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EFFICIENT SUBSURFACE DRAINAGE FOR IMPROVED SOIL HEALTH[1]

EFFICACE DRAINAGE SOUTERRAIN POUR UNE MEILLEURE SOL HEALTH[1]

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ABSTRACT

Soil health and productivity can be obtained through well-drained soils and artificial drainage in agriculture is a practice to improve the natural drainage conditions and has been practiced for many years in the world. In South Africa drainage was introduced in the late fifties and early sixties and various approaches and techniques have been used and are still been used to drain agricultural fields in South Africa. With a Water Research Commission initiated and funded project (K5/2026), in-depth research is now conducted by the ARC-Institute for Agricultural Engineering together with other role players to document and update planning and design approaches. The main aim is to develop technical and financial standards and guidelines for assessment of the feasibility of surface and sub-surface drainage systems under South African conditions.

In the South African context, the refinement and development of drainage standards is coming from two angles, a review of the old drainage standards for South Africa and the use of computer simulations based on the DRAINMOD and spreadsheet models. The models allowed the simulation of a wide range of conditions comprising soil types, crops, water application methods, water tables, salinization, water quality and management practices. These simulations allow one to scope the behaviour of drainage systems and therefore develop standards and practices that are realistic.

The paper demonstrates the methodology and results of one of three areas in South Africa were the models have been successfully tested and verified.

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RÉSUMÉ ET CONCLUSIONS

La santé et la productivité des sols peuvent être obtenues dans des sols bien drainés et drainage artificiel dans l'agriculture est une pratique pour améliorer les conditions de drainage naturels et a été pratiqué pendant de nombreuses années dans le monde . En Afrique du Sud drainage a été introduit dans les années cinquante et au début des années soixante et différentes approches et techniques en retard ont été utilisés et sont encore été utilisé pour drainer les terres agricoles en Afrique du Sud . L'objectif principal de la recherche est de développer des normes et des directives pour l'évaluation de la faisabilité des systèmes de drainage de sous- surface dans des conditions sud-africaines surface et techniques et financières .
En Afrique du Sud une superficie de 18 000 000 ha sont été cultivé et 1 600 000 ha sont irrigués été . Mauvais problèmes de drainage en Afrique du Sud auraient réduit le potentiel de production agricole d'environ un quart de la superficie totale des terres irriguées (Backeberg , 2000) . On estime que 240 000 ha est affectée par la hausse des nappes phréatiques et la salinisation et les problèmes semblent être en expansion. Le drainage des terres est appliquée pour principalement les deux raisons suivantes :

- la remise en état des zones engorgées à usage agricole et
- l'amélioration des conditions de drainage de terres agricoles existantes .

Grâce à une gestion efficace de l'eau et un bon drainage du sous-sol , l'amélioration des conditions de santé des sols sont été créés .
Dans le contexte sud-africain , le raffinement et l' élaboration de normes de drainage est à venir à partir de deux angles , un examen des anciennes normes de drainage pour l'Afrique du Sud qui a été développé par Reinders en 1984 et l'utilisation de simulations informatiques basées sur la DRAINMOD et feuille de calcul modèles. Les modèles ont permis à la simulation d'une large gamme de conditions comprenant les types de sols , les cultures, les méthodes d'application de l'eau , des nappes phréatiques, la salinisation , la qualité de l' eau et les pratiques de gestion . Ces simulations permettent de portée du comportement des systèmes de drainage et donc d'élaborer des normes et des pratiques qui sont réalistes .
Comme l'investissement dans les systèmes de drainage et d'irrigation agricole est de nature à long terme . Il devrait être évident qu'une approche dynamique vers la simulation des systèmes de production est nécessaire pour faire une analyse objective de la viabilité de mettre en œuvre des systèmes de drainage alternatifs . L'approche dynamique est également nécessaire d'évaluer l'impact des interventions gouvernementales possibles pour promouvoir l'utilisation de systèmes de drainage pour réduire l'impact négatif de la salinité et d'autres problèmes connexes . L'objectif de la recherche est de continuer à développer un modèle financier pour analyser et évaluer les décisions d'installation de drainage du sous-sol . Il intègre une série de sous modèles , à la fois technique et financière , à calcule avec précision la viabilité économique et la faisabilité financière de drainage souterrain .
Le modèle financier Drain- Fin a été développé pour analyser et évaluer les décisions d'installation de drainage du sous-sol et le papier démontrer la méthodologie et les résultats de l'une des trois régions de l'Afrique du Sud ont été les modèles ont été testés avec succès et vérifiées .

1. Introduction

Soil health and productivity can be obtained through well-drained soils and artificial drainage in agriculture is a practice to improve the natural drainage conditions and has been practiced for many years in the world. In South Africa drainage was introduced in the late fifties and early sixties and various approaches and techniques have been used and are still been used to drain agricultural fields in South Africa. With a Water Research Commission initiated and funded project (K5/2026), in-depth research is now conducted by the ARC-Institute for Agricultural Engineering together with other role players to document and update planning and design approaches. The main aim is to develop technical and financial standards and guidelines for assessment of the feasibility of surface and sub-surface drainage systems under South African conditions.

In South Africa an area of 18 000 000 ha are been cultivated and 1 600 000 ha are been irrigated. Poor drainage problems in South Africa are reported to have reduced the crop production potential of about a quarter of the total land under irrigation (Backeberg, 2000). It is estimated that 240 000 ha is affected by rising water tables and salinisation and problems appear to be expanding. Land drainage is applied for mainly the two following reasons:

- reclamation of waterlogged areas for agricultural use and
- improvement of the drainage conditions of existing agricultural land.

In the South African context, the refinement and development of drainage standards is coming from two angles, a review of the old drainage standards for South Africa that was developed by Reinders in 1984 and the use of computer simulations based on the DRAINMOD and spreadsheet models. The models allowed the simulation of a wide range of conditions comprising soil types, crops, water application methods, water tables, salinization, water quality and management practices. These simulations allow one to scope the behaviour of drainage systems and therefore develop standards and practices that are realistic.

The objective of the research is further to develop a financial model to analyse and evaluate sub-surface drainage installation decisions. It integrates a series of sub models, both technical and financial, to accurately calculates the economic viability and financial feasibility of sub-surface drainage. In this regard the Drain-Fin financial model was developed to analyse and evaluate sub-surface drainage installation decisions and the paper will demonstrate the methodology and results of one of three areas in South Africa were the models have been successfully tested and verified.

2. Technical research methodology

The main technical objective was to assess the Drainmod model for modelling the mid-span water table and drainage discharge in an irrigated sugarcane field at Pongola in northern KwaZulu-Natal, South Africa. After calibration and validation, the model was then used to simulate water table depths and drainage discharge for various combinations of drain spacing and drain depth for purposes of assessing possible design combinations (for different crops on varied soils and for different climatic conditions).

2.1 Drainmod model

Drainmod is a hydrological model developed at the North Carolina State University (NCSU) which uses functional algorithms to approximate the hydrological components of shallow water table soils, and is widely used in subsurface drainage system design and evaluation (Skaggs, 1976, 1978, 1999; FAO, 2007). The model is based on the water balance of a unit soil sectional area, which extends from the impermeable layer to the surface and is located midway between parallel drains. The change in water pore space at any time increment (Δt) is a function of how much water is flowing into the unit soil as infiltration and flowing out of it through drainage, evapotranspiration and seepage. According to Skaggs (1999), the water balance for a time increment (Δt) may then be expressed as:

$$\Delta V_a = D + ET + DS - F$$

Where: ΔV_a is the change in the water free pore space or air volume, cm; D is the drainage from the section, cm; ET is the evapotranspiration, cm; DS is the deep seepage, cm; F is the infiltration entering the soil section, cm. Drainmod is capable of predicting hourly ground water fluctuations (h), drainage discharges (q) and drainage water salinity levels. Water table fluctuations (depths) at different drain spacing are computed from the modified steady state Hooghoudt equation (Hooghoudt, 1940).

2.2 Model data inputs

For predicting water table fluctuations (h) on an hourly basis, subsurface drainage discharges (q), and the quality of the drained discharge, Skaggs (1978) reports that the model requires data inputs such as; (1) weather data; hourly precipitation (or irrigation), minimum and maximum daily temperatures and the potential evapotranspiration, (2) soil data; the soil hydraulic conductivities (k) for the soil profile layers, the thickness of the soil horizons above the restricting layer; and (3) drainage system parameters; the drain spacing and depth for the existing drainage system.

2.3 Pongola study site

The research study was undertaken at a 32 ha sugarcane field in Pongola, northern KwZulu-Natal province in South Africa. The area is arid and dominated by clay-loam and clay soils with a depth to the impermeable layer of 9 m. During the winter months (April to October), the sugarcane crop depends solely on irrigation and in summer production is dependent on both rainfall and irrigation. Sources of drainage water are excess irrigation water application as well as base flow from the region, especially the Lebombo mountain area that border the whole area. Existing drains had been installed in 2003 for a drainage discharge of 5 mm/day at a depth of 1.8 m, spaced at 54 and 72 m apart, for a design watertable depth of 1 m.

2.4 Data collection

A total of 36 piezometers, manually augered to a depth of 1.7 below the soil surface, were installed on a 54 x 54 m grid in the 32 ha study field. The piezometers were of 50 mm diameter (id) class 4 PVC piping, with perforations cut to allow water entry, back filled with washed coarse sand to minimise entry resistance and blockage of the perforations. Water table depths in each piezometer were measured with a dip meter daily. Drain discharges were measured manually at 3 drain outlets using a bucket and stop watch. Rainfall irrigation inputs were measured using raingauges installed in the field.

The saturated hydraulic conductivity (Ksat) was measured in-situ at 10 locations in the field using the auger-hole method (van Beers, 1983), considered accurate yet very simple. Soil water characteristics (soil water tension vs. soil water content) were measured in the laboratory using the pressure plate approach (Klute, 1986).

A fourteen year record of weather data comprising daily rainfall, potential evapotranspiration and temperature (minimum and maximum) was obtained from the Pongola Weather Station (about 3 km from the field).

2.5 Drainmod calibration and verification

Drainmod was calibrated on a trial-and-error basis, as recommended Dayyani *et al* (2010) by adjusting a set of input parameters (Ksat and soil surface storage) until an optimal agreement between observed and simulated data sets was obtained. The goodness-of-fit was assessed using three measures, namely, the R^2, mean absolute error (MAE) and coefficient of residual mass (CRM).

3. Results

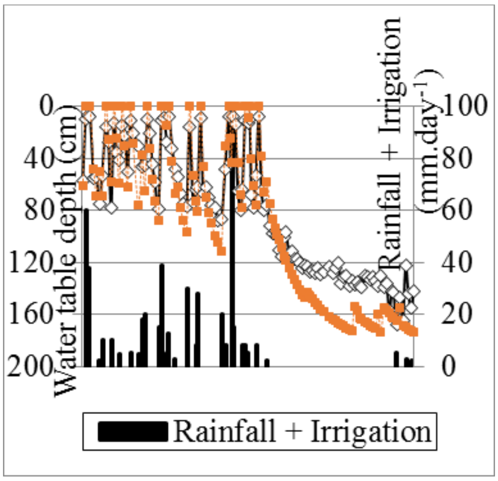
3.1 Field results

The soil bulk density in the top layer was found to be 2.64 g/cm^3 and 1.88 g/cm^3 in the lower layer, respectively, while saturated hydraulic conductivity (Ksat) was found to be 0.32 m/day on average although it varied for the two dominant soil types – averaging 0.24 m/day for the clay and 0.6 m/day for the clay-loam.

The soil water tension vs. soil water content data was fitted to the van Genuchten soil water characteristics curve and the R^2 for the fitting ranged from 0.975 to 0.992 which is considered very strong.

3.2 Modelling calibration results

Observed and simulated watertables are shown in Figure 1 (left), as well as the associated goodness-of-fit measures. As expected, the watertables observed and simulated showed a fluctuating pattern as is normally found under arid and semi-arid conditions indicating transient conditions. Similarly measured and simulated drainage discharges, together with the performance parameters are given in Figure 2 (right).



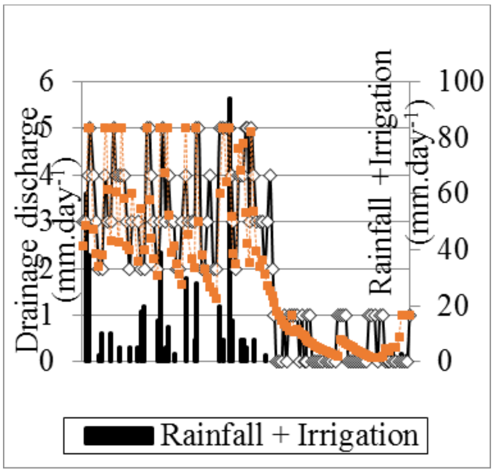


Figure 1: Observed and simulated watertable fluctuations during model calibration
Figure 2: Observed and simulated drain discharges fluctuations during model calibration

2.3 Simulation results for varying drain depths and drain spacing

The calibrated Drainmod model was used to simulate watertable and drainage discharges for sub-surface drains installed in clay (Ksat = 0.24 m/day) and clay loam (Ksat = 0.6 m/day). The mean simulated watertable depths at various combinations of drain depth and drain spacing are shown in Figure 3 for both the clay and clay loam soils.

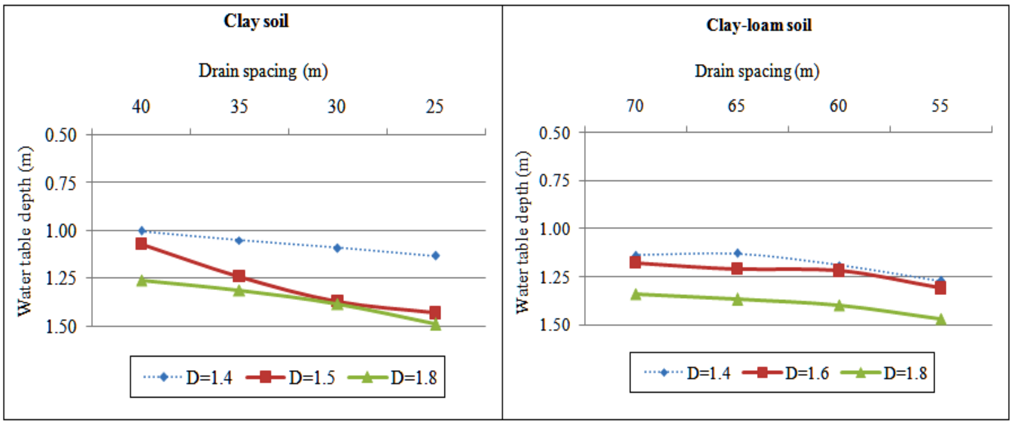


Figure 3: Mean water table depths in clay and clay-loam soils simulated at different drain depth (m) and spacing (m) combinations

The mean drain discharges for the clay and clay-loam soils simulated at different drain depths and drain spacing are shown in Figure 4.

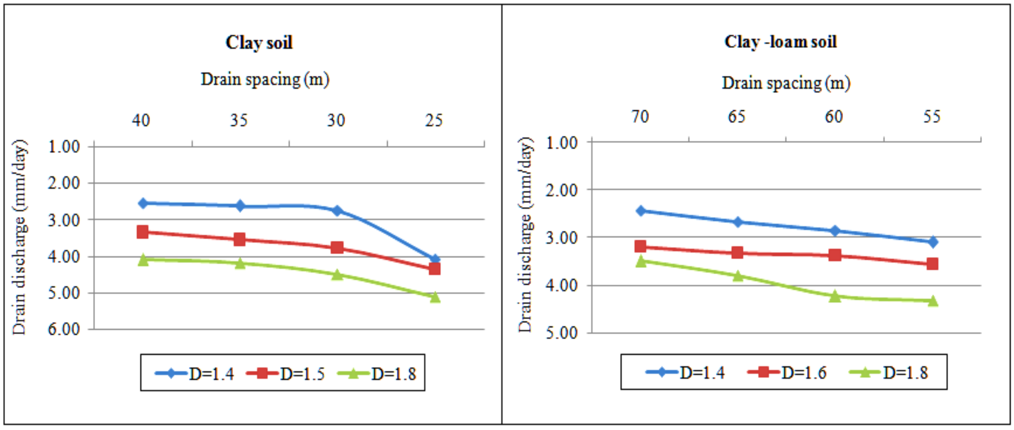


Figure 4: Mean drainage discharges in clay and clay-loam soils simulated at different drain depth (m) and spacing (m) combinations

Overall for the watertable results it can be concluded that in clay soils drains places at 1.4 m to 1.8 m allow the establishment of watertable depths of between 1.0 and 1.5 m if the drains are spaced from 25 m to 40 m. For clay loam soils the same results can be achieved if drained are spaced from 55 to 70 m. The drain discharge results show that the mean discharges at various combinations of drain depth and drain spacing increase with decreasing drain spacing.

2.4 Summary

The results established the reliability of Drainmod model as a tool for predicting watertable fluctuations and drain discharge and hence its application in drainage system designs and evaluation. An analysis of the simulated watertable depths and drain discharges at various drain depths and spacing combinations confirms the generally prevailing idea of installing drain pipes at a closer spacing in soils of low saturated hydraulic conductivities and wider drain spacing in soils of high saturated hydraulic conductivity values. Critically is the fact that the drainage design should be adequate and keep the watertable out of the crop root zone for improved soil productivity and soil health. In countries such as South Africa that are reviewing their drain design procedures, the incorporation of Drainmod as a design tool is strongly encouraged to make sure that the procedures are using state of the art procedures.

3. Cost research methodology

The objective is to develop a financial model to analyse and evaluate sub-surface drainage installation decisions. It integrates a series of sub models, both technical and financial, to accurately calculates the economic viability and financial feasibility of sub-surface drainage.

The integrated model comprises six modules namely: enterprise crop budgets, capital and maintenance budget, whole-farm cash flow budget, projected income statement, projected balance sheet statement and an economic and financial analysis module. The objective is to develop a user-friendly financial model that integrates:

- Whole-farm planning (20-year period)
- Crop yield curves (with and without drainage)
- Capital and maintenance expenditure (sub-surface drainage system)
- Financial analysis (Whole-farm and Per-hectare), and
- Comparison of different scenarios and measuring against norms

The model makes provision for cash flow, income statement and balance sheet statement projections. The model provides step-by-step instructions to ensure an accurate outcome.

3.1 Financial criteria to establish economic viability and financial feasibility

The economic viability of drainage refers to the per hectare ability of the direct increase in profitability as a result of drainage to repay the capital required to drain. Financial feasibility refers to the ability of the farming unit to access sufficient additional funds to pay for the drainage required and maintain an overall increasing cash flow in the long term or positive Net Present Value (NPV). Economic viability is a prerequisite for financial feasibility (Armour & Viljoen, 2008).

3.1.1 Benefit Cost analysis

Benefit Cost analysis is a decision-making tool used by Backeberg (1981) to evaluate capital investment on irrigation drainage. Benefit Cost analysis includes:

- Internal Rate of Return (IRR),
- Net Present Value (NPV), and
- Benefit Cost Ratio (BCR)

The NPV is the difference between the present value of income and present value of the capital and other expenditure. The B/C ratio is obtained by dividing the present value of the income by the present value of capital and other expenditure. The IRR is the breakeven discount rate at which the B/C ratio equals 1, or alternatively where the NPV equals zero.

3.1.2 Commercial Bank financing criteria and norms

Traditionally, lenders apply the five C"s of credit when determining the creditworthiness of agricultural borrowers (Wilson et al., 2006):

- The borrowers **Capacity** to repay the loan obligation and bear the associated financial risks, calculated by analysing both past and projected profitability and cash flow of the farm business. If a farmer has previously installed drainage, increased return as a result of drainage records will be useful; otherwise data from a close neighbour with similar conditions who has installed drainage, or verified simulation models can also be used.

- The borrowers **Capital** available for farm operations, assessed from balance sheets with liquidity and solvency calculations to gauge equity investment in the farm and how effectively it generates cash flows. Without sufficient capital (and managerial expertise) to optimise the returns from the investment in drainage (e.g. planting more capital intensive higher value long term crops), the investment may be underutilised.
- The borrowers' security **Collateral** as a final source of repayment if the borrower defaults on the terms of the loan agreement or dies. The higher the risk of the operation for which the loan is requested, the higher level of Collateral required. As drainage has no salvage value, the full costs of the drains often needs to be covered by some form of collateral. The higher the percentage of a farmers' total land that needs to be drained, the less likely that the land itself can cover the collateral obligations.
- The **Conditions** for use of the funds, or the intended purpose of the funds required by the borrower are considered in terms of general economic conditions, interest rates, inflation and the demand for money in order to come up with a discount rate with which to calculate the net present value (NPV), benefit cost ratio (B/C) and internal rate of return (IRR), all useful in comparing funding alternatives.
- The **Character** of the borrower, i.e. the attitude of the borrower towards risk and financial track record available from credit bureaus, is also a very important factor for commercial lenders considering a loan application. In the case of subsidised state funding and grants the potential recipients character in terms of "money grabbing" and not applying the funds productively also needs to be evaluated to ensure efficient use of public funds.

The model addresses "Capacity" and "Capital" using the following ratios:

- Production cost ratio (to ensure that production costs projections is in line with industry norms)
- Cash flow ratio (an indicator of repayment ability and the enterprise's ability to survive financial setbacks)
- Debt ratio (an indicator of solvency)

"Collateral", "Conditions" and "Character" cannot be calculated using quantitative inputs only and will differ for each analysis and also for different financiers.

3.2 Description of the Pongola case study farm

The Pongola case study entails an 88 hectare sugarcane farm with an asset value of R16 360 000 (US$1 543 396) and a net worth of R14 348 267 (US$.1 353 610)

Table 1 is a summary of sugar cane enterprise budget for Pongola and yield curves used for "with drainage" and "without drainage" scenarios.

Table 1: Crop enterprise budget – Sugarcane (US$1=R10.6)

Sugarcane	1	2	3	4	5	6	7	8	9	10
Yield t/ha (Without drainage)	90	90	90	90	90	90	90	90	90	90
Yield t/ha (With drainage)	115	120	125	130	135	140	140	140	140	140
Additional drainage cost	39,359	1,601	1,283	1,493	2,230	1,913	2,122	2,649	2,122	2,122
Cumulative net margin / ha (without drainage)	13,145	25,980	38,815	51,650	64,485	77,320	90,155	102,990	115,825	128,660
Cumulative net margin / ha (with drainage)	-17,414	4,380	28,252	53,674	80,119	108,641	136,954	164,740	193,053	221,366

3.2.1 Capital budget for installing sub-surface drainage

Drainage is quite expensive and the layout depends on many factors. Heavy soil will require a spacing of 20-30 meters, a medium soil 40 -50 meters and a light soil 70-80 meters in the Pongola area (Van der Merwe, 2013).

Table 2 serves as a guideline to estimate cost of sub-surface drainage installation for different spacing and soil conditions.

Table 2: Guideline estimate cost of sub-surface drainage

Soil	**Drain Spacing (meter)**		
Heavy Clay (>35%)	30	32.5	35
25-35% Clay	55	62.5	70
Sandy soils	70	90	110
Soil	**Meters pipe required per Ha**		
Heavy Clay (>35%)	333.3	307.7	285.7
25-35% Clay	181.8	160.0	142.9
Sandy soils	142.9	111.1	90.9
Soil	**Estimated cost per ha**		
Heavy Clay (>35%)	R 33,333.33	R 30,769.23	R 28,571.43
25-35% Clay	R 18,181.82	R 16,000.00	R 14,285.71
Sandy soils	R 14,285.71	R 11,111.11	R 9,090.91

Source: Van der Merwe (2013)

3.3 Modelling results

3.3.1 Economic Benefit Cost analysis (per hectare)

Table 3 illustrates the Economic Benefit Cost analysis for sugarcane.

Table 3: Economic Benefit Cost analysis

Sugarcane	*(Per hectare drainage installation analysis)*
Benefit-Cost Ratio	2.5 : 1
Rate of return	14.6%
Payback period (average)	4.5 years
Internal Rate of Return (IRR)	39.5%
Net Present Value (NPV)	150,725

The Economic Benefit Cost analysis shows that installation of drainage for sugarcane is economically viable.

3.3.2 Financial Whole-farm analysis

For the Whole-farm analysis, six scenarios were modelled. These are:

- Without drainage – 0% starting debt ratio
- Without drainage – 20% starting debt ratio
- With drainage – 20% starting debt ratio
- With drainage – 40% starting debt ratio
- With drainage – 40% starting debt ratio – 50% subsidy
- With drainage – 30% starting debt ratio – 50% subsidy

Table 4 reflects the production cost ratio, projected cash flow ratio, projected debt ratio and projected end bank balance of the different scenarios.

Table 4: Comparison of Financial Whole-farm analysis scenarios

Scenario nr & description	Production cost ratio *	Projected cash flow ratio *	Highest Projected Debt ratio	End Bank balance	Financially feasible
1 Without drainage - 0% Debt ratio	77%	117%	0%	8,096,598	Yes
2 Without drainage - 20% Debt ratio	77%	86%	126%	-13,239,177	No
3 With drainage - 20% Debt ratio	66%	120%	32%	8,775,831	Yes
4 With drainage - 40% Debt ratio	66%	80%	275%	-29,213,631	No
5 With drainage - 40% Debt ratio - 50% subsidy	66%	103%	54%	-5,668,483	No
6 With drainage - 30% Debt ratio - 50% subsidy	66%	121%	35%	7,483,333	Yes
* *20-year average*					

Without drainage the case study farm will only be financially viable with very low debt levels. Even with a 20% starting debt ratio, the operation will not be financially feasible without drainage (as a result of low yields).

The farm will be financially viable with 20 to 30% starting debt ratio with drainage installed. However, an operation with a starting debt ratio in excess of 30% will not be financially viable without subsidies when drainage is installed.

3.3.3 Financing decision support tool

Table 5 summarises the financing decision support tool indicators for the different scenarios.

Table 5: Summarised financing decision support tool

Scenario Description	Norm	1 Without drainage - 0% Debt ratio	2 Without drainage - 20% Debt ratio	3 With drainage - 20% Debt ratio	4 With drainage - 40% Debt ratio	5 With drainage - 40% Debt ratio - 50% subsidy	6 With drainage - 30% Debt ratio - 50% subsidy
Capacity							
Cash flow ratio	> 115%	Yes	No	Yes	No	No	Yes
Capital							
Debt ratio	< 50%	Yes	No	Yes	No	No	Yes
Collateral							
Sufficient available "yes" or "no"	yes	Yes	Yes	Yes	Yes	Yes	Yes
Conditions							
Benefit Cost ratio (B/C) : 1	> 1	Yes	Yes	Yes	Yes	Yes	Yes
Payback average	< 8	Yes	Yes	Yes	Yes	Yes	Yes
Internal Rate of Return (IRR)	> 8%	Yes	Yes	Yes	Yes	Yes	Yes
Net Present value (NPV)	0	Yes	Yes	Yes	Yes	Yes	Yes
Character							
Trustworthy "yes" or "no"	yes	Yes	Yes	Yes	Yes	Yes	Yes
Economic & Financially feasible		**Yes**	**No**	**Yes**	**No**	**No**	**Yes**

In the economic & financially feasible row the scenarios with a “yes” will most probably get finance from commercial banks in the normal run of business. Scenarios with a “no” will most probably not qualify for commercial finance. Please note that this tool serves as an indicator only.

3.3.4 Summary

This section summarises the modelling results for the Pongola case study. It gave a brief description of the case study farm, sugar cane enterprise budget, the sub-surface drainage installation cost and the modelling results. Several scenarios were run including “with” and “without” drainage for a 0%, 20%, 30% and 40% debt ratio. 30% and 40% debt ratio ”with drainage and 50% subsidy” scenarios were also run to illustrate the impact of subsidies on the economic viability and financial feasibility of sub-surface drainage. It will not be financially viable for a farming operation with a debt ratio in excess of 30% to install drainage without subsidy. Subsidies will ultimately assist the farming operation to stay financially viable while installing drainage. However, it will not be financially viable for farming operations with debt levels in excess of 40% to install drainage, even with a 50% subsidy. In order for farming operations with debt ratios of more than 40% to stay financially viable, the subsidy on installation of drainage should exceed 50% of drainage installation cost.

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