;
- prepare and adopt a budget; and
- have their accounts formally audited annually.

### 7.6 Training and certification

Drainage is the subject of Section 2.5 of the Cane Growing Code of Practice and the COMPASS (COMbining Profitability And Sustainable in Sugar) course. Adherence to the provisions within the Code and following the guidelines within the COMPASS course are sufficient legal evidence of discharge of a duty of care with respect to drainage and environmental matters. Self-assessment within the COMPASS course indicates to the individual his or her level of environmental performance and where improvements may be made.
Provided they are accredited, farmers are permitted to carry out drainage maintenance on freehold or leasehold lands requiring the removal of marine plants, under a strategic permit under Section 51 of the *Fisheries Act 1994*. Accreditation is achieved by attendance at a course and understanding of the Fish Habitat Code of Practice, FHC 003.
8 STEPS TO BETTER SURFACE DRAINAGE

Sections 3 and 4 in the preceding material set out strategies for managing surface water to improve drainage and productivity. Section 5 sets out strategies to minimise soil erosion and sediment transport under current or improved drainage conditions. However, these strategies need to be integrated and they can only be effective if they are applied in the context of the whole farm and the farm production system. This really means that they should be applied in the context of a farm plan. Drainage components of the farm plan need to be integrated with the drainage system of the sub-catchment, be that natural and/or artificial.

The farm plan will need to be:

- long-term – probably covering at least 5 years;
- flexible – to accommodate changing circumstances and technologies; and
- reviewed periodically – to account for progress and changing circumstances including seasonal conditions and finance.

It could be seen as a rolling five-year plan.

The plan will need to include, but not be limited to, consideration of the following factors both as they are now and as they could be in the future:

- drainage;
- drainage and/or soil erosion problem areas and opportunities for improvement;
- soils, topography, drains and potential drain outlets;
- layout of blocks and cropping regime of plant cane, ratoon and fallow;
- crop management strategies including planting times, fertilizer regimes and varieties;
- weed, insect and animal pest-control strategies both in and around the crop;
- finance and cash flow including likely impacts of changes proposed;
- application of some or all of the strategies proposed to improve drainage and reduce soil erosion and how they can be integrated to give best-practice drainage management; and
- possible impacts of any changes proposed on neighbours.
Specialist assistance may be needed to develop the plan and will be needed to implement some of the strategies that the plan requires. Ideally, the whole plan should be committed to paper so progress can be reviewed and components requiring design will need electronic and/or paper-based plans. However, it should be remembered that there are many very efficient farmers who operate by thinking ahead, discussing the future and their plans with family, friends and specialists, committing very little to paper and calling on direct specialist assistance only as needed for specific tasks.
9 REFERENCES AND FURTHER READING

Related industry publications


CANEGROWERS, (2001). COMPASS.

Water planning and legislation


management and the sugar industry. In: Environmental Short Course for Sustainable
Sugar Production – Course Manual, Eds: Bruce, R.C. and Rayment G.E., CRC for
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Farming systems and nutrient management
Bell, M.J., A.L. Garside, G. Cunningham, N. Halpin, J.E. Berthelsen and C.L.
Sugar Cane Technol., 20: 97-103.

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Papers of the Outlook 2003 Conference, ABARE, Canberra.

traffic, minimum tillage, legume based sugarcane farming system.

Soc. Sugar Cane Technol., 18: 84-89.

cane and sugar yield of a following plant cane crop. Proc. Aust. Soc. Sugar Cane
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Drainage and hydrology


Erosion control and water quality improvement


Land use and sediment export


Water quality impacts on freshwater and marine ecosystems


APPENDIX A

Headland drainage design

Headland drainage systems may be of varying levels of complexity. Here details are provided on a simple lowered headland that costs little and will allow surface water to flow from the field.

Lowered headlands are also required to be trafficable and laser levelling may not provide for sufficiently rapid runoff to keep the surface dry enough for traffic. Thus, it is recommended that a narrow trench containing agricultural pipe and filled with gravel to the surface in the middle of the (spoon) drain be incorporated. This will drain the headland and permit linkage to sand filled moles originating in the lower section of the cane block. It will allow for drainage at the ends of fields by allowing water to move through the headland. Discharge of the drainage pipe to an open drain is the lowest cost option but, if there is no outfall, it can drain to a sump that is pumped out.

In contrast to conventional lowered headlands, the system described here results in a very slight fall from the bottom of the drill to the headland. This arrangement allows water to discharge from the field, but at a rate that minimises erosion hazard. After the drill has been filled in, the same holds true for the inter-row, which now carries the bulk of the water leaving the field. Headlands that act as waterways do not erode and will act as sediment traps if grassed, because they are shallow and wide.

The agricultural pipe and sand-filled trench in the lowered headland should be installed before the sand-filled mole drains. First, laser grade the headland and take levels to work out the slope of the installed agricultural pipe. Slopes from 0.1 to 1% work well, but greater attention must be paid to establishing an even grade for the lesser slopes. Even if there is insufficient surface slope, provided the outlet is low enough, extra slope on the pipe may be obtained by bringing the pipe closer to the surface at the far end. A 150 mm (6 inch) trench installed with a 65 mm slotted agricultural pipe works well. This is one case when smaller is better. The cost of 65 mm pipe is half that of the next larger size and flow helps keep it clean. Make special note of the depth of pipe installation to avoid damage if installing sand-filled moles.
The trench can be dug deeper than required and back filled to the required depth. It is much easier to back fill than dig out if too shallow. A trench shovel is an essential tool for this operation and boning rods (T bars) are used to get the floor exactly right.

It is a matter of setting up three T-bars in the trench. The bars at each end are set so the bar is a fixed height above the intended floor of the trench. The middle bar is then put in place so it lines up with the line between the bars on each end. The line between the bars is thus parallel to the slope of the intended floor of the trench. Then the trench is back filled using, as a guide, a beam of timber cut to the right length (distance from the bar to the intended floor of the trench). This way the grade of the floor of the trench will be exactly right.

Add a layer of sand of about 50 mm depth. This can be done easily by placing a mark or nail 50 mm from one end of the timber guide mentioned above and using this mark to view the T bars. Remove the T-bars from the trench, insert the pipe and use shovel fulls of sand every 500 mm or so to hold the pipe in place. This prevents the pipe from being knocked out of place when adding the sand mechanically.

A breather at the top end of the pipe is an essential part of the design as this improves efficiency of the pipe operation. Any open inlet or discharge sections of the pipe should be screened to prevent entry by vermin, toads, snakes, etc., which may block the pipe. Access pipes joined to the main pipe with 45-degree tees at something less than 100 m intervals will allow cleaning if necessary. The access pipes should be installed in such a way that the cleaning nozzle can be inserted in an up-hill direction permitting cleaned material to be ejected towards the outlet.

Sand-filled moles may now be installed at an angle across the drills and should feed into the sand-filled trench at an angle (about 45 degrees) facing downstream. The angle helps feed into the outlet and also preserves the mole from damage by tractor wheels. The sand-filled moles are installed using a standard bullet mole tyne fitted with a chute down the back and hopper for the sand. A gate to cut off the sand when the tyne is lifted from the ground is a good idea. It is best to use dry coarse sand, rather than fine sand. Dry sand, which is sieved, assists with flow. The depth of installation of the sand-filled moles is normally shallow, about 300-400 mm maximum. Grade of the
sand-filled mole is important, as there should be a continuous fall. If the land surface is already graded, achieving smooth fall is easy.

If feeding into the trench from both sides, use a herringbone pattern. The mole should cut across the row (as distinct from the inter-row) as the row is less compact and is the source of subsurface flow. Thus, when installing go that little bit extra if intending to terminate a mole near, but not quite to a row. If an open drain is available along the edge of the field, sand-filled moles can be discharge directly into the drain.

Spacing sand-filled moles at 1.5 m intervals works well. At the angle recommended above, and depending on length, about three moles service each row. Therefore, if one mole blocks, the other two can still do the job. Length depends on the distance into the field that requires draining. If draining just the ends of fields, a distance of 3 to 5 m into the field is adequate. Figure A is a diagrammatic representation of an installation described above.

Figure B shows the water content in near-surface soil adjacent to cane plants towards the row end under conventional, inter-row dammed, and mounded with sand-filled mole drained conditions. This demonstrates the benefits of mounding and sand-filled mole drains.

![Image](headland_drainage_system.png)

**Figure A:** Headland drainage system with sand-filled mole drains feeding into the trench.
**Figure B:** The effect of mounding and sand filled moles on moisture content of the lower ends of fields.

Mounds result in 4-6% less moisture around the cane plant.
Drainage network survey template

DRAIN SURVEY SHEET

General
Identifier (C = culvert, D = drain, H = headland) .................................................................
Location (description): ................................................................................................................
Location (GPS coordinates): ...........................................................................................................
Date: .......................... Surveyor: ..............................................................................................
Order (1,2,3): .............. Length (m): ......................................Fall (m)............................
Slope (%): ..............................................................

Drain cross-sections

Dimensions (m)

Regular

[ ] B1:.............D1:.............W:.......... 

Regular complex

[ ] B1:.............B2:.............W:.......... 

D1:.............D2:.............
Irregular simplex

(Direction)

Irregular complex

Spoon

Condition of drain

<table>
<thead>
<tr>
<th></th>
<th>Side 1</th>
<th>Side 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grass (Y, N)</td>
<td>[ ]</td>
<td>[ ]</td>
</tr>
<tr>
<td>Slashing (Y, N)</td>
<td>[ ]</td>
<td>[ ]</td>
</tr>
<tr>
<td>Spraying (Y, N)</td>
<td>[ ]</td>
<td>[ ]</td>
</tr>
<tr>
<td>Trees (Y, N)</td>
<td>[ ]</td>
<td>[ ]</td>
</tr>
<tr>
<td>Recent grading (Y, N)</td>
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<td>[ ]</td>
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**Bank erosion:**

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<th>degree</th>
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<td>[ ]</td>
</tr>
<tr>
<td>Slight</td>
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<tr>
<td>Moderate</td>
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<td>[ ]</td>
</tr>
<tr>
<td>Severe</td>
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</tbody>
</table>

**Water**

Depth (m): ..................

Direction: ..................

Speed of flow \( [m^3/s] \): ...... Depth......Width......Length.......Time.......

Turbidity: ..................

---

**CULVERT SURVEY SHEET**

**General**

Identifier (C = culvert, D = drain, H = headland) ..................................................

Location (description): ..............................................................................................

Location (GPS coordinates): ..........................................................

Date: ..................  Surveyor: ..........................

Order \(1,2,3\): ...........

Length (m) ............

Cross-section  [ ]  [ ]  [ ]  [ ]  [ ]

Dimensions (m): ..........................................................................................
HEADLAND SURVEY SHEET

General
Identifier (C = culvert, D = drain, H = headland): .................................................................
Drain identifier: ............................................................................................................................
Location (description): .....................................................................................................................
Location (GPS coordinates): ...........................................................................................................
Date: ........................................... Surveyor: ..................................................................................

Grass (Y, N) [ ]
Slashing (Y,N) [ ]
Trees (Y,N) [ ]
Recent grading (Y,N) [ ]

Condition of headland

<table>
<thead>
<tr>
<th>Degree</th>
<th>extent %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Headland</td>
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</tr>
<tr>
<td>Erosion:</td>
<td>slight</td>
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<tr>
<td>Length:</td>
<td>moderate</td>
</tr>
<tr>
<td>Fall:</td>
<td>severe</td>
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</tbody>
</table>
Best-practice Surface Drainage
for Low-lying Sugarcane Lands
Herbert District

John R. Reghenzani and Christian H. Roth
Edited by Robert E. Reid