DEVELOPMENT OF MODELS FOR ECONOMIC EVALUATION OF THE INTEGRATED MANAGEMENT OF THE QUANTITY AND QUALITY OF IRRIGATION WATER WITHIN RIVER CATCHMENTS

by

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Report to the Water Research Commission

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EXECUTIVE SUMMARY

DEVELOPMENT OF MODELS FOR ECONOMIC EVALUATION OF INTEGRATED MANAGEMENT OF QUANTITY AND QUALITY OF IRRIGATION WATER WITHIN RIVER CATCHMENTS

Motivation

Past efforts to protect the quality of South Africa's water resources were concentrated mainly on the control of effluents from point sources. Despite these efforts an apparent deterioration in the water quality of the country's surface waters is being observed (Pegram, Quibell and Görgens, 1997); reasons being that in many catchments there are zones where nonpoint source (NPS) contributions are significant or even dominant. Quibell (2000) argued that a lack of legislative and regulatory authority on the one hand and poorly defined linkages between implementable management actions and the processes that lead to NPS pollution on the other hand hampered the management of NPS pollution sources in the past.

The National Water Act (Act36 of 1998) now for the first time provides the legislative means to target NPS pollution with specific source-directed measures (Quibell, 2000). No specific differentiation is made between point and NPS pollution in the National Water Act which allows for the development of source specific procedures that address both point and NPS pollution from the source. The waste discharge charge system is one way in which the Department of Water Affairs and Forestry is implementing the National Water Act. The basis for this system is the polluter pays principle. The theory behind polluters paying pollution charges was that the individuals must pay for the cost incurred as a result of their pollution (Taviv, Herold, Forster, Roth and Clement, 1999). However, in order to institute a system of waste charges the relevant authority must be able to identify who caused the pollution and precisely how much of it. The last mentioned is a necessary condition for any charge system based on the polluter pays principle (Taviv *et. al*, 1999). Due to the unique characteristics of agricultural NPS pollution it is not straightforward to quantify exactly who has caused the pollution and how much of it. In part this is due to the complex relationship between agricultural production and damages from water pollution involving physical, biological and economic links. How well NPS pollution control policy performed often depends on how well these links are understood (Ribaudo, Horan, and Smith, 1999).

Problem statement and formulation of objectives

Several processes govern NPS pollution. The first process is concerning the production of pollution emissions, and therefore characterises the link between agricultural production practices and the movement of pollutants in the field. Emissions from each field interact with emissions from other fields and the surrounding ecosystem as they move to water resources, thereby altering pollution loads. Once agricultural pollutants are discharged into water resources it might undergo dilution or some form of chemical, physical and biological alteration depending on the assimilative power of the system to yield a final water quality at a specific location. Thus, in-stream water quality, measurements are dependent not only on the quantity of emissions, but also on the spatial interdependencies between different fields and sub-catchments relative to each other as well as the in-stream processes occurring as the pollutants are transported downstream.

A prerequisite for the meaningful formulation of any policy to efficiently control pollution within an integrated catchment management approach is information regarding economic environmental tradeoffs of alternative policy instruments to control NPS pollution. Previous efforts to quantify these tradeoffs involved the reduction of pollution emissions using aggregated field-scale emissions, thereby ignoring all the other processes that yield the final water quality. The implication of ignoring these processes was that areas with high field-scale emissions might not contribute significantly to water pollution at a specific location. Ignoring the interrelated linkages between agricultural production practices and pollution damage, as it has been done often in the past, might therefore stem relative comparisons between alternative policies inappropriate. Cost-effective NPS pollution abatement policy can only advance if economic environmental tradeoffs of alternative policy instruments to control NPS pollution are quantified, taking the spatial interdependencies between alternative pollution sources into account.

The main objective of this research was to develop a spatial decision-support system capable of quantifying economic environmental tradeoffs of alternative NPS pollution abatement instruments.

Specific objectives include:

- Development of procedures to integrate a catchment level NPS pollution simulation model with an economic optimisation model.
- Development of a spatial economic optimisation model capable of linking the spatial use of alternative management practices to a total catchment outlet water quality standard.
- Evaluation of the cost-effectiveness of alternative NPS pollution abatement instruments through the quantification of economic environmental tradeoff curves.

The research was conducted in the Gamtoos river catchment. The Gamtoos River was formed by the confluence of the Kouga and Groot Rivers. The drainage area of the 70 km long Gamtoos River, which is surrounded by the Baviaanskloof Mountains, constitutes an area of 1 357 km^2. About 7 400 ha were utilised to produce citrus, potatoes and other vegetable crops by 242 irrigators using micro-, drip- and centre pivot irrigation.

At the beginning of the project the project team envisaged the use of field-scale pollution loads aggregated over representative farms to quantify economic environmental tradeoffs of lowering nitrate NPS pollution. However, the research methodology changed significantly after the principal researcher had visited the Virginia Polytechnic Institute and State University, USA, in the second year of the research. After his visit the emphasis of the research was shifted towards catchment level analyses using a catchment level NPS pollution model to account for the spatial interdependencies that effect pollution. The Steering Committee agreed that the research team should focus on using a catchment approach when quantifying economic environmental tradeoffs of alternative pollution abatement policies.

The Soil and Water Assessment Tool (SWAT)(Neitsch, Arnold, Kiniry and Williams, 2001) was selected to simulate inputs for the spatial optimisation models that were used to quantify the economic and environmental tradeoffs of alternative policy instruments to combat NPS pollution. Since SWAT was fully integrated with GIS technology, the principal researchers had to learn basic GIS processing commands to convert different spatial data sources into the right format and to facilitate the configuration of the model. Spatial variability in the Gamtoos catchment was taken into account by delineating 22 sub-catchments and 129 hydrological response units of which 53 were used for irrigation purposes. The effects of 229 alternative crop, water and fertiliser input combinations on nitrate pollution parameters were thereafter simulated with SWAT.

The General Algebraic Modelling System (GAMS) (Brooke, Kendrick, Meeraus and Raman, 1998) was used to integrate SWAT with the spatial optimisation models developed in this research. GAMS is a very powerful modelling system that enables the modeller to import data files, manipulate large data sets, calculate input parameters, generate the optimisation matrix, optimise the model through an automatic link to several solvers, read the output from the solver and to generate customised output files. The integration was done through the development of procedures to extract the vast amount of output data which was differentiated by sub-catchment, hydrological response unit, land type, crop, planting date, fertiliser application rate, irrigation level, year of simulation and month of the year from the SWAT output files and to convert it to GAMS readable input files. Excel's macro-language was used to extract the data and to generate the GAMS readable input files. Special GAMS programming features were then used to import about 900 000 lines of output data from SWAT into the modelling system.

Once all the necessary SWAT data was imported into the modelling system, the data were combined with economic data to calculate the necessary technical coefficients for all the activities in the different spatial optimisation models. Due to problems simulating the pollution impact of citrus, potatoes and cabbage were chosen to approximate the impact of pollution control policies on abatement cost in the Gamtoos catchment. Baseline pollution levels were established using an optimisation model without any constraints on pollution. Several optimisation models were then used to model the economic environmental tradeoffs of abating baseline pollution levels. Qiu (1996) developed procedures to link the spatial use of alternative management systems to total catchment water quality through the use of pollution contribution factors, making the assumption that the pollution contribution factors did not change with shifts in landuse changes. These research efforts were improved upon in this research through the development of a non-linear spatial programming model with endogenous pollution contribution rates that were dependent on the spatial use of alternative management actions in the whole catchment. The spatial programming model which consisted of 677 constraints, 12 085 variables and 94 871 technical coefficients was used to establish the cost-effective allocation of management practices that achieved the water quality standard at minimum cost. Results from this model were used as benchmark to compare and determine the cost-effectiveness of increasing water and fertiliser cost as policy instruments to comply with a specific water quality standard. The impact of these policy instruments on landuse changes and associated gross margins was optimised using a programming model without any constraints on pollution. The impact of these policy instruments on pollution abatement was determined exogenously using the optimised landuse, given the policy instrument evaluated and the pollution output from SWAT. Similar procedures were used to determine the impact of a water market on pollution.

Results and conclusions

- Results from the baseline analysis indicated that significant variability exists between different sub-catchments with respect to gross margins per unit emitted nitrate. However, it could not be concluded that sub-catchments with relatively high values would have higher pollution abatement costs when the aim was to abate pollution at the catchment outlet, because each of the sub-catchments was contributing differently to the pollution problem at the catchment outlet.

- The ability of the non-linear spatial programming model to determine cost-effective economic environmental tradeoffs was clearly demonstrated. Significant tradeoffs were modelled at the sub-catcment level due to the existence of both positive and negative tradeoffs, while little trade-off was modelled at the catchment level up to a 20% pollution abatement level. Thus, choice of pollution abatement levels based on catchment level tradeoffs may not be socially acceptable since it may make profitable farming for some farmers impossible.

- Pollution abatement cost was not proportionally related to sub-catchment pollution abatement, indicating the importance of the pollution contribution factors in determining the abatement costs of a sub-catchment.

- Controlling the spatial use of alternative management options (crop, planting date, soil and input use) and a pollution tax were proposed as methods to achieve cost-effective pollution abatement. However, these options were very difficult to implement due to the large number of entities that needed to be controlled and the additional cost of obtaining the necessary water quality data at the sub-catchment level.

- The cost-effectiveness of increasing fertiliser and water cost were evaluated relative to achieving the water quality standard at the catchment outlet cost-effectively. Although increasing fertiliser cost had proved to be more cost-effective than increasing water cost, the cost-effectiveness of the former was still very low. The cost-effectiveness of a fertiliser tax was low because a uniform tax was applied to the catchment that was characterised by considerable spatial variability.

- Another important result was that increasing water cost would not necessarily improved water quality, especially if farmers were using water more efficiently without decreasing the areas irrigated. Increasing water use efficiency would reduce streamflow via reduced return flows. Reducing the amount of water available to dilute the pollution emissions would increase the concentration of the pollutants, thereby decreasing the quality of the water.

- A water market would encourage more efficient use of water, but would reduce irrigation water return flows and therefore the dilution capacity of the water system. To result in a water quality improvement, the landuse resulting from more efficient use of water must also result in a more than proportional decrease in pollution emissions.

- Results from the research not only showed that the developed procedures were suitable to quantify economic environmental tradeoffs necessary for NPS pollution abatement policy, but also suggest important policy implications:

    - To improve the cost-effectiveness of pollution taxes, taxes should be based on the pollution contribution of each source to the pollution problem at a specific location and not on reduced emissions loads or pollution concentrations at the source.

    - The cost-effectiveness of taxes on input use was very low.

    - Water conservation policies with the aim of increasing water application efficiencies would increase water quality problems if farmers were allowed to increase areas irrigated using conserved water.

Achieving set objectives and value of results

The main objective of this research was achieved through the development and application of an integrated modelling system consisting of a catchment level NPS pollution model and a spatial optimisation model to evaluate the cost-effectiveness of alternative policy instruments to abate pollution at the Gamtoos catchment outlet.

More specifically the following objectives were achieved.

- Procedures were developed to integrate SWAT with the spatial optimisation model through the use of macros and special GAMS programming features. The procedures developed in this research can be used to successfully integrate data transfer between any simulation model and GAMS.

- Linking the spatial use of alternative management practices to a catchment water quality standard was accomplished using the concept of pollution contribution factors. A major contribution was made by allowing the contribution factors to vary as the landuse in the catchment changed, resulting in more realistic tradeoffs.

- The greatest value of this research lies in the application of the integrated decision-support system to quantify economic environmental tradeoffs of alternative policy instruments to achieve NPS pollution abatement.

Only through the application of the decision-support system developed in this research would policy makers be convinced about the relative effectiveness of alternative policy instruments to control NPS pollution. Application of these models would further enhance the understanding of the interaction between water legislation, water policy administration, technology, hydrology, NPS pollution and human value systems necessary to advance water policy.

Further research proposals

NPS pollution control policy can only advance through a better understanding of the interrelated linkages between pollution-generating activities at field scale and the resulting damages caused at the catchment scale. Application of catchment scale NPS models may assist in understanding these linkages. However, it is important that these models should be able to quantify the impact of alternative management practices implemented at the field scale on water quality indicators measured at the catchment scale. Thus, there is a clear need for more detailed models that may complement modelling procedures used in South Africa to target problem areas. Due to the complexity of determining economic and environmental tradeoffs, application of these models should take place within multidisciplinary research teams.

More detailed NPS modelling to quantify economic and environmental tradeoffs should recognise that although catchments and sub-catchments are logical management units from an environmental viewpoint, it is decisions made at the farm level that determine pollution abatement cost. Further research is therefore necessary to more closely reflect the farm as management unit when quantifying economic environmental tradeoffs of improving water quality, thereby quantifying the impact of pollution abatement policies on irrigation farming profitability.

To advance the application of more detailed economically linked catchment scale NPS models the development of appropriate GIS data bases cannot be overemphasised. Although GIS soils information is available from the Institute of Soil Climate and Water (ISCW) the data contained in the database are not suited for direct hydrological modelling. Furthermore, most troublesome is the absence of detailed landuse information within the boundaries of water user associations (WUA) necessary for the evaluation of alternative management practices on pollution loads. In many instances the WUAs only know how much water has been distributed to specific farmers without knowing consumptive use patterns. Thus, basic spatial information on temporal cropping patterns and water use is not available in most catchments. A GIS database of temporal cropping patterns and irrigation technology is essential for model validation, and if available may prove to be of benefit to WAUs, given they will have to submit water use plans in future proving efficient use of their water supplies.

The mathematical programming model can be developed further to recognise that pollutant loads are inherently stochastic and that the risky environment in which farmers produce and market their crops may have a significant effect on pollution abatement cost. The procedure used to link the spatial use of different management options to the nitrate water quality indicator using a dynamic pollution contribution factor should be enhanced through the incorporation of pollutant decay rates.

In this research alternative policy instruments were evaluated to reduce NPS pollution assuming transactions cost is zero. Transactions cost include, among other things, the costs associated with implementing, administering, and enforcing policies, as well as the costs of obtaining information to design policies. Future research should also include transaction cost when evaluating alternative NPS control policies.

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INTRODUCTION

CHAPTER 1

1.1 RESEARCH AREA

The research was conducted in the Gamtoos River catchment situated about 100 km west of Port Elizabeth on the Eastern Cape coast between latitude 33°58' and longitude 25°01' east (Pearce and Schumann, 1997). The Gamtoos River is formed by the confluence of the Kouga and Groot Rivers. The drainage area of the 70 km long Gamtoos River, which is surrounded by the Baviaanskloof Mountains, constitutes an area 1 357 km^2. Typically the whole valley is divided into three sub-districts namely Patensie, Hanky and Loerie/Mondplaas with a total listed area of 7 412 ha. The most important crops grown in the valley are citrus, potatoes, maize, wheat and other vegetables. Micro- and drip irrigation is predominantly used to irrigate citrus while the other crops are grown using centre pivot irrigation.

1.2 MOTIVATION

Past efforts to protect the quality of South Africa's water resources were concentrated mainly on the control of effluents from point sources. Despite these efforts an apparent deterioration in the water quality of the country's surface waters is being observed (Pegram, Quibell and Görgens, 1997). The reasons are that in many catchments there are zones where nonpoint source (NPS) contributions are significant or even dominant. Quibell (2000) argued that a lack of legislative and regulatory authority on the one hand, and poorly defined linkages between implementable management actions and the processes that lead to NPS pollution on the other hand, have hampered the management of NPS pollution sources in the past.

The National Water Act (Act36 of 1998) now for the first time provides the legislative means to target NPS pollution with specific source-directed measures (Quibell, 2000). No specific differentiation is made between point and NPS pollution in the National Water Act which allows for the development of source specific procedures that address both point and NPS pollution from the source. The waste discharge charge system is one way in which the Department of Water Affairs and Forestry is implementing the National Water Act. The basis for this system is the polluter pays principle. The theory behind polluters paying pollution charges is that the individuals must pay for the cost incurred as a result of their pollution (Taviv, Herold, Forster, Roth and Clement, 1999). However, in order to institute a system of waste charges, the relevant authority must be able to identify who caused the pollution and precisely how much of it. The last-mentioned is a necessary condition for any charge system based on the polluter pays principle (Taviv *et. al*, 1999). Due to the unique characteristics of agricultural NPS pollution it may not be straightforward to quantify exactly who has caused the pollution and how much of it. In part this is due to the complex relationship between agricultural production and damages from water pollution involving physical, biological and economic links. How well NPS pollution control policy performs often depends on how well these links are understood (Ribaudo, Horan, and Smith, 1999).

1.3 PROBLEM STATEMENT

Several processes govern NPS pollution. The first process concerns the production of pollution emissions and therefore characterises the link between agricultural production practices and the movement of pollutants of the field. Emissions from each field interact with emissions from other fields and the surrounding ecosystem as they move to water resources, which alter pollution loads. Once agricultural pollutants are discharged into water resources it may undergo dilution or some form of chemical, physical and biological alteration depending on the assimilative power of the system to yield a final water quality at a specific location. Thus, in-stream water, quality measurements depend not only on the quantity of emissions, but also on the spatial interdependencies between different fields and sub-catchments relative to each other as well as the in-stream processes occurring as the pollutants are transported downstream.

A prerequisite for the meaningful formulation of any policy to efficiently control pollution within an integrated catchment management approach is information regarding economic environmental tradeoffs of alternative policy instruments to control NPS pollution. Previous efforts to quantify these tradeoffs centred on the reduction of pollution emissions using aggregated field scale emissions, thereby ignoring all the other processes that yield the final water quality. The implication of ignoring these processes is that areas with high field scale emissions may not contribute significantly to water pollution at a specific location. Ignoring the interrelated linkages between agricultural production practices and pollution damage, as has been done often in the past, may therefore stem relative comparisons between alternative policies inappropriate. Cost-effective NPS pollution abatement policy can only advance if economic environmental tradeoffs of alternative policy instruments to control NPS pollution are quantified taking the spatial interdependencies between alternative pollution sources into account.

1.4 OBJECTIVES

The main objective of this research is to develop a spatial decision support system capable of quantifying economic environmental tradeoffs of alternative NPS pollution abatement instruments.

Specific objectives include:

- Development of procedures to integrate a catchment level NPS pollution simulation model with an economic optimisation model.
- Development of a spatial economic optimisation model capable of linking the spatial use of alternative management practices to a total catchment outlet water quality standard.
- Evaluation of the cost-effectiveness of alternative NPS pollution abatement instruments through the quantification of economic environmental tradeoff curves.

1.5 METHODS

Since data relating specific management practices to water pollution is not available, this research relied heavily on the use of the Soil and Water Assessment Tool (SWAT) (Neitsch, Arnold, Kiniry and Williams, 2001) to quantify the effects of alternative management practices on water quality. The impact of spatial interdependencies between alternative pollution sources on pollution abatement cost is a function of the level of heterogeneity that is taken into account when evaluating alternatives. To account for the spatial variability in the Gamtoos catchment, the catchment was delineated into 22 sub-catchments and 129 hydrological response units of which 53 are used for irrigation purposes. The effects of 229 alternative crop, water and fertiliser input combinations on nitrate pollution parameters were simulated with SWAT.

The General Algebraic Modelling System (GAMS) (Brooke, Kendrick, Meeraus and Raman, 1998) was used to integrate SWAT with the spatial optimisation models developed in this research. Procedures were developed to extract the vast amount of output data which are differentiated by sub-catchment, hydrological response unit, land type, crop, planting date, fertiliser application rate, irrigation level, year of simulation and month of the year, and to convert it to GAMS readable input files. Special GAMS programming features were then used to import about 900 000 lines of output data from SWAT into the modelling system. Several optimisation models were developed in this research to evaluate the cost-effectiveness of increasing fertiliser and irrigation cost as instruments to comply with a total catchment nitrate water quality indicator relative to the cost-effective spatial use of the management practices that achieves the standard at minimum cost. Dynamic pollution contribution rates were incorporated into the spatial non-linear programming model to establish the cost-effective allocation of management practices that achieved the water quality standard at minimum cost. The pollution impact of increasing fertiliser, water cost and a water market were determined exogenously using the output from SWAT.

1.6 REPORT STRUCTURE

The contents of this report consist of five chapters as well as an executive summary and research implications.

In Chapter 2 the pollution processes that characterise NPS pollution is reviewed. Next the theoretical framework used to evaluate alternative pollution abatement policies is established and the implementation of alternative policy instruments reviewed. Ways to incorporate pollution risk into programming models are investigated, while the last part is used to give an overview of SWAT.

A short description of the Gamtoos River catchment, its resources and management of the resources is given in Chapter 3.

The procedures used to integrate and use SWAT and the spatial optimisation models to determine the pollution abatement cost used to evaluate the cost-effectiveness of an alternative instrument for complying with a water quality standard are presented in Chapter 4. More specifically the application of SWAT to derive pollution parameters for alternative management scenarios is presented. The second part of the chapter is devoted to the GAMS programming code. The programming code has four distinct sections. The first concerns the unique procedures used to import the large amount of output data from SWAT. Data manipulation and the calculation of the necessary input parameters for the spatial optimisation models is discussed in the second section. The specification of the optimisation models is discussed in the third section, while the last section is devoted to the procedures used to derive the necessary output from the optimisation models to evaluate the cost-effectiveness of the alternative policy instruments.

Chapter 5 presents the economic environmental tradeoffs of the evaluated alternative instruments to achieve a specific water quality standard at the Gamtoos catchment outlet, a discussion of the cost effectiveness of the alternatives, and the conclusions.

The implications for policy and further research are shown at the end of the report.

NON-POINT SOURCE POLLUTION CONTROL: CONSIDERATIONS FOR POLICY EVALUATION

CHAPTER 2

In this chapter a literature review is done regarding NPS pollution control policy to guide the procedures used in the next chapter to quantify NPS pollution abatement cost. The latter part of this chapter is devoted to an overview of the NPS pollution simulation model used in this research to quantify the effects of alternative management options on nitrate pollution in the Gamtoos catchment.

2.1 CHARACTERISING AGRICULTURAL NON-POINT SOURCE POLLUTION

Water pollution can be classified as non-uniformly mixed fund pollutant (Tietenberg, 1992:376). A fund pollutant is one for which the environment has some absorptive capacity, and as long as the emissions do not exceed the absorptive capacity these pollutants do not accumulate. When these pollutants are non-uniformly mixed, it is not only the magnitude of the emissions that counts but also the location where the emissions enter the water resource. These effects are accounted for by using the concentration of the pollutant in the medium.

In order to effectively manage agricultural NPS pollution it is important to understand the processes governing NPS pollution and the linkages between these processes. In this section these processes are used to characterise the relationship between agricultural production and damages from pollution (Ribaudo, Horan, and Smith, 1999; Horan, and Ribaudo, 1999; Quibell, Van Vliet and Van der Merwe, 1997).

The first process concerns the production of pollution emissions and therefore characterises the link between agricultural production practices and the movement of pollutants of the field. The pollution process is characterised as being diffuse or non-point source in origin, since the pollution emissions do not emanate from a single point, but leaves each field in many places. The diffuse nature the emissions of NPS pollution makes it difficult to observe and accurate measurement prohibitively expensive (Lichtenberg, 2000; Ribaudo, Horan, and Smith, 1999). Important factors that influence the production of pollution emissions include the amount of variable production inputs, specific management practices, landuse, rainfall, soil characteristics and topography. Thus, the production process not only depends on deterministic factors (choice of inputs, management practices and landuse), but also on stochastic factors such as weather.

After pollution emissions are produced they interact with emissions from other fields and the surrounding ecosystem as they move to water resources. The amount of pollutants that eventually reach a water resource depends on factors such as distance, rainfall, slope, vegetation, properties of agrichemicals and intervening conservation practices such as riparian buffers and wetlands. Thus, it is clear that the spatial location of one field to another may have a significant impact on the amount of pollution emissions that reaches water resources. An excellent example is the use of riparian buffer strip to reduce pollution emissions. Research has shown that buffer strips may reduce nitrate concentration by up to 75% (Qiu, 1996). Once agricultural pollutants are discharged into water resources they may undergo dilution or some form of chemical, physical and biological alteration depending on the assimilative power of the system to realise a final water quality at a specific location. The final water quality determines the ability of the water resource to provide economic service. Economic damages due to changes in ambient pollution levels will, however, only occur if a demand for a certain water quality standard exists and is a function of the economic (use and non-use) value actually placed on the service. The greater the demand for the services provided by the water resource, the greater the value people place on it and the greater the economic damage if impaired by pollution.

From the above discussion it is clear that the different processes governing agricultural NPS pollution in any catchment are intimately linked to one another and that each component is affected by changes in every other component. Therefore catchments or sub-catchments are logical planning and management units from an environmental viewpoint (Brooks, Ffolliot, Gregersen and Easter, 1994). A catchment not only implies the inclusion of water in all aspects of the hydrological cycle, but also the land through or over which water moves, and land on which human activities or disturbances create impacts which affect the quantity and quality of the resource. All of these interconnected components should be managed in an integrated or systems approach, thereby recognising that a disturbance made at any place/location in the system will be translated to all other parts of the system (DWAF, 2001). The integrated systems approach to managing water resources emphasises the fact that both the magnitude of pollution emissions and the location where they enter water resources are important in controlling NPS pollution.

2.2 A FRAMEWORK FOR NON-POINT SOURCE POLLUTION CONTROL

Griffen and Bromley (1982:548) distinguished the economic problem of agricultural pollution into three separate categories. First, the sediment, nutrients, and chemicals removed by runoff represent a loss of resources to the individual farmers. These costs are borne privately by farmers. Second, a temporal externality exists if the discount rate of the individual farmer is greater than the social discount rate, or if the farmer has a planning horizon which is shorter than society's, the farmer will mine the soil resource at a faster rate than is socially optimal.

Third, physical resources lost by the individual farm must appear elsewhere in the environment. In sufficient quantities, these resources are pollutants. Since water is the primary transport media for these resources, water pollution by soil, nutrients and chemicals is an agricultural externality. More specifically it is classified as a spatial externality emphasising the location of pollution. Although agricultural runoff generates two kinds of externalities, only the spatial externality was considered in this research. Spatial externalities exist because farmers have no incentive to consider the cost of pollution imposed on others and therefore pollution occurs at insufficiently high levels (Baumol and Oates, 1988 cited by Qiu, 1996). More specifically agricultural NPS pollution can be classified as technological diseconomy (negative externality) since it causes a misallocation of resources and benefit conflict between the polluters and pollution victims (Qiu, 1996).

Coase (1960) reasoned that an externality results because of the absence of efficient property rights. According to his theorem, in the presence of well-defined property rights, low bargaining costs, perfect competition, perfect information and the absence of wealth and income effects, resources will be used efficiently and identically regardless of who holds the property rights. Under these restrictive conditions no government regulation of the externality is needed since the social optimal level of pollution will be determined through the market process. However, according to Pearce and Turner (1990) Coase’s theorem will not attain the social optimal level of pollution due to the following reasons: a) the real world is not perfect and the bargaining power only has power under perfect competition; b) several affected parties have to bargain resulting in high transaction cost of bargaining; c) identifying the polluters and the affected parties who need to bargain may be difficult; d) with common property rights the polluters and the affected parties may be the same people; and e) it offers potential for making an economic activity out of threat-making. Given the above criticism to Coase’s theorem, the market process through well-defined property rights will not lead to socially optimal pollution levels. Some sort of intervention is needed to assure socially optimal levels of pollution.

A fundamental goal of environmental policy is to induce polluters to explicitly consider the cost they impose on society through their production-related activities with the ideal aim of maximising the expected net benefits to society from pollution control (Ribaudo, Horan, and Smith, 1999). The socially optimal level of pollution can be achieved through the use of a Pigovian tax approach (Pearce and Turner, 1990). The misallocation of resources is corrected by levying a tax on each unit of an activity that contributes to pollution. The tax is set equal to the marginal pollution damage at the socially optimal level of pollution.

Applying the Pigovian tax approach is troublesome because there is no easy way to calculate marginal pollution damage, since it does not enter the market system. Thus, achieving the economically efficient outcome (first best solution) is often impossible, because the relationship between economic damage and NPS pollution is seldom known and therefore does not constitute a measurable policy goal (Horan and Ribaudo, 1999). Instead, policies should be designed to achieve specific environmental goals at least cost (Ribaudo, Horan, and Smith, 1999). These policies are referred to as cost effective policies[1]. Economically efficient and cost-effective outcomes provide benchmarks from which to guide alternative policies, especially in the absence of data on transaction cost (Ribaudo, Horan, and Smith, 1999). The process of designing comprehensive policies for controlling NPS pollution therefore consists of defining appropriate policy goals, choosing appropriate instruments and setting these instruments at levels that will achieve the goals at least cost (Ribaudo, Horan, and Smith, 1999).

In the next section different pricing and standards are evaluated as instruments to control agricultural NPS pollution.

2.3 ECONOMIC POLICY AND STANDARD APPROACH TO AGRICULTURAL NON-POINT SOURCE POLLUTION CONTROL

Economic policy instruments in the form of taxes and subsidies and standards are often used to control externalities, both of which may attain the same pollution reduction if appropriately specified. However, the base to which it is applied has far-reaching implications when it comes to the implementation of these policies. In this section the theoretical foundation of incentives and standards when applied to different bases are summarised, starting with a point source and extending it to NPS. The implementation of these policies is discussed in the following section.

2.3.1 POINT SOURCE EMISSIONS BASED CONTROL POLICY

If the polluters are profit maximises and there is perfect competition, the pricing and standard method can be presented using profit maximisation framework, as shown by Griffin and Bromley (1982) which was summarised as follows by Qiu(1996).

Suppose there are J farms which have their own production activities which generate emissions. Let y^j be the production bundle of farm j with y_n^j being the n^{th} element (positive or negative) of that vector. Positive activities represent outputs and negative ones are inputs. There are N goods or activities, i.e., n = 1, ..., N. Emissions by farm j are nonnegative and are denoted z^j. Total emissions from all the farms are limited to Z^*. Farm j*'s* production set is given implicitly by $f^j(y^j, z^j) \leq 0$. These relationships become equalities when the farms fully exploit their production abilities, which are assumed here.

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[1] Cost-effective policies are in essence also second best since they do not attain the economically efficient outcome.

Given these specifications, society's problem is to:

Maximise: $\sum_{j=1}^{J} py^j$ (2.1)

subject to: $f^j(y^j, z^j) \leq 0$ for all j (2.2)

$\sum_{j=1}^{J} z^j \leq Z^*$ (2.3)

where:

p price vector (1 x N)

Society's Lagrangian is:

$$L = \sum_{j=1}^{J} py^j - \sum_{j=1}^{J} \alpha^j f^j(y^j, z^j) - \mu\left(\sum_{j=1}^{J} z^j - Z^*\right) \tag{2.4}$$

where:

α^j and μ are appropriate Lagrange multipliers

Assuming that the implicit production functions are concave and that all constraints are binding, the following first-order conditions (FOCs) describe the optimal choice of production activities:

$p_n - \alpha^j f_n^j = 0$ for all j and n (2.5)

$-\mu - \alpha^j f_n^j = 0$ for all j (2.6)

Subscripts on functionals denote partial derivatives and those on vectors denote particular vector elements.

Consider the private side. Without consideration of the externality, the farm j*'s* problem is to maximise profit (py^j) subject to the constraints on production, $f^j(y^j, z^j) \leq 0$. The FOC for this problem is equation (2.5).

The above problem can be modified by introducing an economic incentive for reducing emissions. Let s represent the per unit incentive on emissions and Z be the incentive base level, a predetermined quantity from which greater emissions are charged at rate s and lesser emissions are subsidised at the same rate. Farm j*'s* problem is now:

Maximise $py^j + s(Z - z^j)$ (2.7)

subject to: $f^j(y^j, z^j) \leq 0$ for all j (2.8)

The Lagrangian function is:

$$L^j = py^j + s(Z - z^j) - \delta^j f^j(y^j, z^j) \tag{2.9}$$

Optimality conditions are derived from the following FOCs:

$$p_n - \delta^j f_n^j = 0 \quad \text{for } n \tag{2.10}$$

$$-s - \delta^j f_z^j = 0 \tag{2.11}$$

Comparing equations (2.5) and (2.6) to equations (2.10) and (2.11) shows that the social optimum (not necessarily being Pareto optimum) can be realised by choosing an economic incentive which equals the shadow price of the environmental constraint, i.e., $s=\mu$. In this case, the optimal incentive, s^*, is the same for all farms and depends on the incentive base level, Z. Later, it is shown that the optimal incentive may vary across farms when different farms make different contributions to the externality.

An equally efficient set of regulations can be mathematically derived using profit functions. Let $\pi^j(p,s)$ represent farm j*'s* optimal profit function, which is specified as a function of the price vector and the incentive level:

$$\pi^j(p,s) = Max \;\; py^j + s(Z - z^j) \tag{2.12}$$

subject to: $f^j(y^j, z^j) \leq 0$ (2.13)

Applying Hotelling's lemma, the farm's optimal output of pollution is the derivative of the profit function with respect to the cost of emitting the pollutant. Evaluating this partial derivative at the appropriate prices and the optimal incentive, we have an equally optimal emission standard for farm j.

$$z^j = z^j(p, s^*) = \left. \frac{\partial \pi^j(p,s)}{\partial s} \right|_{p,s^*} \quad \text{for each } j \tag{2.14}$$

Equation (2.14) describes a set of optimal emission standards which, when enforced, will achieve the targeted aggregate emissions such as Z at least-cost. The emission standard defined by equation (2.14) are as efficient as the least-cost incentive, $s^*=\mu$. Each of the policies is the dual of the other. Due to this dual relationship the allocative efficiency of both programs is guaranteed to be the same (Griffin and Bromley, 1982).

2.3.2 NON-POINT SOURCE EMISSION BASED CONTROL POLICY

Implementation of the two policies discussed above requires that the pollutant be monitorable. In the case of NPS pollution, monitoring of non-point source emissions is either infeasible or impractical. However, the inputs and outputs of production activities are monitorable. As shown by Griffin and Bromley (1982), the least-cost framework developed in the previous section can be extended to develop some environmental policies which target the inputs and outputs associated with NPS pollution. They extended the framework by introducing an emission generating function.

Returning to the specification of the previous model, assume that every farm is fully utilising its productive abilities, i.e., $f^j(y^j, z^j) = 0$ for all j. Applying the implicit function theorem, a neighbourhood exists about y^j and smooth function g^j such that $f^j[y^j, g^j(y^j)] = 0$ for all j throughout the neighbourhood. The only restrictive assumption necessary to apply this theorem is $f_z^j \neq 0$. In the presence of unabated pollution, each farm chooses $f_z^j = 0$. However, environmental policy is intended to direct the farm away from this point and therefore the assumption is valid. The implication of this theorem is that an emission generating function is expressible as a continuously differentiable function of all inputs and outputs. The formulation, is completely general, accommodating inputs and/or output determinants of NPS pollution. For convenience, assume that the emission generating function, $g^j(y^j)$, does not differ among farms, so the superscripts on this function can be dropped.

Based on this functional relationship, Griffin and Bromley proposed four least-cost environmental policies to control NPS pollution. The first is a non-point incentive, which is equivalent to the incentive formulation given in the previous section and denoted as $s*$. The second is a system of non-point standards, which is still expressed by equation (2.14). The difference between point and non-point incentives and standards is not based on the theoretical formulation, but on the operation and enforcement. Non-point incentives and standards can be implemented through monitoring the farm agricultural activities and then calculating the emissions using the emission generating function $g^j(y^j)$.

The third is called management incentives. Instead of a tax or subsidy based on emissions, the management incentives are imposed on inputs and outputs of agricultural activities. Let σ denote the vector of incentives attached to the elements of y^j and σ_n is the incentive on activity y_n^j. Let Y represent the management incentive base levels. Each Y_n in Y is a predetermined and arbitrary quantity from which greater activity levels are charged and lesser activity levels are subsidised at the rate σ_n. The private problem for farm j can be formulated as follow:

Maximising $$py^j + \sigma(Y - y^j) \qquad (2.15)$$

subject to $$f^j[y^j, g^j(y^j)] = 0 \qquad (2.16)$$

The private Lagrangian function and the FOC for the above problem are as follows:

$$L^j = py^j + \sigma(Y - y^j) - \delta^j f^j[y^j, g(y^j)] \qquad (2.17)$$

$$p_n - \sigma_n - \delta^j(f_n^j + f_n^j g_n) = 0 \qquad \text{for all } n \qquad (2.18)$$

Society's problem is slightly different because of the removal of z^j as an independent variable. The social Lagrangian and FOC are specified as:

$$L = \sum_{j=1}^{J} py^j - \sum_{j=1}^{J} \alpha^j f^j[y^j, g(y^j)] - \mu\left[\sum_{j=1}^{J} g(y^j) - Z^*\right] \qquad (2.19)$$

$$p_n - \mu g_n - \alpha^j(f_n^j + f_z^j g_n) = 0 \qquad \text{for all } n \text{ and } j \qquad (2.20)$$

Comparison of (1.18) and (1.20) identifies the least-cost management incentives as:

$$\sigma_n^* = \mu g_n = s^* g_n \qquad \text{for all } n \qquad (2.21)$$

This system of incentives is not necessarily the same for all farms because derivatives of the emission generating function are evaluated at different activity levels.

The fourth environmental policy is management practices, which is the dual of management incentives. Let $\pi^j(p,\sigma)$ denote farm *j's* profit function in the presence of management incentives. Hotelling's lemma can be used to specify the optimal levels on individual agricultural activities. These optimal activity levels are called management practices, and are defined as:

$$y_n^{j*} = y_n^j(p,\sigma^*) = \left|\frac{\partial \pi^i(p,\sigma)}{\partial \sigma_n}\right|_{p,\sigma^*} \qquad \text{for all } n \text{ and } j \qquad (2.22)$$

The management practices will induce the least-cost achievement of the environmental emission standards.

2.3.3 WATER QUALITY BASED CONTROL POLICY

Ambient-based instruments have the advantage that they shift the location of monitoring from the production choices (technology, input use, crops, etc.) of farms that are suspected of contributing to environmental degradation to the environmental media itself (Horan, Shortle and Abler, 1998).

Segerson (1988) was the first to propose the use of an ambient-based tax to control NPS pollution. Her research showed that a uniform tax based on ambient water quality can achieve an efficient level of NPS pollution in a catchment with multiple polluters only when the marginal benefits of abating pollution are constant. Horan, Shortle and Abler (1998) extended Segerson's analysis by exploring the design of uniform ambient-based taxes when each firm has a multiple choice set. Although the polluters pay a uniform marginal tax rate per unit of additional ambient pollution the correct marginal incentives are maintained since the polluters do not pay the same rate per unit of pollution abatement (Segerson, 1988). The latter depends on each polluter's contribution to marginal ambient water quality levels.

Qiu (1996) used the concept that each polluter (catchment) contributes differently to marginal water quality problems to derive a conceptual framework with variable economic incentives that allows for the implementation of the tax at sub-catchment level. Following Qiu (1996), the least-cost framework with variable economic incentives can be developed by introducing the concept of pollution contribution rate.

Suppose the objective of society is to limit the aggregate pollution to Z^*. Aggregate pollution is a continuous and differentiable function of emissions generated by all farms, $h(z)$, where z is a vector of emissions generated by farms. The constraint on the relationship between emission at all farms and aggregate pollution is:

$$h(z) \le Z^* \qquad (2.23)$$

Instead of using $\sum_{j=1}^{J} z^j \le Z^*$, society's problem can be reformulated using constraint (2.23). The social Lagrangian becomes:

$$L = \sum_{j=1}^{J} py^j - \sum_{j=1}^{J} \alpha^j f^j(y^j, z^j) - \mu\left[h(z) - Z^*\right] \qquad (2.24)$$

The FOCs are:

$$p_n - \alpha^j f_n^j = 0 \qquad \text{for all } n \text{ and } j \qquad (2.25)$$

$$-\mu h_z^j - \alpha^j f_z^j = 0 \qquad \text{for all } j \qquad (2.26)$$

where:

h_z^j partial derivative of the contribution function, $h(z)$, with respect to z^j and interpreted as farm j's pollution contribution rate.

By comparing equations (2.25) and (2.26) to equations (2.5) and (2.6), the optimal economic incentive for farm j with minimum costs is shown to be:

$$s_j^* = \mu^* h_z^j$$

The optimal economic incentives vary across farms when farms have different contributions to aggregate pollution. Similarly, a system of standards on emissions from all farms can be derived as the dual of the variable economic incentive using the same framework presented above.

2.4 IMPLEMENTING COST-EFFECTIVE NON-POINT SOURCE POLLUTION POLICY

From the previous section it is clear that with the usual caveats concerning the omission of income effects, transaction costs and time, the specified emission incentives or standards and the management incentives or standards are equally allocatively efficient in achieving a certain emission target. Implementation of these policies differs considerably in terms of the number of entities that should be controlled and the information needed. The last-mentioned is affected by the base to which the instrument is applied, the instrument itself, and whether the marginal damage costs are constant or variable.

When controlling NPS pollution under heterogeneous conditions through pollution-based (emissions or ambient water quality) standards a separate standard needs to apply to each farmer to achieve the water quality objective at minimum cost. On the other hand a uniform pollution-based incentive will be allocatively efficient when applied to heterogeneous pollution sources, since the marginal costs of abatement are equalised across the pollution sources yielding the least cost method of achieving the specified pollution target. A necessary condition for this to happen is that the marginal damages from each source should be constant regardless of the source of the extra pollution (Griffen and Bromley, 1982; Segerson, 1988). However, marginal damages from different pollution sources might vary, as in the case of emissions entering a river at different places with different assimilative capacities (Helfand and House, 1995). Qiu (1996) clearly demonstrated that one needs differentiated incentives/standards when some farms are likely to contribute more heavily to marginal ambient water pollution than others. By implication this means that two farms with the same production and pollution emission generating potential will need differentiated economic incentives if they contribute differently to water quality problems. Think of two farms where one farm is close to the water source and the other further away. From the above discussion it is clear that pollution-based discriminatory standards, taxation or subsidisation, which may not be socially acceptable, will only occur when farms contribute differently to pollution (Griffen and Bromley, 1982; Segerson, 1988). Given the fact that emission-based policies are infeasible due to prohibitively expensive monitoring (Shortle and Dunn, 1986), ambient water quality will be the preferred pollution base. However, ambient water quality measures the resulting water quality from a group of farmers, and therefore farmers within this group are not subsidised or taxed on their own performance but on that of the group (Segerson, 1988). Free riding may be a problem when policy instruments are used to control pollution from a group of farmers. An important feature of an ambient-based policy is that it shifts the information burden from the regulators to the farmers. Cabe and Herriges (1992) demonstrated that ambient-based policy may not achieve the desired outcome if farmers' beliefs regarding the fate and transport of pollutants are different from those of the regulators. The desirability of the policy may hinge strongly on the regulator's ability to ascertain farmers' beliefs about pollutant fate and transport, or to influence these beliefs through education or extension (Cabe and Herriges, 1992).

Controlling management practices that lead to pollution were proposed in literature as a practical alternative to controlling pollution itself, since management practices are observable whereas emissions are difficult or prohibitively expensive to observe. Shortle and Dunn (1986) extended Griffen and Bromley's analysis (Griffen and Bromley, 1982) by incorporating the stochastic nature of pollution generation. Furthermore they assumed that the farmers have better information regarding the effects of changing management practices on farm profits when reallocating resources in response to policy than the regulators when choosing a policy. Their general conclusion was that incentives on management practices (which may be inputs) would generally outperform quantity controls. However, cost-effective control may be very restrictive, since differentiated economic incentives need to apply to each management practice on each farm even though marginal pollution damages may be constant across farms, as long as the farms are heterogeneous. Therefore input-based, cost-effective solutions to NPS pollution depend on having detailed information on input usage and on the ability to regulate all inputs contributing to pollution simultaneously (Larson, Helfand and House, 1996). By implication each farmer's inputs need to be priced or subsidised individually. Discriminatory taxes are always the case if one is concerned with cost-effective solutions. Another problem arises when those farmers facing lower taxes buy large quantities and resell to those farmers who face high taxes (Helfand and House, 1995).

From this section it is clear that the implementation of cost-effective policies is difficult, because of the difficulty to observe pollution emissions, free riding, information needs on management practices, number of controlling entities to achieve cost-effectiveness and the fact that discriminatory taxes might be socially unacceptable. Uniform incentives will only achieve cost-effectiveness in the rare situation where marginal damages from different pollution sources are equal. However, cost-effective policies provide us with benchmarks by which the efficiency of alternative policies to achieve the cost-effective outcome can be evaluated.

2.5 SECOND-BEST ALTERNATIVE POLICIES AND TARGETING

Given the problems concerning information needs and practical problems regarding implementation of cost-effective policies, various researchers sought alternative policies which are easier to implement. These instruments to control NPS pollution will necessarily be of second best[2] nature because they do not achieve the cost-effective outcome. Second-best alternatives are usually compared to cost-effective or efficient policies to determine their efficiency.

Helfand and House (1995) compared four relatively easily implementable alternative second-best policies to control nitrate leaching from two soils used for lettuce production. These include a) uniform input tax applied to all pollution sources; b) uniform reduction in inputs contributing to pollution based on a specific percentage reduction for all sources; c) uniform tax on single inputs contributing to pollution and d) uniform input restrictions. Uniform NPS pollution policies are not cost-effective because the same set of instruments applies to all farmers under heterogeneous conditions. These researchers found little difference between the cost-effective solution and the alternative second-best uniform policies even when applied to heterogeneous conditions. However, generalisation of the results is not possible, since it depends on the degree of heterogeneity taken into account.

An innovative approach to increase the efficiency of second-best policies to achieve cost-effective outcomes is targeting of pollution reduction responsibilities. Given the high cost of pollution control, targeting is an attractive option to NPS pollution control, since it improves the cost-effectiveness of pollution control expenditures by governments and it can allocate pollution reduction responsibilities to areas in the catchment having the lowest control cost (Bosch and Wolfe, 1998). Dickinson, Rudra and Wall (1990) questioned the effectiveness and efficiency of a targeting approach to control NPS pollution in all situations, reasoning that the desirability and necessity of targeting is primarily a function of the spatial variability of factors relating to pollutant loads. In fact, spatial variability in terms of resource base, geographical location and weather can be identified as the rationale for using targeting to improve cost-effectiveness since differences in these factors are likely to result in varying pollution loadings and marginal abatement costs. Empirical evidence shows that when ignoring the spatial variability in a catchment the estimated pollution levels and pollution reduction costs will be biased if pollution is correlated to agricultural productivity (Opaluch and Segerson, 1991). Furthermore, ignoring

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[2] In this research the same classification used by Ribaudo *et al.* (1999) to distinguish between cost-effective and second-best alternatives is used. Cost-effective policies as referred to in this research are those that achieve a specific pollution target at minimum cost whereas second-best alternatives are those policies that are easier to implement without being cost-effective.

the spatial variability in the catchment may cause the researcher to overlook: 1) pollution control opportunities available to the farmers thereby possibly overestimating the control cost and 2) opportunities to reduce cost by targeting areas with low cost of pollution control (Bosch, Pease and Stone, 1998).

Various criteria such as productivity index (Runge, Larson and Roloff, 1986), sediment delivery rate, sediment delivery ratio, slope and distance to the nearest water source (Fox, Umali and Dickinson, 1995) have been evaluated for targeting purposes. However, it is still unclear what criteria should be used, since one criterion may not be as effective as the other when applied to different catchments emphasising the site-specific nature of the problem. Empirical evidence has shown that targeting strategies based on economic criteria are more cost-effective than targeting strategies based on physical or pollution related criteria such as sediment delivery ratios (Fox, Umali and Dickinson, 1995; Ribaudo, 1989). Thus, the ability of a targeting scheme to increase the cost-effectiveness of programmes to reduce agro-pollution depends on two aspects: a) how well the targeting scheme approximates the marginal cost of pollution reduction and b) the total area (hectares/farms/sub-catchments) affected (Carpentier, 1996). Using these criteria, Carpentier, Bosch and Batie (1998) showed that targeting based on spatial information reduced compliance cost by nearly 80% when compared to the uniform standard that ignores spatial variability.

It is concluded from this section that detailed information about the spatial variability of factors influencing pollution loads may hold promise to further reduce compliance cost by targeting the pollution reduction responsibilities to those having the lowest control cost.

2.6 *INDIRECT INSTRUMENTS FOR CONTROLLING NON-POINT SOURCE POLLUTION*

All the instruments described thus far were aimed at reducing pollution itself. Because pollution is a process whereby pollutants are transported through various pathways and mediums, controlling factors that influence these pathways or the transport medium will necessarily have an impact on pollution levels. The objective of this section is to evaluate the potential of water markets as an indirect method of controlling NPS pollution.

Lee and Howitt (1996) suggested that on-farm water conservation offers great potential to improve water quality through reduced drainage. Weinberg, Kling and Wilen (1993) included on-farm water conservation strategies when evaluating the impacts of water markets on water quality externalities and concluded that a water market provides the necessary economic incentives to conserve water resulting in water quality improvements through reduced drainage. The impacts of water markets on NPS pollution are of particular interest, since it has been proposed as an alternative to reallocate South Africa's scarce water resources (Backeberg, 1996).

Given fully allocated water supplies, water can be conserved from agriculture and made available for sale in three ways (Weinberg, Kling and Wilen, 1993): a) water applications can be reduced *ceteris paribus*, potentially reducing crop yields due to water stress; b) irrigation system performance can be improved to maintain crop yields as water applications are reduced; or, c) cropping patterns can be changed. However, these strategies may not always prove to reduce drainage. If land is available and farmers are allowed to expand their irrigation operations drainage may increase during some periods of the growing season (Oosthuizen and Grové, 2001). Furthermore, while reduced drainage may lead to reduced pollution emissions, reduced drainage can also reduce the volume of water in rivers and hence its dilution capacity (Connor and Perry, 1999). When taking dilution into account, Connor and Perry (1999) showed that negative groundwater externalities may result from water trade even when institutional protection for return flow externalities is provided.

An important conclusion from this section is that pollution loads cannot be separated from the medium in which they are dissolved when evaluating alternative policies to control NPS pollution.

2.7 INCORPORATING RISK INTO NON-POINT SOURCE POLLUTION CONTROL ANALYSES

Previously in this chapter NPS pollution was characterised as being uncertain due to stochastic processes governing agricultural NPS pollution. Several researchers (Shortle and Dunn, 1986; Segerson, 1988; Horan, Shortle and Abler, 1998) have shown that uncertain environmental outcomes have a significant effect on policy design. When environmental outcomes are stochastic, pollution control strategies should be aimed at improving the distribution of outcomes rather than some scalar value (McSweeny and Shortle, 1990). Mapp, Bernardo, Sabbagh, Geleta and Watkins (1994) used a biophysical simulation model to determine the pollution variability of alternative strategies to limit nitrogen use to protect water quality. However, most frequently pollution variability of alternatives is incorporated into mathematical programming models to explicitly model the economic environmental trade-offs within a chance constraint framework (Koo, Williams, Schurle and Langemeier, 2000; Zhu, Taylor, Sarin and Kramer, 1994; Segarra, Kramer and Taylor, 1985).

2.7.1 CHANCE CONSTRAINT PROGRAMMING

Chance constraint programming can be used to guarantee that a specific water quality target will be met with some degree of confidence. Following Biosvert and McCarl (1990) a chance constraint with stochastic pollution emissions can be written as follows:

$$\sum_j \bar{a}_{ij} x_j - \theta \sum_k \sum_j x_j x_k \sigma_{ikj} \le b_i \tag{2.27}$$

where:

$\bar{a}_{ij}$	mean value stochastic emission of pollutant i associated with cropping activity j
x_j	amount of cropping activity j
θ	distribution specific constant
σ_{ikj}	variance-covariance matrix of a_{ij}'s coefficients of activities k and j (variance when $k = j$)
b_i	water quality standard of pollutant i

In equation (1.27) the mean ($\sum_j \bar{a}_{ij} x_j$) level of the joint distribution of pollution emissions is adjusted by multiplying the distribution specific constant (θ) with the variance ($\sum_k \sum_j x_j x_k \sigma_{ikj}$) of the joint distribution of pollution emissions to ensure that the water quality target will be met α per cent of the time. The value of θ can be determined using distributional assumptions about the stochastic coefficients or Chebyshev's inequality.

The specified distributions of stochastic pollution emissions have a significant impact on the optimal combination of activities and therefore also on the economic environmental tradeoffs (Zhu, Taylor, Sarin and Kramer, 1994). Determination of the distributions may be tedious, since the same distribution may not hold in all situations due to the site specific nature of agricultural NPS pollution (Qiu, Prato and McCamley, 2001).

2.7.2 ENVIRONMENTAL TARGET MOTAD

Target MOTAD (Tauer, 1983) models have traditionally been used as a method to include objective function risk. However, Target MOTAD can also be modified to model deviations above a specified environmental target (Teague, Bernardo and Mapp, 1995). The model has the advantage over chance constraint programming in that it treats the sample of pollution emissions as an empirical distribution while optimising over the column space of the sample. Mathematically the environmental Target MOTAD model can be stated as:

$$MAX \;\; E(z) = \sum_j c_j x_j \tag{2.28}$$

subject to:

$$\sum_j a_{kj} x_j \leq b_k \tag{2.29}$$

$$T - \sum_j e_{rj} x_j - d_r \geq 0 \tag{2.30}$$

$$\sum_r p_r d_r = \lambda \tag{2.31}$$

where:

$E(z)$	expected return of the farm plan
c_j	expected return of activity j
x_j	level of activity j
a_{kj}	technical requirement of activity j for resource k
b_k	level of resource k available
T	environmental pollution target
e_{rj}	pollution emissions for activity j in state of nature r
d_r	deviation of pollution emissions above the pollution target in state of nature r
p_r	probability that state of nature r will occur
λ	risk measure

Equation (2.30) and (2.31) are added to a standard linear programming model to include environmental risk. More specifically equation (2.30) estimates the amount of pollution above the specified pollution target in each state of nature. The expected pollution level above the pollution target is estimated in equation (2.31) by weighting each deviation by its probability of occurrence. The only difference between the traditional Target MOTAD model and the environmental version is that the environmental version is concerned with deviations above a target rather than below as in the original specification.

Both the target pollution level (T) and the level of compliance (λ) must be specified to apply the Target MOTAD model. The environmental regulator using environmental objectives can easily specify reasonable pollution targets. However, specification of the compliance level is more complicated and the scientific basis for guiding the decision is weak (Qiu, Prato and McCamley, 2001). These problems may be overcome by using an upper partial moment inequality to enforce the safety margin.

2.7.3 SAFETY-FIRST CONSTRAINTS USING AN UPPER PARTIAL MOMENT INEQUALITY

Qiu, Prato and McCamley (2001) built on research done by Antwood (1985) to develop an upper partial moment (UPM) inequality approach to impose the safety-first constraint in a

Target MOTAD framework that will ensure that the target pollution level will be met at a certain specified probability level. A UPM is defined as follows for the discrete case:

$$\rho(\alpha,t)=\sum(x_i-t)^{\alpha} f(x_i) \qquad x_i \geq t \tag{2.32}$$

where:

α constant greater than zero

t reference pollution level

x_i pollution variable

$f(x_i)$ relative frequency distribution of the pollution variable x_i

Qiu, Prato and McCamley (2001) demonstrated that:

$$\Pr(x \geq g)=\Pr(x \geq t+p\theta(\alpha,t)) \leq (1/p)^{\alpha} \tag{2.33}$$

with

$$\theta(\alpha,t)=[p(\alpha,t)]^{1/\alpha} \geq 0 \tag{2.34}$$

$$(g-t)/\theta(\alpha,t) \tag{2.35}$$

where

g is the pollution standard set for pollution variable x

Using equation (2.33) it is proved that enforcing the following:

$$t+q^{*}\theta(\alpha,t) \leq g \tag{2.36}$$

is sufficient to guarantee the following:

$$\Pr(x \geq g) \leq (1/p)^{\alpha} \leq (1/q^{*})^{\alpha} \tag{2.37}$$

Now let's assume the decision-maker wishes to impose the following safety-first constraint for environmental quality:

$$\sum_r PR\left(\sum_j e_{rj} \geq G\right) \leq 1/L^{*} \tag{2.38}$$

where G is the environmental goal set by the environmental regulator. The complete model enforcing the safety-first constraint by means of the UPM can be specified as follows:

$$MAX\ \ E(z)=\sum_j c_j x_j \tag{2.39}$$

subject to:

$$\sum_j a_{kj} x_j \leq b_k \tag{2.40}$$

$$t - \sum_j e_{rj} x_j - d_r \geq 0 \tag{2.41}$$

$$\sum_r p_r d_r - \theta(t) = 0 \tag{2.42}$$

$$t + L^* \theta(t) \leq G \tag{2.43}$$

where:

t	endogenously determined reference level for the environmental variable
$\theta(t)$	$\theta(t) = \theta(1,t) = \rho(1,t)$, endogenously determined environmental risk level or the expected deviation above the reference level t

The safety-first constraint using UPM is enforced within a Target MOTAD framework as is evident from the structure of the specification above. The main difference being the specification of L^* rather than λ as required with the Target MOTAD specification. L^* can be interpreted as the inverse of the acceptable probability of environmental pollution greater than the environmental goal G (Qiu, Prato and McCamley, 2001).

Results obtained with the UPM model are very conservative, as it is influenced by the variability and the underlying distribution of the variables and are therefore prone to data mining problems (Qiu, Prato and McCamley, 2001).

2.8 QUANTIFYING NON-POINT SOURCE POLLUTION

As NPS pollution has the property that it is not easily observed, pollution flows from fields are difficult to measure, or if possible very expensive to do so. To overcome these problems, numerous hydrological process models and statistical models have been developed to assess these pollution flows given measurements of appropriate land characteristics, weather and farm production practices (Shortle and Griffin, 2001). Models do not only help in assessing pollution flows from existing resource use and management practices, but also allow you to quantify the potential impact of alternatives.

The main emphasis of this section is not to give an exhaustive literature review of alternative NPS pollution models, but rather to give an overview of the Soil and Water Assessment Tool (SWAT) (Neitsch, Arnold, Kiniry and Williams, 2001) which is used in this research to quantify the pollution impact of alternative management practices. Only an overview of the processes of

SWAT models is given in this section and the reader is referred to Neitsch *et al.* for the details. Pegram and Görgens (2001) gave an overview of alternative models to quantify NPS pollution at various scales and levels of detail.

2.8.1 SOIL AND WATER ASSESSMENT TOOL (SWAT)

From previous discussions it is clear that a catchment scale model that accounts for the production, delivery and transport of pollutants will be the ideal tool to quantify the impact of alternative management practices on ambient pollution levels. SWAT fulfils these needs, since it is a physically based catchment scale model that was developed to simulate the impacts of alternative management practices on surface and ground water, sediment and agricultural chemical yields on a continuous daily time-step over a long period of time. Since SWAT is physically based, the model requires specific information about weather, soil properties, topography, vegetation, and land management practices occurring in the watershed. These inputs are then used to model the physical processes associated with water movement, sediment movement, crop growth, nutrient cycling, etc. The ability of SWAT to model the actual processes governing NPS pollution makes the application of this type of model more appropriate in catchments with little monitoring data in comparison with models that use regression equations to describe the relationship between inputs and output variables. Furthermore the model is computationally efficient in handling complex catchments.

2.8.1.1 Development of SWAT

NPS pollution modellers started off by developing field scale models characterising the production process. Field-scale models are used extensively in literature to quantify pollution loadings (Chemicals, Runoff, and Erosion from Agricultural Management Systems) (Knisel, 1980), GLEAMS (Groundwater Loading Effects on Agricultural Management Systems) (Leonard, Knisel and Still, 1987), and EPIC (Erosion Productivity Impact Calculator) (Williams, Jones and Dyke, 1984). After these developments, NPS pollution modelling was directed towards catchment scale models. The Simulator for Water Resources in Rural Basins (SWRRB) (Arnold, Williams, Nicks and Sammons, 1989) was developed from CREAMS by modifying the hydrology component of the model to provide a continuous catchment scale NPS pollution model. Further developments to SWRRB include the addition of the EPIC crop growth model and the pesticide fate subroutines from GLEAMS. SWAT was developed by merging SWRRB and a model called ROTO (Routing Outputs To Outlet) (Arnold, Williams and Maidmentm, 1995) which was used to route the outputs from several SWRRB simulations through reservoirs and stream channels to overcome the 10 sub-catchment limit of SWRRB. The latest development integrates GIS technology with SWAT in a version called ArcView SWAT.

2.8.1.2 Model working

The ability to accurately predict the movement of pesticides, sediments and nutrients depends on accurate water balance simulations which are the driving force behind the hydrology of any catchment. SWAT operates in a distributed mode whereby the total catchment is partitioned into a several sub-catchments. Each of the sub-catchments is further partitioned into hydrological response units (HRUs), which are lumped areas within the sub-catchment with different hydrological impacts that comprise unique land cover, soil and management combinations. The hydrological processes are simulated separately for each of these HRUs, thereby increasing the accuracy of the predictions.

SWAT separates the simulation of the hydrology of the total catchment into two phases, the land and routing phase. The land phase controls the amount of water, sediment, nutrients and pesticide loadings to the main channel in each sub-catchment whereas the routing phase controls the movement of water and pollutants through the channel network to the outlet of the total catchment.

2.8.1.2.1 Land phase

Climate data provide the moisture and energy inputs that control the water balance of the land phase and determine the relative importance of the different components of the hydrologic cycle. Climatic variables required by SWAT consist of daily precipitation, maximum/minimum air temperature, solar radiation, wind speed and relative humidity. These parameters can be input from records of observed data or can be generated during the simulation using a weather generator.

Figure 2.1 shows the potential pathways of water movement simulated with SWAT.

As precipitation descends, it may be intercepted and held in the vegetation canopy or fall to the soil surface. Water on the soil surface will infiltrate into the soil profile or flow overland as runoff. The surface runoff volume is computed using a modification of the SCS curve number method (USDA Soil Conservation Service, 1972) where the curve number varies non-linearly with the moisture content of the soil or the Green & Ampt infiltration method, (Green and Ampt, 1911). Infiltration is not directly modelled when using the curve number method, but is calculated as the difference between rainfall and the estimated runoff. The Green & Ampt method requires sub-daily precipitation data and calculates infiltration as a function of the wetting front matric potential and effective hydraulic conductivity. Water that does not infiltrate becomes surface runoff when using the Green & Ampt method.

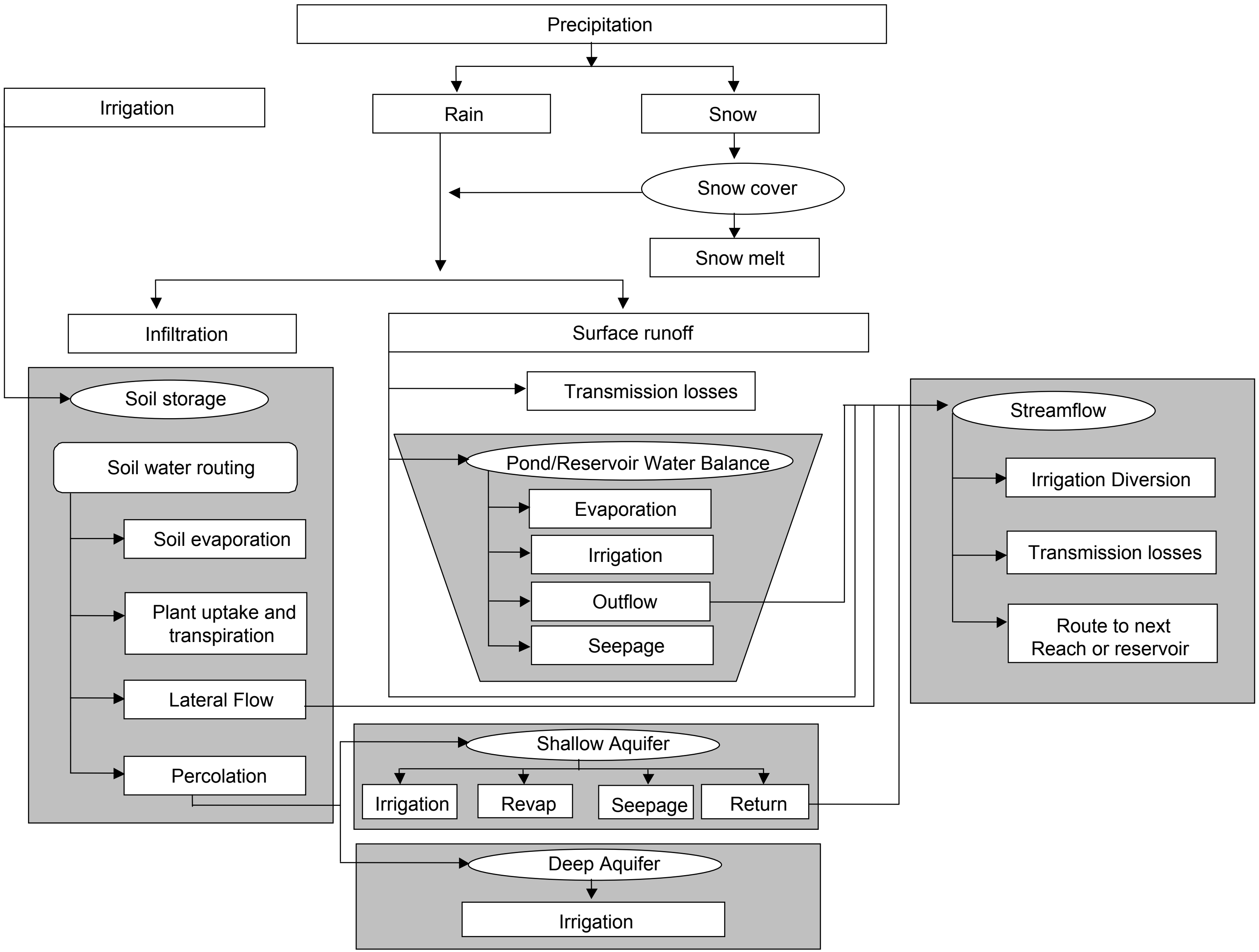

Figure 2.1: The potential pathways of water movement simulated with SWAT.

After water has entered the soil profile through irrigation or rainfall it is redistributed through the different soil layers using a storage routing technique. Evaporation from the soil and plant uptake (transpiration) are calculated separately as a function of potential evapotranspiration and are important factors that determine the amount of water that is available for redistribution. SWAT includes three alternative options for estimating potential evapotranspiration: Hargreaves (Hargreaves, Hargreaves and Riley, 1985), Priestley-Taylor (Priestley and Taylor, 1972), and Penman-Monteith (Monteith, 1965). Downward flow, or percolation, occurs when field capacity of a soil layer is exceeded and the layer below is not saturated. The flow rate is governed by the saturated conductivity of the soil layer. Water that percolates past the root zone enters the shallow aquifer from which revaporation, seepage to a deep aquifer or return flows may occur. Water in the deep aquifer is only available for irrigation and does not contribute to streamflow while return flows from the shallow aquifer contribute to streamflow. Lateral flow also contributes to streamflow and is calculated simultaneously with redistribution. A kinematic storage model is used to predict lateral flow in each soil layer. SWAT accounts for variation in conductivity, slope and soil water content when calculating the amount of water that contributes to streamflow via lateral flow.

SWAT has a pond or reservoir component in which surface runoff may accumulate. The water balance of the pond/reservoir consists of evaporation losses, irrigation abstractions, seepage to the shallow aquifer and outflow, which contributes to streamflow. Simulated streamflow is used for irrigation purposes or is routed to the next reservoir or stream reach.

In addition to simulating the hydrology of each HRU, several processes need to be simulated to track pollutant flows. These include the impact of different management practices, crop growth and nutrient uptake, soil erosion, components of the nitrogen and phosphorus cycles and pesticide fate.

SWAT has a comprehensive module to model the impact of alternative management practices on pollutant loads. The farm manager determines the crop rotation, fertiliser and pesticide type, application rates, tillage operations and irrigation applications and timing thereof. Several databases are supplied with SWAT to facilitate proper modelling of alternative management actions on pollutant loads from each HRU.

A single crop growth model is used to simulate all types of land covers. The potential increase in biomass for a day is a function of intercepted energy and the plant's efficiency in converting energy to biomass. Energy interception is estimated as a function of solar radiation and the plant’s leaf area index. Nutrient uptake (nitrogen and phosphorus) is estimated with a supply and demand approach where the daily plant nitrogen and phosphorus demands are calculated as the difference between the actual concentration of the element in the plant and the optimal concentration, which is allowed to vary with growth stage. Water and temperature also impose growth constraints besides nutrients.

SWAT tracks the movement and transformation of several forms of nitrogen and phosphorus in the soil where the transformation of these nutrients are respectively controlled by nitrogen and phosphorus cycles as depicted in Figure 2.2 and Figure 2.3 respectively.

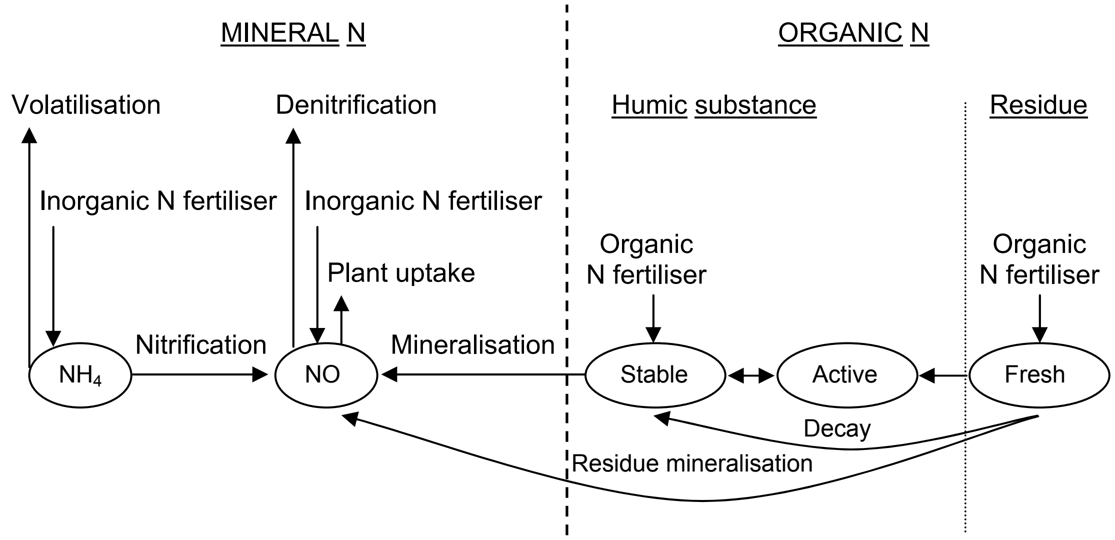

Figure 2. 2: Partitioning of nitrogen in SWAT for modelling nitrogen transformations.

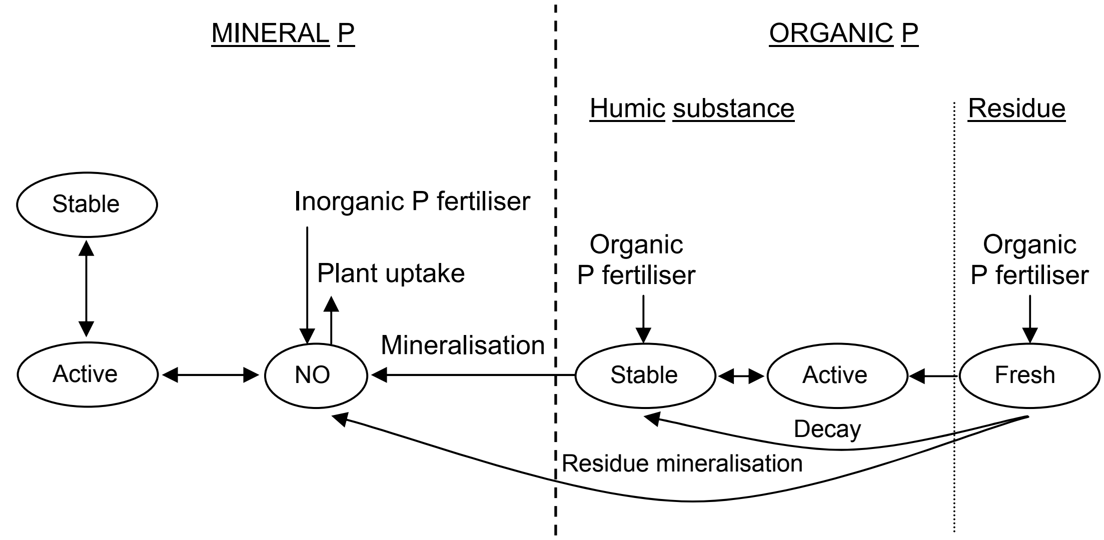

Figure 2. 3: Partitioning of phosphorus in SWAT for modelling phosphorus transformations.

The most important processes governing nitrogen transformation are mineralisation, nitrification, denitrification and volatilisation whereas the phosphorus transformation is governed by mineralisation. In addition to plant use, nitrate, organic N, soluble phosphorus and organic P may be removed from the soil via mass flow of water. Amounts of NO_3-N contained in runoff, lateral flow and percolation are estimated as products of the volume of water and the average concentration of nitrate in the layer. Since phosphorus is not a mobile nutrient, the amount of soluble phosphorus is predicted using the soluble phosphorus concentration in the top 10 mm of soil, the runoff volume and a partitioning factor. Organic N and phosphorus transport with sediment is calculated by means of a loading function developed by McElroy *et al.* (1976) and modified by Williams and Hann (1978) for application to individual runoff events. The loading function estimates the daily nutrient loss based on the concentration of the nutrient in the top soil layer, the sediment yield, and the enrichment ratio. The enrichment ratio is the concentration of the specific nutrient in the sediment divided by that in the soil.

Erosion and sediment yield are estimated for each HRU with the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). While the USLE uses rainfall as an indicator of erosive energy, MUSLE uses the amount of runoff to simulate erosion and sediment yield.

SWAT simulates pesticide movement into the stream network via surface runoff (in solution and sorbed to sediment transported by the runoff), and into the soil profile and aquifer by percolation (in solution). The movement of the pesticide is controlled by its solubility, degradation half-life, and soil organic carbon adsorption coefficient. Pesticide on plant foliage and in the soil degrades exponentially according to the appropriate half-life. Pesticide transport by water and sediment is calculated for each runoff event and pesticide leaching is estimated for each soil layer when percolation occurs.

2.8.1.2.2 Routing phase

Once SWAT has determined the loadings of water, sediment, nutrients and pesticides to the main channel, the loadings are routed through the stream network. Routing in the main channel can be divided into four components: water, sediment, nutrients and organic chemicals.

As water flows downstream, a portion may be lost due to evaporation and transmission through the bed of the channel. Another potential loss is removal of water from the channel for agricultural or human use. Rainfall directly on the channel and/or addition of water from point source discharges may supplement flow. Flow is routed through the channel using a variable storage coefficient method developed by Williams (1969) or the Muskingum routing method.

The transport of sediment in the channel is controlled by the simultaneous operation of two processes, deposition and degradation. Degradation is modelled as a function of channel slope and velocity, and the maximum amount of sediment that can be transported from a reach segment is a function of the peak channel velocity.

Nutrient transformations in the stream are controlled by the in-stream water quality component of the model. The in-stream kinetics used in SWAT for nutrient routing are adapted from QUAL2E (Brown and Barnwell, 1987). The model tracks nutrients dissolved in the stream and nutrients adsorbed to the sediment. Dissolved nutrients are transported with the water while those sorbed to sediments may deposit on the bed of the channel.

While an unlimited number of pesticides may be applied to the HRUs, only one pesticide may be routed through the channel network of the watershed due to the complexity of the processes simulated. Pesticide transformations in the dissolved and sorbed phases are governed by first-order decay relationships. The major in-stream processes simulated by the model are settling, burial, resuspension, volatilization, diffusion and transformation.

2.8.1.3 Conclusions

SWAT has its roots in several field scale NPS pollution models and is theoretically sound. The model is physically based, thereby modelling the actual processes governing NPS pollution using data on the physical characteristics of the catchment. Although the model is data intensive, the parameters needed should be readily available. The physically based nature of the model also makes it more applicable to catchments where detailed water quality data are lacking.

Furthermore the model has the capability to model the impact of alternative management practices on NPS pollution easily through the use of several databases and a user-friendly interface. The linked SWAT-GIS version will also help with managing and input of the spatially distributed parameters needed to run SWAT.

The version of SWAT used in this research does not directly model the impact of vegetative buffer strips on pollution loads to streams. However, research is being done to enhance the capabilities of SWAT to model vegetative buffer zones. Qiu (1996) provided a procedure to quantify the impact of vegetative buffer strips on pollution loads using SWAT output and empirical research results on the impact of buffer strips on pollution loads.

RESEARCH AREA:
GAMTOOS RIVER CATCHMENT

CHAPTER 3

3.1 GENERAL DESCRIPTION OF THE GAMTOOS VALLEY

The Gamtoos Valley is situated about 100 km west of Port Elizabeth on the Eastern Cape coast between latitude 33°58' and longitude 25°01' east (Pearce and Schumann, 1997). The Gamtoos River is formed by the confluence of the Kouga and Groot Rivers. The combined drainage area of these two rivers constitute an area of 34 000 km^2. On the other hand a fairly small area of 1 357 km^2 is drained by the 70 km long Gamtoos River which is surrounded by the Baviaanskloof Mountains. The only tributary river of the Gamtoos River is the Loeriespruit, which enters the Gamtoos estuary about 8.5 km inland of the point of discharge into the sea.

The Beervlei Dam on the Groot River near Willowmore was completed in 1956 and was the first dam to impact on the water availability of the Gamtoos River. Although the dam proved to be of benefit to control the adverse effects of floods in the valley, the quality of the water was poor. Due to high evaporation during water storage in the Beervlei Dam salts accumulated to concentration levels in excess of 700 mg/l which is harmful to the production of tobacco and citrus. A year later the construction of the Kouga Dam, about one kilometre upstream of the confluence of the Kouga and Groot Rivers, and an irrigation water distribution network to the Gamtoos Valley, was approved by parliament. However, all the water was not allocated to agriculture and the dam also had to supply water to the metropolitan area of Port Elizabeth. Due to an intensive network of canals and pipelines the Gamtoos River was no longer used for the conveyance of water to the various users and no commitment exists to release water into the Gamtoos River from the Kouga Dam. Today the only river that constantly feeds the Gamtoos River is water that is released from the Beervlei Dam.

Typically the whole valley is divided into three sub-districts namely Patensie, Hankey and Loerie/Mondplaas with a total listed area of 7 412 ha.

3.2 CLIMATE

The Gamtoos Valley has a moderate climate and is situated in an intermediate zone between the winter and summer rainfall zones of South Africa. Figure 3.1 gives the average monthly minimum and maximum temperatures, rainfall and reference evapotranspiration (ET0). All the values in Figure 3.1 are calculated using data from the Patensie weather station obtained from the South African Weather Bureau for the period 1975 to 2000.

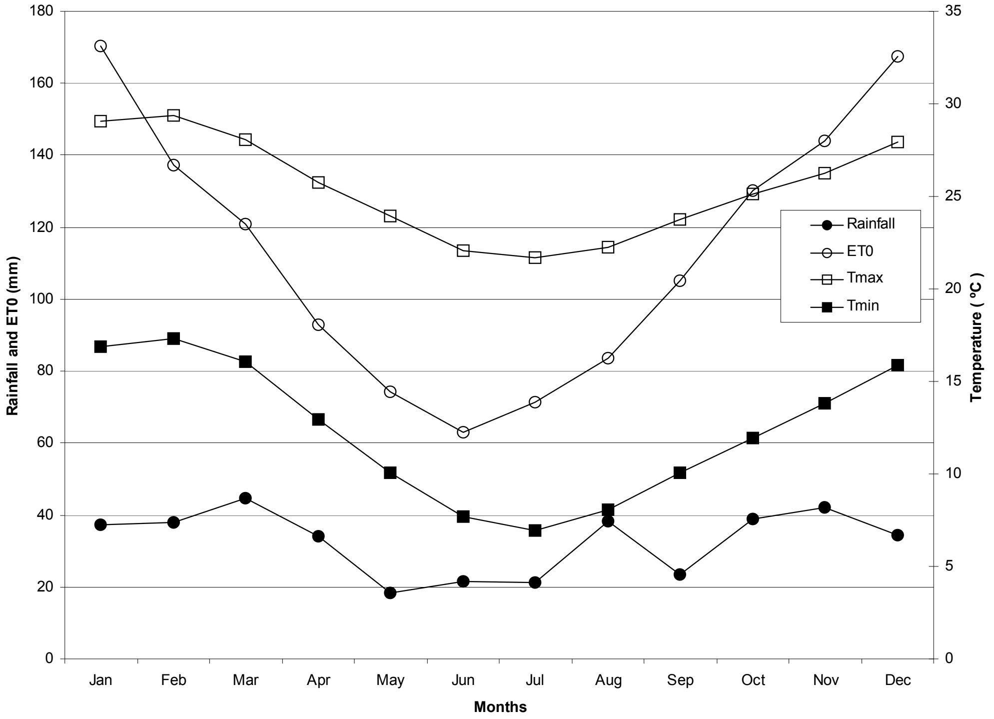

Figure 3.1: Average monthly rainfall, minimum and maximum temperatures and reference evapotranspiration calculated from the Patensie weather station (1975 to 2000).

Although the Gamtoos Valley is situated in a intermediate rainfall zone, it is clear from Figure 3.1 that average rainfall tends to be lower in the winter months of May, June and July. The average annual rainfall amounts to about 400 mm which is far below evaporative demand of 1 360 mm, necessitating irrigation to produce crops in the valley.

Average daily maximum temperature reaches a high in February with temperatures of 29ºC and a low in July with temperatures of 22ºC, only 7 degrees separate these two extremes. Average daily minimum temperatures follow the same pattern with July's temperature being 10ºC less than February's temperature of 17ºC. Average minimum temperatures are, however, still fairly high and only light frost occurs in winter.

3.3 SOILS

In general the soils in the valley are made up of sea deposits of the Uitenhage series, composed of rounded rocks, shale and clay which form more or less vertical faces of conglomerate (MBB, 2001). Layered alluvium is prominent in the flood plains which was mainly brought in as silt by the waters of the Groot River out of the Karoo plains where most of its drainage region is found. More specifically Figure 3.2 shows the distribution of the different Land types in the Gamtoos valley.

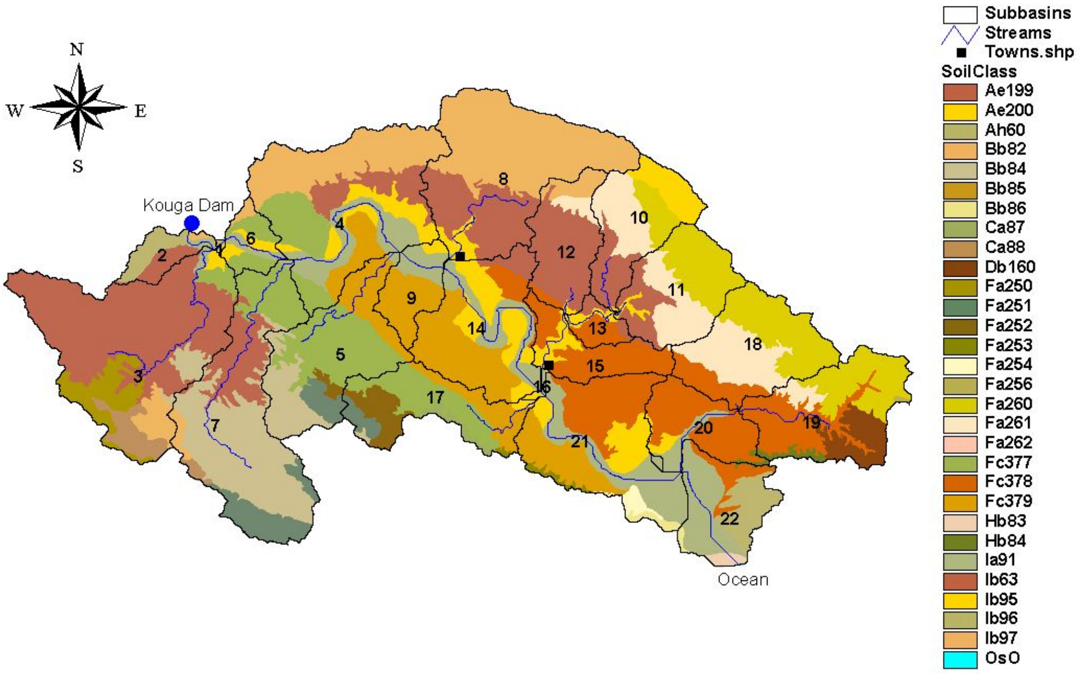

Figure 3. 2: Spatial distribution of Land types in the Gamtoos river catchment below the Kouga Dam, 2001.

The total catchment is made up of 29 different Land types, of which 10 are partially used for irrigation purpose. The percentage distribution of specific Land types used for irrigation purposes and the associated dominant soil form of the Land types are shown in Table 3.1. From Table 3.1 it is clear that the Land types used most frequently for irrigation are Ia91 and Ae200. Predominant soil series in these two Land types are from the Oakleaf and Hutton soil forms respectively. When considering the total irrigation area, 51% of the area is represented by a Land type that has Oakleaf as the dominant soil form and 34% by Hutton as the dominant soil form. These two soil forms represent deep soils, which are very suited for irrigation.

Table 3.1: Distribution of Land types and associated soil forms used for irrigation in the Gamtoos river catchment below Kouga Dam, 2001.

	Distribution of land types as a percentage of total irrigated land in catchment (%)										
Land type:	**Ae199**	**Ae200**	**Ah60**	**Db160**	**Fa260**	**Fc377**	**Fc378**	**Fc379**	**Ia91**	**Ib63**	**Total**
Soil form:	**Hutton**	**Hutton**	**Hutton**	**Kroonstad**	**Cartref**	**Glenrosa**	**Cartref**	**Oakleaf**	**Oakleaf**	**Cartref**	
Subcatchment :1		0.06							0.05		0.11
2									0.38		0.38
3		0.63							0.52	0.20	1.35
4		7.12						1.99	9.21		18.32
5								0.35	0.32	0.16	0.83
6		1.53				0.29			0.98		2.8
7						0.14			0.17		0.31
8	0.15	1.75							0.11		2.01
9		0.91						0.61	3.37		4.89
10	0.29	0.07									0.36
11	0.31	0.48									0.79
12	0.19	0.08					0.09				0.36
13	0.11	0.89					0.20				1.20
14		10.19					1.32		5.35		16.86
15		1.14					1.36				2.50
16		0.27							0.30		0.57
17		0.29						0.03			0.32
18					3.23		0.31				3.54
19				5.15	0.45						5.60
20		0.28					2.34		2.20		4.82
21		4.32							13.09		17.41
22			2.58						12.09		14.67
Total	1.05	30.01	2.58	5.15	3.68	0.43	5.62	2.98	48.14	0.36	100

3.4 CROPS

Table 3.2 show the area planted to different crops in the Gamtoos valley.

Table 3.2: Area planted to different crops in the Gamtoos valley during 2001.

Crop	Planted (ha)	Percentage (%)	Cumulative Percentage (%)
Citrus	2250	22.54	22.54
Potatoes	2050	20.54	43.08
Kikuyu-rye	720	7.21	50.29
Carrots	690	6.91	57.20
Maize	685	6.86	64.07
Wheat	670	6.71	70.78
Cabbage	455	4.56	75.34
Cucurbits	445	4.46	79.79
Lucerne	405	4.06	83.85
Tobacco	370	3.71	87.56
Beans-Green	220	2.20	89.76
Lettuce	165	1.65	91.41
Sweet Potatoes	165	1.65	93.07
Sweet Corn	160	1.60	94.67
Cauliflower	140	1.40	96.07
Chicory	122	1.22	97.30
Beetroot	120	1.20	98.50
Fodder	65	0.65	99.15
Broccoli	32	0.32	99.47
Deciduous Fruits	30	0.30	99.77
Tomato	20	0.20	99.97
Dry beans	3	0.03	100.00
Total area planted	9982		

Source: MBB, 2001.

From Table 3.2 it is clear that that a variety of crops is grown in the area, especially different vegetable crops. Although some of these vegetable crops constitute a significant area it does not form part of the cropping system per se. Mainly these crops are grown on parcels of land that is not utilised by the main cropping system.

The main cropping systems vary between the three sub-districts because of different soils and climatic conditions. In the Patensie area almost 50% of the land resources are used for the production of citrus. Potatoes are the next most important crop, followed by annual cash crops which are mainly grown on a contractual basis with frozen vegetable companies. In general the rotation of the lands used for vegetable production consists of a potato crop followed by either wheat or cucurbits. The plating date of the next potato crop usually determines which crop will follow potatoes. Cabbage is planted whenever land resources are not utilised for the other crops.

The importance of citrus decreases as you move to the Patensie area while that of annual cash crops increase. Potatoes are still the most important annual cash crop and are followed by either maize or wheat in the rotation.

The occurrence of high velocity cold winds in the Loerie/Mondplaas area prohibits the production of citrus. Farmers concentrate on the production of vegetables in the Loerie area whereas dairy is dominant in the Mondplaas area, which stretches from the Loerie to the coast. The most important vegetables produced in the Loerie area are cabbage, carrots, lettuce and beans followed in a rotation. However, one should not assume consistency in the cropping system since the market fluctuations play an important role in cropping decisions. Furthermore it is easy to change from one crop to another due to the short growing season and the fact that the crops can be produced year-round.

3.5 IRRIGATION SYSTEMS AND MANAGEMENT

The most dominant irrigation systems in the Gamtoos Valley are centre pivot and drip irrigation. Centre pivot irrigation is mainly used to irrigate annual cash crops while draglines and quick couples are used to irrigate the corner areas associated with centre pivot irrigation systems. Permanent crops are irrigated with drip or micro-irrigation systems. However, a shift towards drip irrigation is evident due to less weed problems associated with drip irrigation. A small number of the farmers are also experimenting with fertigation of citrus.

Most of the farmers base their irrigation scheduling practices on experience of irrigation water demand of the crops. Only three per cent of the farmers in the Patensie area use a scheduling service, while five per cent of the farmers use such a service in the Hankey area. No farmers in the Loerie area use a scheduling service to schedule their irrigation water. Although very few farmers adopted the use of an irrigation scheduling service several farmers use tensiometers to determine the soil water content which is used to plan their irrigation. More specifically 20% of the farmers in the Patensie area and 40% of the farmers in the Hankey area use tensiometers whereas only one per cent of the farmers uses tensiometers to determine soil water content in the Loerie area.

3.6 WATER SUPPLY MANAGEMENT BY THE GAMTOOS WATER USER ASSOCIATION

3.6.1 WATER USERS AND THE WATER DISTRIBUTION SYSTEM

The Gamtoos water user association (WUA) manages the supply of water to various users of which irrigation is the largest user. The quotas for each of the different users are as follows:

- Irrigation – 59.3 million m^3 per year
- Port Elizabeth Municipality – 23 million m^3 per year
- Hankey Municipality – 450 000 m^3 per year
- Patensie Municipality – 428 000 million m^3 per year

Water from the Kouga Dam is conveyed to the Loerie Dam through the use of a 67 km long canal which includes 8 km of tunnels and 17 km of siphons. Carrying capacities decrease as one nears Loerie Dam and vary between 5.6 m^3/s to 2.3 m^3/s. Three balancing dams are built on the canal to ensure the smooth operation of the conveyance system by keeping the flow rate from Kouga Dam fairly constant. Loerie Dam acts as a balancing dam for the supply of water to the Port Elizabeth Municipality. To ensure good quality water in Loerie Dam, the Chief Water Control Officer has to keep the dam at 80% of its capacity.

Irrigation water is distributed to 242 irrigators with an allocation of 800 m^3 per listed hectare through the use of the main canal, five branch canals (30 km) and pipelines (91 km) that branch off these canals. The system is designed so that water is available on a continuous basis at the 950 irrigation off-takes. Farmers are entitled to an off-take for each 20 ha block of scheduled irrigation land. Each off-take is equipped with a mechanical water meter with a design irrigation stream of 150 m^3/hour. The basic tariff for irrigation water is R718.20 per ha for the first 80% of the allocated quota per annum or R1.12 per m^3, while the remainder is charged at a rate of R82.08 per ha or R0.51 per m^3. Farmers are allowed to transfer water from one farmer to another at the beginning of the water year for use during that year. To administrate these changes in the allocation system an administrative fee of R104 is charged. Transfers are only allowed if the capacity of the distribution system allows such transfers.

3.6.2 WATER SHORTAGES

On March 1 and September1 of every year the water status at the Dam is evaluated. Restrictions are applied if the level of the Kouga Dam is lower than 60% on March 1 or lower than 49% on September 1. The DWAF decides on how severe the restrictions should be, based on the levels of the Kouga and Loerie Dams that are submitted every week by the WUA. The

DWAF in collaboration with the WUA works out monthly water demand, which farmers are not allowed to surpass. The curtailment is therefore enforced monthly.

Gamtoos WUA Water Control Officers enforce the restriction by daily inspection of water meters, which allows for the early identification of violators. During severe restrictions farmers receive monthly allocations. Meters are continuously monitored and if the monthly allocation is consumed before the month-end, sluice valves are closed and locked.

3.7 WATER QUALITY

Before the Kouga Dam was built, irrigation water quality was low due to salt loads from the Beervlei Dam in the Groot River. After the construction of the Kouga Dam these problems were largely overcome and total dissolved solids in irrigation water are now about 140 ppm, which means the water is of a good quality. The concentration of total dissolved solids does, however, vary with the dam level. However, one has to keep in mind that due to an intensive network of canals and pipelines the Gamtoos River is no longer used to convey water to the various users and no commitment exists to release water into the Gamtoos River from the Kouga Dam. Today the only river that constantly feeds the Gamtoos River is water that is released from the Beervlei Dam, drainage from the surrounding Gamtoos River catchment, and irrigation return flows.

Previously the Department of Water Affairs and Forestry measured water inflow and water quality at the inlet of the Gamtoos estuary at Boschoek, but it does not deem it necessary to measure these inputs any longer, since the environment does not constitute a water user. The Water Act (Act 36 of 1998) does, however, recognise the environment as a lawful water user. Pearce and Schumann (1997) found alleviated nitrate levels above EPA's drinking water standard of 10 mg/l in the upper estuary. Furthermore nitrate levels of groundwater were found to range from 0.1 mg/l to 27.1 mg/l, which was attributed to agricultural inputs.

PROCEDURES: QUANTIFYING NON-POINT SOURCE POLLUTION CONTROL ABATEMENT COST

CHAPTER 4

The contents of this chapter are divided into two sections. Section one discusses the data and procedures used to configure SWAT and how the model is used to simulate the necessary data for the mathematical programming models that are used to quantify economic environmental trade-offs of alternative NPS pollution abatement policies. Section two of this chapter is devoted to the mathematical programming model. More specifically the procedures used to integrate SWAT with the programming models, data manipulation and the calculation of the necessary input parameters, specification of the optimisation models and the generation of the economic environmental trade-offs of alternative policy instruments to abate pollution are discussed.

4.1 SIMULATING NON-POINT SOURCE POLLUTION FROM AGRICULTURAL ACTIVITIES USING SWAT

4.1.1 CATCHMENT DELINEATION AND STREAM NETWORK

The first step in any hydrological simulation application is to determine the catchment that feeds the streams as well as the stream network that links individual sub-catchments together. AVSWAT2000 is fully integrated with ArcView GIS (Environmental Systems Research Institute, 1996) and Spatial Analyst (Environmental Systems Research Institute, 1996) extension functions that are used to automatically delineate the catchment and stream network based on a Digital Elevation Model (DEM) in ArcInfo grid format and some other user specified input parameters.

The DEM (20 m resolution) of the larger Port Elizabeth area is obtained from GIMS Pty (Ltd) as two separate grid data files. The data are projected using Transverse Mercator with Clarke 1880 as the spheroid and a central meridian of 25. GIS processing using ArcView extensions is used to combine the two files into one data source, which was then used in the automatic delineation process. The calculations done are complex and due to the resolution of the DEM the calculations are slow. Some pre-processing was done to remove and fill sinks holes in the DEM to allow proper delineation of the stream network. Once all the pre-processing was done a threshold of 3 800ha was used to define the minimum drainage area required to form the origin of a stream and therefore the size of the sub-catchments and the detail of the stream network.

Several smaller thresholds were tested to increase the detail of the simulation. However, when smaller thresholds were used to determine the stream network, problems were encountered due to the very flat topography at the coast. Once the stream network was determined, the sub-catchments were delineated from user-specified outlets for the main catchment and inlets. An inlet was used to determine the upper boundary of the main catchment. The confluence of the Gamtoos and the Groot rivers and the Kouga Dam outlet were specified as inlets and therefore everything downstream of these points to the coast were considered in the delineation of the Gamtoos catchment.

Based on these inputs, 22 sub-catchments were delineated for the Gamtoos catchment. A comparison between the quaternary catchments delineated by the Department of Water Affairs and Forestry and AVSWAT delineated catchments revealed that AVSWAT did a good job in delineating the catchment boundary based on the DEM.

4.1.2 SOILS

Defining the soil information consists of two steps. First one needs to provide the model with a GIS coverage showing the spatial extent of the different soils in the Gamtoos valley. Thereafter the attributes of the soils used in the simulation must be specified and correctly linked to the Soils coverage. Typical soils information needed by AVSWAT is hydrological grouping, maximum rooting depth, depth of each layer, each layer's bulk density, available water capacity, hydraulic conductivity, organic carbon, clay, silt, sand and rock contents, albedo and USLE (Universal Soil Loss Equation) erodibility factors.

The most comprehensive set of mapped soils information available to hydrologists on a near countrywide basis in South Africa is the Land type database of the Institute for Soil, Climate and Water (ISCW). The GIS format of this database for the larger Port Elizabeth area was used as the basis for constructing appropriate soils parameters for the simulations and for specifying the spatial extent of the soils. Using ArcView extensions the larger spatial database was reduced to that of the Gamtoos catchment.

Unfortunately the attribute tables describing the land types were insufficient and could not be used directly in AVSWAT. The Land type database only contains information regarding the aggregate percentages of different soil families in a specific Land type, the overall depth and some information on texture. Furthermore it is also highly aggregated spatially. Each Land type is broken down into different land classes or soil forms, which may consist of many different soil families. These soil families are only named, and only total hectares of all the soil families in a specific soil form are known. An estimate of the total area of the Land type that falls within a specific terrain unit is also given and can be used to obtain better spatial distribution. However, the ISCW was unable to supply GIS coverage of terrain units. Deriving specialised databases of terrain units from DEMs were beyond the scope of this research and was therefore not undertaken due to the time-consuming nature of the process. A short description of the geology of the land type is also given. Hydrological interpretation of soils information requires quantitative magnitudes and rates to be assigned to those properties controlling hydrological processes into, out of and within the soil profile (Schulze, Angus and Guy, 1995). The information contained in the modal profile database is much more detailed and useful, with relevant data for each soil layer. However, the modal profile database is incomplete, since information on only 6 modal profiles is available to describe the 29 Land types of the Gamtoos catchment.

Based on the individual soil series of each Land type, weighted average parameters were derived for the necessary soil parameters used in AVSWAT to simulate NPS pollution as described below. The soil horizon is subdivided into two layers based on the working rules developed by Schulze *et*. *al*. (1995). To establish the soil particle size distribution of the two soil layers, different clay distribution models (Schulze, Hutson and Cass, 1985) were used to assign clay percentages to the different soil layers. The percentage silt and sand was then determined, based on the assigned clay percentage and the typical proportion of clay, silt and sand of the typical soil texture class of the soil series. Bennie (2001) suggested that the typical soil particle distribution should be calculated using soils information from the Gamtoos area only, since these distributions may differ from the distributions determined by Smithers and Schulze (1995) using data for South Africa as a whole.

Other parameters calculated based on the assigned textural particle distributions include the available water content and the erodibility factors. Available water content for each layer was calculated using equations developed by Bennie, Strydom and Vrey (1998):

$$AW = 0.0037(S+C) - 0.139 - 0.00385(S+C) - 0.013$$

where:

AW	available water (mm water per mm soil depth)
S	percentage silt particles
C	percentage clay particles

The calculated particle distribution of each layer was also used to calculate the erodibility factors (K_{USLE}) using equations proposed by Williams (1995):

$$K_{USLE} = f_{csand} * f_{cl\text{-}si} * f_{orgc} * f_{hisand}$$

Where:

f_{csand}	low erodibility factor for soils with a high coarse sand content and high values for soils with little sand

f_{cl-si}	low soil erodibility for soils with high clay to silt ratios
f_{orgc}	low soil erodibility for soils with high organic carbon content
f_{hisand}	low soil erodibility for soils with extremely high sand contents

Calculation procedures for each of these factors are given in Neitsch, Arnold, Kinery and Williams (2000).

The remainder of the soil inputs is taken from data compiled by Schulze *et. al*. (1995) for each of the typical textural classes. Appendix A contains the relevant soils information used in this research.

4.1.3 LANDUSE

Landuse determines the purpose for which the soil is used. At first the landuse was divided into two broad categories, irrigated and non-irrigated. The irrigation areas in the Gamtoos irrigation valley was digitised from 1:50 000 digital orthophoto images obtained from the Department of Land Affairs, Chief Directorate, Surveys and Mapping. Once the irrigation theme was established it was combined with the catchment theme to determine the non-irrigated areas using GIS processing.

4.1.4 HYDROLOGICAL RESPONSE UNITS

Once the land use and soil data layers have been imported, the distribution of hydrologic response units (HRUs) within the watershed must be determined. HRUs allows for a better physical representation of the catchment, since each HRU is simulated separately and then aggregated to determine the resulting pollution loading for the sub-catchment as a whole.

An HRU consists of a specific landuse soil combination. AVSWAT allows for the creation of only one HRU for each sub-catchment based on the dominant landuse and soil or multiple HRUs. Multiple HRUs were used in this research to distinguish between irrigation and non-irrigation landuses. However, not all the landuse soil combinations were specified as separate HRUs. A threshold of 5% was used on soils to create the HRUs. Only soils consisting of more than 5% of the total area of the sub-catchment were therefore taken into consideration when creating the HRUs. The total area of the created HRUs was adjusted upwards to the area of the sub-catchments if soils with an area smaller than 5% of the total area of the sub-catchment were present. In total 129 HRUs were created, of which 53 were used for irrigation purposes.

4.1.5 WEATHER DATA

AVSWAT uses daily rainfall, minimum and maximum temperatures, solar radiation, wind speed and relative humidity to simulate the water balance of the catchment. The model allows the user to use historical data or generated values from the WXGEN weather generator model (Sharpley and Williams, 1990), using monthly average data summarised over a number of years. Specifying the inputs for the weather generator is compulsory, since it is also used to fill the gaps in historical data.

Daily weather data on rainfall, minimum and maximum temperatures and wind speed were available from the South African Weather Bureau for the Patensie weather station. However, only limited data on wind speed were available. No data were available on solar radiation and relative humidity and these inputs together with wind speed were generated. The South African Weather Bureau suggested using data from Port Elizabeth as a proxy for solar radiation and relative humidity.

All the weather data were obtained from the South African Weather Bureau in a text file format. Unfortunately the data were grouped in table format, and some data processing using Microsoft Excel was necessary to get the data in the correct format. For this purpose Visual Basic macros were written to format the data and to calculate relevant parameters for the weather generator. The relevant data were then exported to Microsoft Access and saved in the correct file structure to enable AVSWAT to read the data.

Appendix B contains the necessary data to run WXGEN.

4.1.6 AVSWAT DERIVED AND MISCELLANEOUS OTHER PARAMETERS

Since AVSWAT is integrated with GIS, it has the capability of deriving some geographically and topographically linked parameters such as the length, depth and width of the tributary channels and the slope of the HRUs and sub-catchments using the DEM as inputs.

Default values were used to specify all the remaining parameters needed to run AVSWAT.

4.1.7 SPECIFYING ALTERNATIVE MANAGEMENT SCENARIOS

AVSWAT allows the user to quantify the impact of various management practices on pollution loads using a crop management file. These management options include application of inputs such as inorganic and/or organic fertilisers, irrigation water and different pesticides during different periods of the growing season, tillage operations and planting dates. Specification of the management file is important since it is used to link the management options with spatially distributed characteristics of the catchment such as soils with different slopes. To limit the amount of data generated by AVSWAT that must be transferred to the optimisation model only

a few of all the possible alternatives were considered and the rest of this section is devoted to the procedures used to specify this limited number of management options.
Plant growth is controlled in AVSWAT through the use of the crop database and the amount of heat units necessary to reach maturity using a single crop growth model for all the crops. No adjustments were made to the crop database to reflect cultivar specific parameters for the Gamtoos valley. Heat units control the length of the growing season, which was adjusted to ensure proper growth lengths for each of the planting dates of the different crops. An iterative procedure using daily simulations with different heat units for each of the crops and planting dates was used to determine appropriate number of heat units. Problems were encountered when simulating crops that grow during the summer months, since AVSWAT reduces the leaf area index from mid-November to mid-February due to dormancy. To overcome the problem, the seasons in the weather database were switched so that winter became summer. However, problems were encountered when running the model for cabbage planted in January and July as well as potatoes planted in January.

Once appropriate growth lengths were established for each of the crops and associated planting dates, the model was used to develop alternative fertiliser and water application rates which were identified as key control variables that a farmer may alter to reduce NPS pollution. AVSWAT has a built-in option that allows the modeller to specify the amount of stress the crop must sustain before applying fertiliser or irrigation water. Simulations indicated that the model is not very sensitive to these stress factors, especially when small deviations from optimal growth occurred. Instead of using the auto-fertilisation and irrigation options in AVSWAT, physical amounts of fertiliser and irrigation water were applied. However, the auto-fertilisation and irrigation options were used to determine the amount of fertiliser and irrigation water needed to sustain optimal growth. Two alternative application rates below the optimal rates were chosen to represent variable fertiliser and water application alternatives. However, fertilisers are applied with a single application of inorganic fertiliser currently used by the farmers and irrigation water is applied within a fixed cycle fixed amount. AVSWAT link the user specified management file with each of the HRUs that were utilised for irrigation purpose to simulate the spatial extent of these management options on NPS pollution loadings within the catchment.

Table 4.1 shows the variation in net irrigation requirements, nitrogen applied, uptake and losses as well potential crop yields in the Gamtoos valley for potatoes and cabbages simulated for all the HRUs with AVSWAT.

From Table 4.1 it is clear that the simulated results indicated that more nitrates are lost when producing potatoes in comparison with cabbages. One explanation might be the longer growing season of potatoes and the fact that split application of nitrogen fertiliser is not considered. Potential crop yields based on nutrient uptake are reported, because the simulated SWAT crop yields are not very sensitive to different management practices. However, potential crop yields determined from nutrient uptake are within the ranges established by the Gamtoos pilot project on Water Conservation and Demand Management in the Agricultural Sector (MBB, 2001) which are between 50 − 90 t/ha for cabbage and 25 − 35 t/ha for potatoes.

Table 4.1: Net irrigation requirements, nitrogen applied, uptake and losses and crop yield potential for potatoes and cabbages in the Gamtoos valley.

		Net irrigation requirement (mm.ha)	**Nitrogen**			**Crop yield potential[2] (tons/ha)**
			Applied (kg/ha)	**Uptake (kg/ha)**	**Loss[1] (kg/ha)**	
Potatoes	**Average**	307	160	134	22	27
	Minimum	204	85	84	7	17
	Maximum	385	238	212	57	42
	Standard deviation	52.91	41.90	34.45	10.10	6.89
	Coefficient of variation	0.17	0.26	0.26	0.46	0.26
Cabbages	**Average**	171	179	176	3	52
	Minimum	87	84	88	0	26
	Maximum	236	245	247	24	73
	Standard deviation	37.32	39.28	35.82	3.81	10.53
	Coefficient of variation	0.22	0.22	0.20	1.12	0.20

1 Includes inorganic nitrogen losses
2 Expected yield is a function of nitrogen uptake

4.1.8 OUTPUT GENERATION

Before running SWAT several additional input parameters need to be specified. These include the length of simulation, runoff routing method, rainfall distribution type used to generate missing rainfall, method used to calculate potential evapotranspiration, whether crack flow needs to be modelled, channel routing method and whether in-stream water quality must be simulated. After specifying appropriate inputs one may proceed to run the model.

The water quality impacts of the alternative management scenarios were simulated over a period of 15 years using a skewed normal distribution to generate missing rainfall data and the curve number method of quantifying runoff. Simulated runoff was routed through the stream channels using the variable storage method while no degradation of pollutants was assumed.

The same management alternative was applied to all the different HRUs that are used for crop production while keeping the impact of the others constant when simulating the water quality impacts of a specific management alternative. Thus, a separate simulation was needed for each of the management scenarios, which amounted to 228 SWAT runs. Monthly results for each of the HRUs were saved in the basins.sbs file that was created during each SWAT run.

The basins.sbs files contain all the necessary information needed to quantify the pollution impact of the alternative management practices, which are needed by the optimisation model.

4.2 GAMS PROGRAMMING MODEL

The General Algebraic Modelling System (GAMS) (Brooke, Kendrick, Meeraus and Raman, 1998) was used to evaluate the impact of alternative policies to reduce nitrate pollution in the Gamtoos valley on irrigation farming profitability. The GAMS code allowing these evaluations consists of four distinctive modules. The first module imports all the necessary SWAT simulation data on the pollution impacts of alternative management actions into GAMS. Economic parameters are combined with the imported pollution data from SWAT to yield the gross margins for each management alternative. The optimisation model is specified in Module 3 while the most important output parameters from the optimisation model are summarised using report-writing facilities in Module 4.

4.2.1 SECTION 1: IMPORT SWAT DATA

A major challenge existed in transferring the vast amount of output from SWAT to GAMS. GAMS is only able to read input files in a certain format and is therefore unable to extract the necessary pollution data for each of the management alternatives from the different basin.sbs files created during each SWAT simulation. To facilitate data transfer, the monthly data over a period of 15 years for each management scenarios were saved to a separate Excel file. Visual Basic macros were then used to filter the data to contain only data specific to the crop growing season and to save the extracted data to different files. Two separate macros were used for data extraction. The first macro extracted data on crops type, planting date, fertiliser application rates, irrigation quantities, water yield and pollution loads from each HRU in each sub-catchment, while a second extracted the simulated crop yields of the specific management scenario. Once all the necessary data were extracted and saved, another macro was used to format and create GAMS readable input files.

The following GAMS code was used to import the data generated with SWAT for cabbage planted in April:

```
*=== initialise the sets ==========================================
SET g  global set
          /area, nir, perc, surq, tloss, latq, gwq, wyld, napp,
          papp, nup, pup, nsurq, nlatq, nlch, gwn/
    a  other global set
          /area, swat_y/
    y  years in simulation
```

```
          /y1*y15/
      t   months of the year
          /m1*m12/

      j   crops
          /cabg,pota/
      p   plant month
          /Jan, Feb, Mrt, Apr, May, Jun, Jul, Aug, Sep, Oct, Nov,
          Dec /
      n   fertiliser application levels
          /N120, N170, N180, N190, N200, N210, N220, N230, N240,
          N250, N260, N270, N280, N290, N300, N310, N320, N350/
      ir  irrigation levels
          /Ir10, Ir15, Ir20/
      l   land types
          /Ae200, Ia91, Ib63, Fc379, Fc377, Ae199, Fc378, Fa260,
          Db160, Ah60/
      h   hydrological response units
          /HRU1, HRU2, HRU6, HRU7, HRU11 * HRU13, HRU18 * HRU20,
          HRU26, HRU27, HRU32 * HRU34, HRU39, HRU40, HRU45 * HRU47,
          HRU50 * HRU52, HRU55, HRU56, HRU61, HRU62, HRU66 * HRU68,
          HRU72 * HRU74, HRU78 * HRU80, HRU86, HRU87, HRU90, HRU91,
          HRU94, HRU95, HRU101, HRU102, HRU106, HRU107, HRU112 *
          HRU114, HRU118, HRU119, HRU125, HRU126 /
      s   subcatchments
          /Sub1*Sub22/
  ;
      alias(s,ss);

*=== import the data files ==========================================
*--- import swat pollution parameters: cabbage april -----------------
  TABLE CabAprN190Ir10(s,h,l,j,p,n,ir,y,t,G)  SWAT pollution data
  $INCLUDE "D:\..\Cab_Apr\CabAprN190Ir10.prn"
  TABLE CabAprN190Ir15(s,h,l,j,p,n,ir,y,t,G)  SWAT pollution data
  $INCLUDE "D:\..\Cab_Apr\CabAprN190Ir15.prn"
  TABLE CabAprN190Ir20(s,h,l,j,p,n,ir,y,t,G)  SWAT pollution data
  $INCLUDE "D:\..\Cab_Apr\CabAprN190Ir20.prn"
  TABLE CabAprN240Ir10(s,h,l,j,p,n,ir,y,t,G)  SWAT pollution data
  $INCLUDE "D:\..\Cab_Apr\CabAprN240Ir10.prn"
  TABLE CabAprN240Ir15(s,h,l,j,p,n,ir,y,t,G)  SWAT pollution data
  $INCLUDE "D:\..\Cab_Apr\CabAprN240Ir15.prn"
  TABLE CabAprN240Ir20(s,h,l,j,p,n,ir,y,t,G)  SWAT pollution data
```

```
$INCLUDE "D:\..\Cab_Apr\CabAprN240Ir20.prn"
TABLE CabAprN290Ir10(s,h,l,j,p,n,ir,y,t,G)  SWAT pollution data
$INCLUDE "D:\..\Cab_Apr\CabAprN290Ir10.prn"
TABLE CabAprN290Ir15(s,h,l,j,p,n,ir,y,t,G) SWAT pollution data
$INCLUDE "D:\..\Cab_Apr\CabAprN290Ir15.prn"
TABLE CabAprN290Ir20(s,h,l,j,p,n,ir,y,t,G) SWAT pollution data
$INCLUDE "D:\..\Cab_Apr\CabAprN290Ir20.prn"

*--- add imported pollution data to swat table------------------------
parameter swat(s,h,l,j,p,n,ir,y,t,g) all SWAT pollution data;
swat(s,h,l,j,p,n,ir,y,t,g) = CabAprN190Ir10(s,h,l,j,p,n,ir,y,t,g)
                           + CabAprN190Ir15(s,h,l,j,p,n,ir,y,t,g)
                           + CabAprN190Ir20(s,h,l,j,p,n,ir,y,t,g)
                           + CabAprN240Ir10(s,h,l,j,p,n,ir,y,t,g)
                           + CabAprN240Ir15(s,h,l,j,p,n,ir,y,t,g)
                           + CabAprN240Ir20(s,h,l,j,p,n,ir,y,t,g)
                           + CabAprN290Ir10(s,h,l,j,p,n,ir,y,t,g)
                           + CabAprN290Ir15(s,h,l,j,p,n,ir,y,t,g)
                           + CabAprN290Ir20(s,h,l,j,p,n,ir,y,t,g);

*--- import swat crop yields: cabbage april --------------------------
TABLE CabAprN190Ir10Yield(s,h,l,j,p,n,ir,y,a) SWAT crop yield data
$INCLUDE "D:\..\Cab_Apr\CabAprN190Ir10Yield.prn"
TABLE CabAprN190Ir15Yield(s,h,l,j,p,n,ir,y,a) SWAT crop yield data
$INCLUDE "D:\..\Cab_Apr\CabAprN190Ir15Yield.prn"
TABLE CabAprN190Ir20Yield(s,h,l,j,p,n,ir,y,a) SWAT crop yield data
$INCLUDE "D:\..\Cab_Apr\CabAprN190Ir20Yield.prn"
TABLE CabAprN240Ir10Yield(s,h,l,j,p,n,ir,y,a) SWAT crop yield data
$INCLUDE "D:\..\txtinout\Cab_Apr\CabAprN240Ir10Yield.prn"
TABLE CabAprN240Ir15Yield(s,h,l,j,p,n,ir,y,a) SWAT crop yield data
$INCLUDE "D:\..\Cab_Apr\CabAprN240Ir15Yield.prn"
TABLE CabAprN240Ir20Yield(s,h,l,j,p,n,ir,y,a) SWAT crop yield data
$INCLUDE "D:\..\Cab_Apr\CabAprN240Ir20Yield.prn"
TABLE CabAprN290Ir10Yield(s,h,l,j,p,n,ir,y,a) SWAT crop yield data
$INCLUDE "D:\..\Cab_Apr\CabAprN290Ir10Yield.prn"
TABLE CabAprN290Ir15Yield(s,h,l,j,p,n,ir,y,a) SWAT crop yield data
$INCLUDE "D:\..\Cab_Apr\CabAprN290Ir15Yield.prn"
TABLE CabAprN290Ir20Yield(s,h,l,j,p,n,ir,y,a) SWAT crop yield data
$INCLDE "D:\..\Cab_Apr\CabAprN290Ir20Yield.prn"

*--- add imported crop yield data to swat_yield table-----------------
parameter swat_yield(s,h,l,j,p,n,ir,y,a) SWAT yields;
```

```
72   swat_yield(s,h,l,j,p,n,ir,y,”swat_y”) =
73                      + CabAprN190Ir10Yield(s,h,l,j,p,n,ir,y,"swat_y")
74                      + CabAprN190Ir15Yield(s,h,l,j,p,n,ir,y,"swat_y")
75                      + CabAprN190Ir20Yield(s,h,l,j,p,n,ir,y,"swat_y")
76                      + CabAprN240Ir10Yield(s,h,l,j,p,n,ir,y,"swat_y")
77                      + CabAprN240Ir15Yield(s,h,l,j,p,n,ir,y,"swat_y")
78                      + CabAprN240Ir20Yield(s,h,l,j,p,n,ir,y,"swat_y")
79                      + CabAprN290Ir10Yield(s,h,l,j,p,n,ir,y,"swat_y")
80                      + CabAprN290Ir15Yield(s,h,l,j,p,n,ir,y,"swat_y")
81                      + CabAprN290Ir20Yield(s,h,l,j,p,n,ir,y,"swat_y");
```

Sets (1-24) specify the indices over which the data were defined and were the basic building blocks of a GAMS model. Furthermore sets correspond exactly to the indices used to represent algebraic models. Set g contains all the names of the pollution related parameters simulated with SWAT and are defined to facilitate the use of data table swat(s,h,l,j,p,n,ir,y,t,g) which contains all the pollution related data from the different SWAT simulations. A separate data table, swat(s,h,l,j,p,n,ir,y,t,g), is defined for the crop yields. A sequential procedure is used to create the two data tables. First separate tables were created for each management scenario's pollution parameters (25-42) and associated yields (53-70) by importing the prn files created with the macros. Once these parameters were imported and in GAMS format, all the information in the separate data tables was combined (43-52 and 71-81) into one data table called swat.

Both data tables were indexed over the sub-catchments (s), HRUs (h), Land types (l), crops (j), plant month (p), fertiliser application rate (n), irrigation level (ir), months (t), and the years (y) to keep track of the specific management scenario and to what resource base it was applied, with the exception that the yields were not defined for each month. Since each index added to the dimension of each table creating the two data tables, swat used a lot of computer resources and it was impossible to import all the data all at once. To overcome the problem, the save and restart GAMS programming features were used to facilitate the creation of the data tables. With the save option the modeller was able to compile the GAMS code up to any specific point and to save the information to scratch files. The restart option was then used to compile the rest of the code taking the compiled code in the scratch files into account without needing to compile all the code from the start.

The save and restart option were used 21 times, once for each of the different crops to create the data tables using the above coding structure. The final swat(s,h,l,j,p,n,ir,y,t,g) and swat_yield(s,h,l,j,p,n,ir,y,a) data tables consist of 5 871 151 and 155 290 data values greater than zero respectively. The magnitudes of these two tables are large because they contain monthly and annual data respectively.

4.2.2 SECTION 2: DATA MANIPULATION AND INPUT PARAMETER CALCULATION

The main aim of Module 2 of the programming model is to specify or calculate all the necessary input parameters used by the optimisation models. A major portion of the Gams code contained in this section concerns the calculation of parameters that is used to calculate the gross margins of each management alternative.

Module 2 of the programming model consists of the following GAMS code:

```
*=== initialise the sets ==============================================
SET f  fertilisers
          /234, LAN, 321, KNO3/
    fg fertiliser global set
          /price, nitrogen/
    eg economic global set
          /income, area, harvest, irrigation/
    cy(s,h,l,j,p,n,ir,y)  set  mapping  obsevations  with  positive
          value for swatyields;
    cy(s,h,l,j,p,n,ir,y)
          $(swat_yield(s,h,l,j,p,n,ir,y,"swat_y")gt 0 )=yes;

*=== initialise the parameters ========================================
Parameters
area(s,h,l,a)     area of each land type in sub-catchment - ha
water_alloc(s)    water allocated to each sub-catchment –m3
crop_perc(j,p,a)  maximum percentage of a specific crop in crop mix
time_use(j,p,t)   time used for cultivation
convert_y(j)      nutrient to yield conversion factors - ton per kg
                  nitrogen uptake
convert_f(j,f)    applied   nitrogen   to   fertiliser   application
                  conversion factors
fert(f,fg)        price and percentage nutrients per kg fertiliser
econ(j,eg)        economic parameters
y_pot(j,p,n)      yield  potential  for  each  crop  based  on  nutrient
                  uptake
yp_temp(j,p,n)    temporary yield potential
sy_temp(j,p,n)    temporary simulated swat yield
sy_max(j,p,n)     maximum swat yield
sy_index(s,h,l,j,p,n,ir,y) yield potential adjustment factor
yield(s,h,l,j,p,n,ir,y) final adjusted crop yield – tons per ha
```

```
agmargin(s,h,l,j,p,n,ir)  average  annual  income  above  specified
                 costs - per ha
air_cost(s,h,l,j,p,n,ir) average annual irrigation cost - R
afert_cost(s,h,l,j,p,n,ir,f) fertiliser application rates - R
anloss(s,h,l,j,p,n,ir) average annual nitrate loss - kg per ha
;
*=== import data files created in excel ==============================
TABLE area(s,h,l,a)
$INCLUDE "D:\..\gams\soils&area.prn"
Table crop_perc(j,p,a)
$INCLUDE "D:\..\GAMS\crop_perc.prn"
TABLE time_use(j,p,t)
$INCLUDE "D:\..\GAMS\time_use.prn"

*=== specify the data ================================================
scalar  eff   irrigation application efficiency   /0.9/;
scalar util land utilisation factor               /1.341/;
scalar alloc water allocation per listed ha       /6400/;
scalar tariff weighted average water tariff       /0.998/;
parameter convert_y(j)
        /cabg      3.4
        pota       5.0
        /;
Table fert (f,fg)
        Price      Nitrogen
234     2763.20    0.067
LAN     2089.60    0.280
321     2377.20    0.125
KNO3    2622.00    0.130
;
Table econ(j,eg)
        Income     Area       Harvest    Irrigate
Cabg    1028.40    4862.33    174.08     0.65
Pota    1469.63    5226.73     97.77     0.65
;
Table convert_f(j,f)
        234        LAN        321        KNO3
Cabg    3.6145     2.7108
Pota               1.8665     2.7998     0.9799
;

*=== calculate parameters ============================================
```

```
*--- calculate: yield potential of each N application rate based on
     maximum N uptake as well as the maximum simulated crop yield----

*~~~ set parameters equal to zero ~~~~~~~~~~~~~~~~~~~~~
yp_temp(j,p,n)=0;
y_pot(j,p,n)=0;
sy_temp(j,p,n)=0;
sy_max(j,p,n)=0;

*~~~ loop to determine yield potential and maximum simulated yield
Loop((j,p,n),
 Loop((s,h,l,ir,y),

   yp_temp(j,p,n)
   = sum(t,swat(s,h,l,j,p,n,ir,y,t,"nup"))/convert_y(j);

   y_pot(j,p,n)
   $(yp_temp(j,p,n)>y_pot(j,p,n))
   = yp_temp(j,p,n);

   sy_temp(j,p,n)
   =swat_yield(s,h,l,j,p,n,ir,y,"swat_y");

   sy_max(j,p,n)
   $(sy_temp(j,p,n)> sy_max(j,p,n))
   = sy_temp(j,p,n);

   )
);

*--- calculate crop yield index -------------------------------------
sy_index(s,h,l,j,p,n,ir,y)
 $cy(s,h,l,j,p,n,ir,y)
 = swat_yield(s,h,l,j,p,n,ir,y,"swat_y") / sy_max(j,p,n);

*--- calculate crop yields ------------------------------------------
yield(s,h,l,j,p,n,ir,y)
 $cy(s,h,l,j,p,n,ir,y)
 =sy_index(s,h,l,j,p,n,ir,y)*y_pot(j,p,n);

*--- calculate average irrigation cost--------------------------------
air_cost(s,h,l,j,p,n,ir)
 $(sum(y,cy(s,h,l,j,p,n,ir,y)))
```

```
  =sum(t,
       swat(s,h,l,j,p,n,ir,y,t,"nir")/eff
       )*(econ(j,"irrigate")+tariff)/card(y) ;

*--- calculate average fertiliser cost -------------------------------
afert_cost(s,h,l,j,p,n,ir,)
  $(sum(y,cy(s,h,l,j,p,n,ir,y)))
  = sum(t,
        swat(s,h,l,j,p,n,ir,y,t,"napp")*convert_f(j,f))
      * fert(f,"price")/1000
        )/card(y) ;
```

```
*--- calculate average gross margin per hectare-----------------------
176 agmargin(s,h,l,j,p,n,ir)
177   $(sum(y,cy(s,h,l,j,p,n,ir,y)))
178   = sum(y,
179         econ(j,"income")*yield(s,h,l,j,p,n,ir,y)
180       - econ(j,"area")
181       - econ(j,"harvest")*yield(s,h,l,j,p,n,ir,y)
182         )/card(y);

*--- calculate average nitrate emissions per hectare------------------
183 anloss(s,h,l,j,p,n,ir)
184   $(sum(y,cy(s,h,l,j,p,n,ir,y)))
185   = sum((y,t),
186         swat(s,h,l,j,p,n,ir,y,t,"nsurq")
187       + swat(s,h,l,j,p,n,ir,y,t,"nlatq")
188       + swat(s,h,l,j,p,n,ir,y,t,"nlch" )
189       + swat(s,h,l,j,p,n,ir,y,t,"gwn"  ))
190         )/ card(y);

*--- calculate average runoff per hectare-----------------------------
191 awyld(s,h,l,j,p,n,ir)
192   $(sum(y,cy(s,h,l,j,p,n,ir,y)))
193   = sum((y,t),
194         swat(s,h,l,j,p,n,ir,t,y,"wyld")
195         )/card(y);

*--- calculate water allocation---------------------------------------
196 water_alloc(s)
197   = sum((h,l),
198         area(s,h,l,"area")*alloc
199         );
```

Lines 82-89 contain the additional sets used to define the data. Set cy(s,h,l,j,p,n,ir,y) is defined in line 89 to contain only definitions for those entities s, h, l, j, p, n, ir, and y for which a nonzero crop yield exist. Set cy is used extensively in this module to make calculations faster through the use of conditional compilations.

The areas of the different HRUs in each sub-catchment, the maximum percentages of a specific crop in the optimal solution and a table specifying the months when land was utilised by a certain crop were imported as prn files in lines 110-115. These data tables were used directly by the optimisation model. All the other data needed by the optimisation model were either specified directly in the GAMS code or calculated from the imported data. Scalars specified directly in the code (116-119) include the irrigation application efficiency, land utilisation factor and allocation per listed hectare. The parameter tables that are directly specified in the code consist mainly of economic data and conversion factors used to calculate gross margins for each of the management alternatives as described below.

Calculating the gross margin for each of the management scenarios was not straightforward. Since the single crop growth model is unable to model the responsiveness of crop yield to alternative management alternatives satisfactorily, Qiu (1996) proposed using a composite crop yield to capture the economic effects associated with alternative management scenarios. A two-step procedure was used to calculate the composite crop yields. The first step was to determine the maximum yield potential of a specific management alternative. In this research nitrogen uptake by the crop was used to determine the maximum yield potential. With the second step the crop yield potential was multiplied by a yield index based on simulated SWAT crop yields to capture the spatial variability of final crop yields due to variation in soil, and topographic and hydrologic conditions in the different subcatchment.

A double loop was used to determine the maximum crop yield potential. An outer loop (145) was used to differentiate the yield potential based on the specific crop (j) that was planted on a certain date (p) using a specific fertiliser application rate (n). No further differentiation was done and the inner loop (146) was used to determine the maximum nitrogen uptake while evaluating all the simulated values for each of the sub-catchments, HRU's, Land types and irrigation levels over a period of 15 years. Nitrogen uptake was converted to potential yield using nitrogen to yield conversion factors for each crop contained in parameter convert_y(j) from line 120-123. The calculated crop yield potential values did not vary between different resource bases in each of the catchments or due to different irrigation levels.

Spatial variations over geographical space in crop yields due to variation in soil, and topographic and hydrologic conditions that were a function of weather as well as different irrigation levels were captured using a crop yield index. Although the SWAT simulated crop yields were insensitive to changes in fertiliser application levels, they did vary spatially across the sub-catchments and it was this variation in simulated crop yields that was used to calculate the crop yield index. The same loop used to determine maximum nutrient uptake was used to determine the maximum simulated crop yield for each the crops and fertiliser application rates. The crop yield index (159) was calculated by dividing the simulated crop yields by the calculated maximum simulated crop yield, which represented the fraction of the maximum potential yield obtainable. Once the crop yield index was multiplied by the yield potential the resulting final crop yields (162) varied spatially across sub-catchments.

Gross margins were calculated in the optimisation model using three distinct categories, namely irrigation cost, fertiliser cost and gross income above specified cost. Average annual irrigation cost was calculated in line 165 as the annual net irrigation requirement (swat(s,h,l,j,p,n,ir,y,t,"nir")) divided by the irrigation application efficiency (eff) multiplied by the irrigation cost (econ(j,"irrigate")) divided by the cardinal value of y, which was 15 years. An irrigation application efficiency of 90% was assumed for the centre pivot irrigation systems in the area. Calculating fertiliser cost was a little bit more complicated, since the swat data table only gives the amount of nitrogen applied and not the amount of fertiliser used to supply the nutrients. Furthermore several fertilisers are usually used to supply the crop with nutrients. The proportion of total nitrogen supplied to the crop by the specific fertiliser in comparison to the other fertilisers and the percentage of the fertiliser that consisted of nitrogen was used to determine the amount of a specific fertiliser used. Cabbage was used as an example to demonstrate the calculation of the nitrogen to fertiliser conversion factors in table convert_f(j,f) that was used to convert nitrogen applied to fertiliser use. Both LAN and 2:3:4 were used to supply cabbage with its needed nutrients. Based on the amount of fertiliser applied, LAN supplied 76% and 2:3:4 only 24% of the nitrogen used to produce cabbage. Thus, given these proportions one needs 3.61 kg (0.76/0.28) of LAN and 2.71kg (0.24/0.067) of 2:3:4 fertiliser to supply 1 kg of nitrogen to the crop using these two fertilisers in the given proportions. Fertiliser cost was calculated by converting the nitrogen applied to fertiliser use and then multiplying it by the price of the fertilisers in lines 170-175. Gross income above specified costs was calculated in lines 176-182 and was a function of gross income minus yield dependant harvesting cost and area dependant costs.

Other parameters needed by the optimisation model that were calculated in this module included average nitrate loadings, runoff and the amount of water allocated to each sub-catchment based on the area of the sub-catchment. Nitrate loadings were calculated as the sum of all the potential losses including nitrate in surface runoff, lateral flow, leachate and groundwater contributions to stream flow. Average runoff was calculated using the water yield simulated with SWAT. Water allocated to each sub-catchment was calculated by multiplying the area of a sub-catchment by the water allocation per listed hectare. The total irrigation area of the catchment was calibrated in Excel to correspond to total area listed before importing it into GAMS.

4.2.3 SECTION 3: OPTIMISATION MODEL

Module 3 of the GAMS code consists of the specification of the optimisation models used to quantify the economic environmental trade-offs of increasing nitrate water quality at the outlet of the Gamtoos catchment. Three distinct models are specified in this section of the code. The Baseline model is used to determine baseline pollution levels at the outlets of the sub-catchments as well as the total catchment. The baseline model is also used to determine the impact of increasing water and fertiliser cost on nitrate pollution levels. The Compliance model is used to determine the spatial use of the alternative management alternatives that achieve the catchment water quality standard at least cost, assuming producers maximise profits subject to certain resource constraints. The third model determines the impact of a water market on nitrate pollution levels. The GAMS code below specifies these optimisation models.

```
*=== initialise the parameters =======================================
Parameters
BaseSubI(s)     Baseline – sub-catchment water quality indicator
BaseI           Baseline - total catchment water quality indicator
water_80        water availability reduced to 80% of baseline
inc_ir          parameter used to increase irrigation cost
inc_fert        parameter used to increase fertiliser cost
alpha           parameter  used  to  specify  level  of  pollution
                abatement
;
*=== initialise the free variables of the model =====================
Free variable
WGM             total catchment gross margin
;
*=== initialise the positive variables of the model =================
Positive variables
QCROP(s,h,l,j,p,n,ir) quantity  of  crop  that  is  produced  using  a
                specific management scenario
ABATE(s)        water quality abatement at each sub-catchment
SUBWYLD(s)      water yield from each sub-catchment
SUBEM(s)        nitrate emmisions from each sub-catchment
POLLUTION(s)    sub-catchment pollution level
CONTRIB(s)      contribution to catchment outlet water quality
TOTWATER        total runoff from all catchments

;
*=== initialise the equations of the model ==========================
Equations
MAXZ            objective function
LANDMAX(s,h,l,t) satisfy total land availability
QCROPMAX(j,p)   maximum percentage of a crop allowed in solution
WATERBAL(s)     water balance for each sub-catchment
WATERBAL2       used for water market
COMPLY_SUB(s)   comply with nitrate water quality standard at each
                sub catchment
COMPLY          comply  with  nitrate  water  quality  standard  at
                catchment outlet
```

```
C_CONTRIB(s)    calculate endogenous contribution factors
C_SUBWYLD(s)    calculate water yield from each sub-catchment
C_SUBNLOSS(s)   calculate nitrogen loss from each sub-catchment
C_POLLUTION(s)  calculate pollution at each sub-catchment
;

*=== model construction ==============================================
*--- base model ------------------------------------------------------
MAXZ..
  sum((s,h,l,j,p,n,ir)
      $(sum(y,cy(s,h,l,j,p,n,ir,y))),
      QCROP(s,h,l,j,p,n,ir)*(agmargin(s,h,l,j,p,n,ir)
                           - air_cost(s,h,l,j,p,n,ir)*inc_ir
                           - afert_cost(s,h,l,j,p,n,ir)*inc_fert
                             )
      )                                                    =E= WGM;

LANDMAX(s,h,l,t)
  $(area(s,h,l,"AREA") and sum((j,p),time_use(j,p,t)))..
  sum((j,p,n,ir)
      $(sum(y,cy(s,h,l,j,p,n,ir,y))),
      QCROP(s,h,l,j,p,n,ir)*time_use(j,p,t)
      )                                    =L= area(s,h,l,"area");

QCROPMAX(j,p)
  $(sum((s,h,l,n,ir,y),cy(s,h,l,j,p,n,ir,y)))..
  sum((s,h,l,n,ir)
      $(sum(y,cy(s,h,l,j,p,n,ir,y))),
      QCROP(s,h,l,j,p,n,ir)
      )
      /sum((s,h,l),
           area(s,h,l,"AREA")*util
           )                            =L= crop_perc(j,p,"perc");

WATERBAL(s)..
  sum((h,l,j,p,n,ir)
      $(sum(y,cy(s,h,l,j,p,n,ir,y))),
      QCROP(s,h,l,j,p,n,ir)*agir(s,h,l,j,p,n,ir)
      )*10                                     =L= water_alloc(s);

*--- compliance model: equations added to base model -----------------
COMPLY_SUB(s)..
```

```
  BaseSubI(s)-ABATE(s) - POLLUTION(s)                 =G= 0;

COMPLY..
  sum(s,
      ABATE(s) * CONTRIB(s)
      )                                      =G= BaseI*alpha;

C_SUBWYLD(s)..
  sum((h,l,j,p,n,ir)
      $(sum(y,cy(s,h,l,j,p,n,ir,y))),
      QCROP(s,h,l,j,p,n,ir)*awyld(s,h,l,j,p,n,ir)
      )                                       =E= SUBWYLD(s);

C_SUBNLOSS(s)..
  sum((h,l,j,p,n,ir)
      $(sum(y,cy(s,h,l,j,p,n,ir,y))),
      QCROP(s,h,l,j,p,n,ir)*anloss(s,h,l,j,p,n,ir)
      )                                         =E= SUBEM(s);

C_POLLUTION(S)..
  SUBWYLD(s) * POLLUTION(s)                     =E= SUBEM(s);

C_CONTRIB(s)..
  sum(ss,
      SUBWYLD(ss)
      ) * CONTRIB(s)                          =E= SUBWYLD(s);

*--- water market model: equation replacing the water balance of base model -----------------------------------------------------
WATERBAL2..
  sum((s,h,l,j,p,n,ir)
      $(sum(y,cy(s,h,l,j,p,n,ir,y))),
      QCROP(s,h,l,j,p,n,ir)*agir(s,h,l,j,p,n,ir)
      )*10                                      =L= water_80;

*=== define the models =============================================
MODEL BASELINE
  / MAXZ, LANDMAX, QCROPMAX, WATERBAL / ;
  BASELINE.workspace = 6;

MODEL COMPLIANCE
```

```
293    / MAXZ, LANDMAX, QCROPMAX, WATERBAL, COMPLY_SUB, COMPLY,
         CALC_CONTRIB, CALC_SUBWYLD, CALC_SUBNLOSS, CALC_POLLUTION /;
294    COMPLIANCE.workspace = 10;

295  MODEL MARKET
296    / MAXZ,LANDMAX,QCROPMAX,WATERBAL2 / ;
297    MARKET.workspace = 6;
```

Although all the data necessary to run the models are contained in the previous module five extra parameters are specified in this section. The values of these parameters depend on the results of the baseline model or are used to specify the magnitude of input cost increases and pollution abatement levels. Use of these parameters is discussed once the models are specified.

Baseline model

The baseline model consists of the objective function, constraints on land resource availability, equations regulating the maximum percentage of a certain crop in the crop mix, and the water balance.

The objective function (233-240), equation MAXZ, maximises total catchment gross margins (WGN). WGM is calculated as the sum of the income above specified cost minus fertiliser and irrigation cost which were calculated in the previous section. Fertiliser and irrigation cost are, however, multiplied by inc_fert and inc_ir respectively which are used to model the effect of any exogenous increase in these costs on the spatial allocation of management alternatives.

Equation LANDMAX (241-246) ensures that no greater area than that available in each time period is utilised for crop production. Land resource usage is linked to the quantity of a specific crop grown in each time period using table time_use(j,p,t).

Ideally the optimal solution from the baseline should closely represent the current landuse in the Gamtoos Valley. Due to problems simulating pollution parameters for all the important crops in the valley, it was decided to use cabbages and potatoes to proxy the economic impact of pollution abatement in the valley. Equation QCROPMAX is used to ensure that the relevant importance of the two crops planted at different stages during the year is portrayed in the optimal solution by specifying the maximum percentage of each crop by plant date. MBB (2001) compiled data on land utilisation by plant date which was used to specify the data in table crop_perc(j,p,”perc”). Since only data on cabbages and potatoes were used in the model, the compiled percentages were scaled up proportionally to sum to 100%. Due to the short growing season of potatoes and cabbages, land utilisation factors well above 100% are possible. Careful inspection of equation LANDMAX showed that the percentage of each crop in the optimal solution was calculated by dividing through the total area multiplied by scalar util, which specifies the land utilisation factor, thereby ensuring that land utilisation factor was no more than 1.341.

Equation WATERBAL ensures that each sub-catchment used less water than that allocated to the specific sub-catchment using parameter water_alloc(s). Gross irrigation requirements were converted to cubic meters by the multiplication of a factor 10.

Compliance model

The compliance model consists of the Baseline model with some constraints added to model compliance with the nitrate water quality standard at the catchment outlet. More specifically equations COMPLY_SUB and COMPLY were used to model compliance while the other equations were used to calculate the variables of these two equations. COMPLY_SUB (261-262) ensured that the baseline pollution levels (BaseSubl(s)) minus the optimised pollution abatement level (ABATE(s)) minus the optimised pollution level (POLLUTION(s)) was greater than zero. Thus, no water quality standard as such was stipulated. However, this set of equations was always binding on the optimal solution and ensured that each sub-catchment did not pollute more than baseline levels. Each sub-catchment's pollution abatement level was multiplied by its pollution contribution factor (CONTRIB) to yield total pollution abatement at the catchment outlet. The calculated total catchment pollution abatement level was constrained by equation COMPLY to be greater than the baseline pollution level (Basel) multiplied by a factor (alpha) specifying the percentage abatement necessary. The pollution level from each catchment was calculated by dividing total nitrate loadings by total runoff in equation C_POLLUTION while total runoff and emissions were calculated by equations C_SUBWYLD and C_SUBNLOSS respectively. The pollution contribution factors were calculated endogenously based on each subcatchment's water yield in relation to that of the total water yield from the entire catchment in equation C_CONTRIB. A shortcoming of the contribution factors was that it assumed no decay in the pollutant as it is transported to the total catchment outlet.

Water market

The only change made to the Baseline model to model the reallocation of the available water economically using a water market was the replacement of the water balance equations. More specifically equation WATERBAL(s) was replaced by WATERBAL2, which ensured that total water use was less than or equal to total water availability.

4.2.4 SECTION 4: OUTPUT GENERATION

The last section of the GAMS code consists of running the models calculating output parameters and writing the output to files. The parameters used to output the data are initialised and thereafter the calculations of the specified parameters are shown. A rather stylised representation of the loop used to generate the output is then discussed. The Gams code used in this section follows.

```
*=== initiate output parameters ======================================
Parameters
SubGm(s)        sub catchment gross margin
Gm              total catchment gross margin
SubEmis(s)      emissions from sub-catchment
Em              emissions from total catchment
SubWl(s)        runoff from sub-catchment
Wl              runoff from total catchment
SubWq(s)        water quality indicator at sub-catchment outlet
CSubWq(s)       water quality indicator at sub-catchment outlet
                for the compliance model
Wq              water quality indicator at total catchment outlet
CWq             water quality indicator at total catchment outlet
                for the compliance model
SubHa(s)        hectare irrigated in sub-catchment
Ha              hectares irrigated in total catchment
SubMarginal(s)  marginal pollution abatement cost – sub-cathment
Marginal        marginal pollution abatement cost – cathment
Contribution(s) contribution factors
;

*=== calculate output parameters based on optimal solution ==========
*--- gross margins ---------------------------------------------------
SubGm(s)
  =sum((s,h,l,j,p,n,ir)
       $(sum(y,cy(s,h,l,j,p,n,ir,y))),
       QCROP.l(s,h,l,j,p,n,ir)*(agmargin(s,h,l,j,p,n,ir)
                             – air_cost(s,h,l,j,p,n,ir)*inc_ir
                             - afert_cost(s,h,l,j,p,n,ir)*inc_fert
                               )
       );
Gm
  = WGM.l;
*--- emissions -------------------------------------------------------
SubEmis(s)
  =sum((h,l,j,p,n,ir)
       $(QCROP.l(s,h,l,j,p,n,ir)),
       QCROP.l(s,h,l,j,p,n,ir)*anloss(s,h,l,j,p,n,ir)
```

```
       ) or SUBEM.l(s);
Em
  =sum(s,
       SubEmis(s)
       );
*--- runoff -----------------------------------------------------------
SubWl(s)
  =sum((h,l,j,p,n,ir)
       $(QCROP.l(s,h,l,j,p,n,ir)),
       QCROP.l(s,h,l,j,p,n,ir)*awyld(s,h,l,j,p,n,ir)
       ) or SUBWYLD.l(s);
Wl
  =sum(s,
       SubWL(s)
       );
*--- water quality indicators ----------------------------------------
SubWq(s) or CSubWq(s)
  =SubEmis(s)/SubWl(s);
Wq or CWq
  =Em/Wl;
*--- hectares irrigated ----------------------------------------------
SubHa(s)
  =sum((h,l,j,p,n,ir)
       $(QCROP.l(s,h,l,j,p,n,ir)),
       QCROP.l(s,h,l,j,p,n,ir)
       );
Ha
  =sum(s,
       SubHa(s)
      );
*--- marginal values -------------------------------------------------
SubMarginal(s)
  = COMPLY_SUB.m(s);
Marginal
  = COMPLY.m;
*--- contribution factors --------------------------------------------
Contribution(s)
  =SubWL(s)/WL or CONTRIB.l;
*=== solve models in a loop to generate output ======================
*--- establish baseline output parameters ----------------------------
inc_ir = 1;
inc_fert = 1;
```

```
364  SOLVE baseline using LP MAXIMIZING WGM ;
365  .
366  calculate output parameter using code in lines 320-366
367  .
*--- initiate scalars ------------------------------------------------
368  scalar count count iterations in loop /0/;
369  scalar increase /0.2/;
370  scalar iter;

*--- generate output for different scenarios -------------------------
371  for(iter = 1 to 20,
*~~~ compliance model ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
372     alpha          = (increase + count)
373     BaseSubI(s)    = SubWq(s);
374     BaseI          = Wq;
375     SUBWYLD.lo(s)  = 1;
376     SOLVE COMPLIANCE using NLP MAXIMIZING WGM ;
377     .
378     calculate output parameters using code in lines 320-366
379     write output to file using put statement
380     .
*~~~ baseline model: irrigation cost increase ~~~~~~~~~~
381     inc_ir         = (1 + count);
382     SOLVE BASELINE using LP MAXIMIZING WGM ;
383     .
384     calculate output parameters using code in lines 320-366
385     write output to file using put statement
386     .
*~~~ baseline model: fertiliser cost cost increase ~~~~~
387     inc_fert       = (1 + count);
388     SOLVE BASELINE using LP MAXIMIZING WGM ;
389     .
390     calculate output parameters using code in lines 320-366
391     write output to file using put statement
392     .
393     count = count + increase;
394     );
```

Output from each optimisation is contained in the calculated parameters in lines 318-361 based on the optimal results from the specific optimisation. The suffix .l is used to specify optimised values of the variables, whereas the suffix .m is used to retrieve the marginal values of the water quality compliance constraints at sub-catchment and catchment levels. The output parameters consist of the gross margins generated, pollution loads, runoff, resulting water quality standards, hectares planted to each crop using a specific management scenario, marginal pollution abatement costs and pollution contribution rates. When the baseline model is optimised, pollution parameters are not optimised, but are calculated exogenously using the optimal of the quantities of each crop (QCROP.l(s,h,l,j,p,n,ir)) in the optimal solution.

Lines 362-394 represent the stylised version of the loop used to generate the output. First the baseline pollution levels were established by optimising the unconstrained Baseline model with the parameters of inc_ir and inc_fert set to 1, thereby modelling no increase in these costs. Output parameters were calculated using lines as described above. A FOR statement was used to facilitate commands to optimise the different models in a loop. Additional parameters needed were parameter count which counted the number of iteration, and parameter increase which specified the change in inc_fert, inc_ir and alpha used to alter the input data of the programming model. When solving the Compliance model the values of inc_ir and inc_fert were still equal to one as specified in the baseline solve. However, BaseSubl(s) and Basel were assigned to the water quality indicators calculated from optimised baseline solution. After each solve, the value of alpha was increased by count before resolving the model. To quantify the impact of an increase on fertiliser and water cost on pollution levels the values of inc_fert and inc_ir were increased by count plus one before resolving the next model. Optimal output levels were used to determine the pollution impact exogenously. Each of the separate models solved consisted of about 677 constraints, 12 085 variables and 94 871 technical coefficients.

4.3 GENERAL COMMENTS ON QUANTIFYING NON-POINT SOURCE POLLUTION ABATEMENT COST USING AVSWAT AND GAMS

The procedures described in the previous sections of this chapter demonstrates how NPS simulation modelling using AVSWAT can be used to generate the necessary information for a GAMS optimisation model to quantify economic and environmental trade-offs. Although the procedures proved to work, several assumptions and shortcomings had to be overcome.

Most limiting was the level of expertise available in South Africa regarding the use and application of comprehensive catchment level NPS pollution models such as AVSWAT.

RESULTS AND CONCLUSIONS

CHAPTER 5

The main objective of this chapter is to demonstrate the use of the mathematical programming models in quantifying the economic environmental tradeoffs associated with improving nitrate water quality which are necessary prerequisites for the formulation of meaningful pollution abatement policies. After these tradeoffs are quantified alternative instruments to achieve a specified pollution standard are discussed.

5.1 BASELINE

Given the specification of the mathematical programming model in the previous chapter, baseline pollution levels are needed from which to model the economic environmental tradeoffs regarding nitrate water quality improvement. Since only two crops were used to approximate the impact of alternative strategies to lessen the harmful effects of nitrate pollution, the actual landuse could not be used as a baseline. Instead, a programming model with no constraints on pollution was used to determine the optimal landuse for the Gamtoos irrigation valley, given only potato and cabbage crops could be planted during different time periods. Pollution parameters were calculated from the optimised landuse using information generated with the SWAT model. The economic and environmental impacts of the optimised baseline are given in Table 5.1.

When using potato and cabbage as proxies for the other crops grown in the Gamtoos catchment a total gross margin above specified cost of R325 million is generated. In total 9 690 ha is irrigated through the year giving a land utilisation factor of 1.43. Constraints in the programming model on the maximum percentage of hectares planted to a certain crop with a specific planting date ensured that the proportion between potatoes and cabbage in the baseline portrays the relative importance of these crops in the catchment. In total 1 805 ha of cabbage and 7 885 ha of potatoes were planted in the optimal baseline solution. Gross margins per hectare planted in a sub-catchment ranged from a minimum of R23 240 in Sub13 (sub-catchment) to a maximum of R43 108 in Sub5. The average gross margin per hectare was R31 765.

Table 5.1: Optimised baseline economic and nitrate pollution parameters for the Gamtoos catchment, 2002.

Sub-Catchment	Area (ha)	Gross margin				Nitrate emissions		Nitrate Water quality Indicator	Contribution Factor
		Total (R)	Hectare (R/ha)	Emission (R/kg/ha)	Contribution[1] (R/kg/ha)	Total (kg)	Hectare (kg/ha)		
1	11	375884	34662	1937	2	194	18	0.1377	0.0012
2	70	2655148	37669	1927	17	1378	20	0.1381	0.0088
3	136	4606908	33873	1839	29	2505	18	0.1410	0.0157
4	2188	82346843	37631	2094	532	39318	18	0.1368	0.2538
5	100	4324114	43108	2068	25	2091	21	0.1514	0.0122
6	281	10049178	35814	1583	53	6350	23	0.1656	0.0338
7	35	1238162	35588	1649	6	751	22	0.1698	0.0039
8	157	3934395	25021	1432	23	2748	17	0.1479	0.0164
9	491	18071410	36774	1711	97	10563	21	0.1638	0.0569
10	27	644410	24173	1179	4	547	21	0.1368	0.0035
11	59	1619382	27569	1504	12	1076	18	0.1140	0.0083
12	27	654691	24149	1193	4	549	20	0.1345	0.0036
13	89	2068665	23240	1289	12	1604	18	0.1489	0.0095
14	1250	35915930	28738	1399	223	25670	21	0.1419	0.1597
15	185	4358894	23587	1009	19	4321	23	0.2010	0.0190
16	85	3489684	41081	4061	24	859	10	0.1299	0.0058
17	24	715146	29863	1129	3	634	26	0.2032	0.0028
18	263	6438254	24525	1260	43	5108	19	0.1333	0.0338
19	415	10324701	24864	2120	63	4871	12	0.1439	0.0299
20	508	18728679	36866	4076	168	4595	9	0.0986	0.0411
21	1596	50159158	31426	2063	279	24312	15	0.1587	0.1352
22	1693	62325403	36821	2842	411	21933	13	0.1337	0.1448
Total[2]	9690	325 045 039	33546	2007	-	161978	17	0.1430	-

1 Gross margin per unit nitrate emitted multiplied with the contribution factor

2 Total catchment

Pollution potential is usually quantified as the total amount of nitrate that is lost for crop production. In general the nitrate emissions simulated with SWAT are low. Nitrate emissions in the optimised baseline were the highest in Sub17, which emitted 26 kg nitrate per hectare and the lowest in Sub20 with an emission rate of 9 kg/ha. However, it is not the amount of the emissions that determines pollution, but the proportion of emissions to water that is of concern. Highest nitrate water quality indicators were calculated for Sub15 and Sub17 with values of 0.2010 and 0.2032 respectively. In conjunction with relatively high nitrate water quality indicator Sub15 also had the lowest gross margin per kilogram of nitrate emitted (R1009). On the other hand Sub16 had the second highest gross margin per kilogram of nitrate emitted (R4061) and a relatively low nitrate water quality indicator of 0.1299 which was lower than that of the total catchment. Given the above information one is tempted to conclude that Sub15 will have to abate more than Sub16 when having to reduce pollution at the catchment outlet. However, these two catchments will have similar abatement levels due to the fact that Sub16 is contributing 69% (1-(0.0058 / 0.0190)) less to the catchment nitrate water quality indicator when compared to Sub15 under the condition that the contribution factor for these two catchments stays the same. The concept of contribution factors was used to simplify the modelling of pollutant transport from the sub-catchment it was emitted into the water way to the place ambient water quality is measured and is a function of runoff. When taking each catchment's pollution contribution to the catchment outlet into account, Sub15 and Sub16 had gross margins per unit pollution of R19 and R24 respectively. These values are low when compared to the highest value of R532 in Sub4.

Although only two crops were used to approximate the landuse of the Gamtoos catchment, and nitrate water quality indicators for each of the sub-catchments were low, the spatial variability of the water quality indicators and gross margins were significant. Thus, one can conclude that enough spatial variability was included in the data set to quantify economic environmental tradeoffs with the mathematical programming model.

In the next section the nitrate water quality indicators at the catchment and sub-catchment level calculated from the optimised baseline landuse with only potatoes and cabbage are used as baseline pollution levels from which economic environmental tradeoffs are quantified.

5.2 COST-EFFECTIVE ECONOMIC ENVIRONMENTAL TRADEOFFS

Recall that a cost-effective pollution control policy was previously defined as one which achieves a specific pollution level at minimum cost. Although cost-effective control does not constitute an economically efficient solution, it does provide benchmarks by which alternative control policies can be guided.

Thus, the main objective of this section is to determine the spatial allocation of alternative management practices that will achieve a specific reduction in the water quality indicator relative to the baseline catchment indicator determined in the previous section at least cost. The economic environmental tradeoffs are evaluated with the programming model specified in the previous chapter by lowering the baseline nitrate water quality indicator through by multiplication of appropriate reduction levels. The programming model is structured so that each sub-catchment cannot pollute more than the baseline pollution levels. However, the pollution contribution rates are not kept constant, since each sub-catchment's contribution rate may be altered through changes in irrigation scheduling strategies or when some land has to go out of production.

The trade-off between gross margins and the nitrate water quality indicator at the catchment level is evaluated first at the total catchment level and thereafter at the sub-catchment level.

5.2.1 TOTAL CATCHMENT LEVEL

The typical downward sloping trade-off curve between nitrate water quality improvement at the catchment outlet and total gross margins for the total catchment is shown in Figure 5.1.

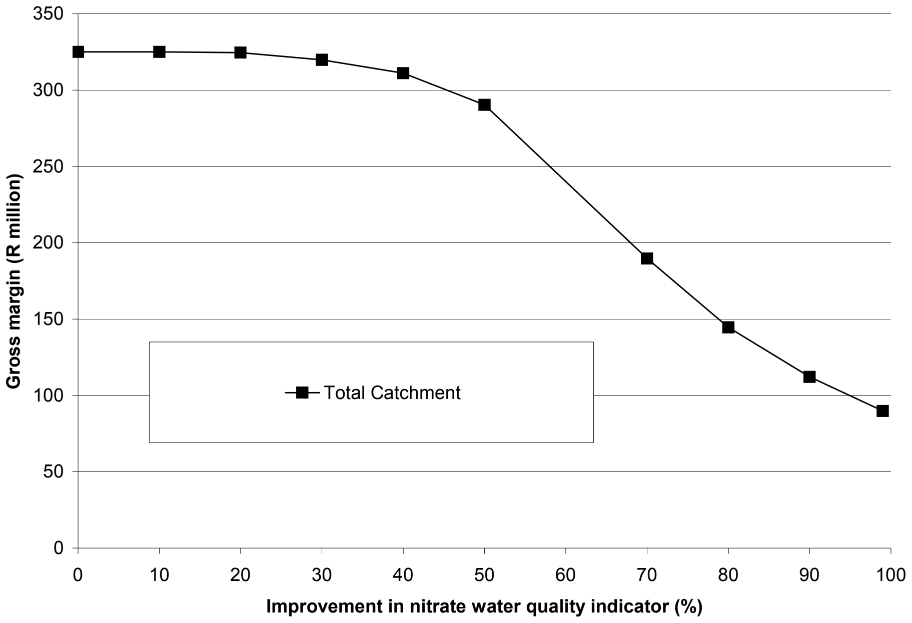

Figure 5.1: Catchment level cost-effective economic environmental tradeoffs of improving nitrate water quality in the Gamtoos irrigation valley, 2002.

From Figure 5.1 it is evident that an improvement of 20% in the nitrate water quality indicator at the catchment outlet is possible without reducing total catchment gross margins significantly. To improve the water quality indicator by 20%, total catchment gross margin was reduced by only R1 million. Total catchment gross margin was reduced more severely between the 20% and 50% levels of improving the catchment water quality indicator. Improving water quality by another 30 percentage points from the 20% level will reduce total catchment gross margins by another R35 million from R325 million to R290 million. At up to a 50% improvement in the water quality indicator, farmers are able to minimise abatement cost through their choice of management practices and by reallocating production spatially over the catchment without lowering the land utilisation factor of 1.43 established in the baseline. To improve water quality by more than 50 %, some land has to go out of production, resulting in drastic reductions in total catchment gross margin. Abatement cost amounts to R135 million to improve water quality by 70%.

Results from the above discussion clearly show that the programming model is capable of quantifying the necessary economic environmental tradeoffs of increasing water quality. One can conclude that water quality improvements of up to 20% will come at low cost, given the spatial allocation of the management practices is obtained. However, more important are the tradeoffs at the sub-catchment level when trying to implement socially acceptable pollution abatement policies especially if it means that some farmers have to stop farming while others are increasing their production.

5.2.2 SUB-CATCHMENT LEVEL

Tradeoffs at the sub-catchment level are used to explain the trade-off at the catchment level. To gain a better understanding of the type of tradeoffs that exist at the sub-catchment level, sub-catchments were grouped into two groups based on the shape of their tradeoffs up to the 20% pollution abatement level. The tradeoffs that exist within these two groups are shown in Figure 5.2.

Significant tradeoffs exist for both groups, with the main difference being that both positive and negative tradeoffs are modelled up to a 20% improvement in the nitrate water quality indicator. For Group A total gross margins are reduced by R56 million from R213 million to R157 million, which is R21 million more than at the total catchment level. In contrast the total gross margin for Group B increases by R55 million, resulting in a net effect of R1 million at the total catchment level.

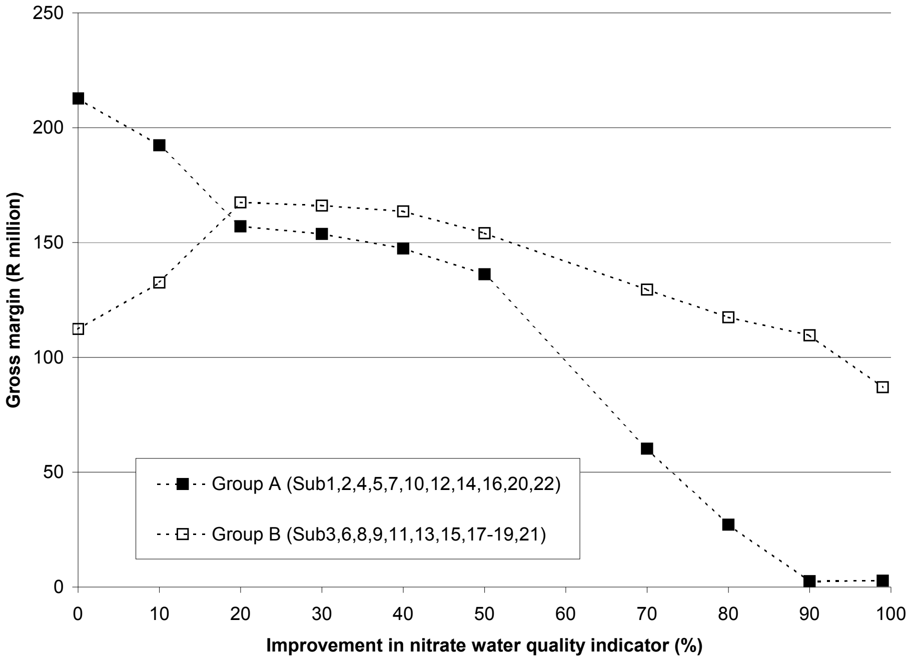

Figure 5.2: Sub-catchment level cost-effective economic environmental tradeoffs of improving nitrate water quality in the Gamtoos irrigation valley, 2002.

The inverse trade-off modelled was mainly due to a decrease in the area under irrigation in the first group and an equal increase in the area in the second group. Thus, a spatial redistribuion of production took place without lowering the land utilisation factor. Most of the crops in the Gamtoos valley are grown on contract. Only a limited number of contracts are available each year, and therefore it is possible that some catchments with lower abatement cost may acquire more production contracts. Mostly cabbage areas were reduced in the first group. Within the sub-catchments of each group and between the two groups tradeoffs between fertiliser application rates, irrigation level, gross margins, nitrate emissions and each catchment's pollution contribution rate determined the unique spatial landuse that complied with the nitrate water quality indicator levels set at each sub-catchment and at the total catchment outlet. An important result was that although the total amount of nitrate emission in Group B increased due to an increase in area irrigated, each sub-catchment still complied with the water quality indicator. Thus, changes in irrigation schedules resulted in increased dillution capacity.

Once pollution reduction was shifted between different catchments, the tradeoffs tended to stabilise up to a 50% pollution abatement level. Beyond the 50% level total gross margins for the subcatchments in Group A were reduced very significantly due to reductions in the area irrigated while those of the sub-catchments in the second group stayed relatively constant.

The above results clearly indicates that despite the fact that little trade-off existed at the catchment level significant tradeoffs existed at the sub-catchment level. When expressed per hectare planted, the abatement cost at the catchment level was R103 whereas it was R5 779 for Group A. Given the high cost in Group A it is concluded that the choice of pollution abatement levels based on catchment level tradeoffs may not be accepted at the sub-catchment level because it will make it unprofitable for some farmers. Furthermore using a reduction in pollution emissions as policy goal may result in trade-off curves with high abatement cost, since it ignores the dilution capacity of water and changes in contribution rates.

Figure 5.2 gives a clear indication of the positive and negative tradeoffs associated with increasing water quality, but gives no indication of the spatial variability of the magnitude of pollution abatement necessary to comply with specific water quality standards nor the associated economic impact.

5.2.2.1 Spatial variability

Figure 5.3 shows the spatial variability in pollution abatement for each of the 22 sub-catchments for three different pollution abatement levels at the total catchment level. If the nitrate water quality indicator has to improve by 10%, it is clear that some sub-catchments need not abate any pollution. The variability in the magnitude of the sub-catchments that needs abate pollution to comply with the water quality standard at the catchment outlet is significant. Sub17 has to abate about 55% of its pollution whereas Sub9 has to reduce its pollution levels by about 4%. As the water quality standard at the catchment outlet is increased, more sub-catchments need to abate pollution. To improve the overall water quality indicator by 50% all the sub-catchments need to abate some pollution, with most of them having to abate more than 40% of their pollution to comply with the standard at the catchment outlet. All the sub-catchments have to abate pollution when improving the water quality indicator by 90%. Furthermore some catchments will have to go out of production to comply with the water quality standard. An abatement level of 100% is modelled for none of the sub-catchments due to lower bounds on the amount of runoff from each sub-catchment to prohibit division by zero in the programming model. The pollution contribution factors optimised for these sub-catchments are, however, so low that the water quality abatement levels have little effect on the overall result. The conclusion is drawn that water quality abatement at the sub-catchment will not give a true indication of water quality improvement at the catchment outlet if evaluated in isolation of the specific catchment's contribution factor. In addition significant variation exists in sub-catchment pollution abatement levels to comply with the catchment water quality standard. Next the spatial variability of gross margins associated with the pollution abatement levels at sub-catchment level is evaluated.

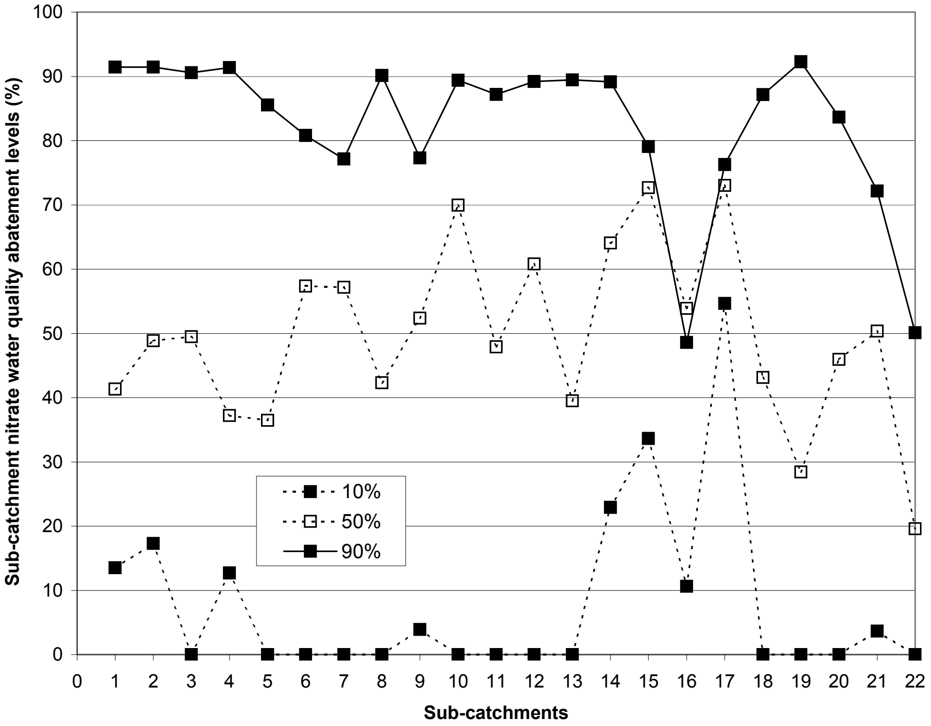

Figure 5.3: Spatial variability of sub-catchment pollution abatement when complying to three different water quality abatement levels at the catchment outlet.

Figure 5.4 shows the associated variability in abatement cost for the three different levels of pollution abatement at the catchment outlet. A negative abatement percentage for a specific catchment represents gains above the specified baseline gross margins. From Figure 5.4 it is clear that abatement cost is high, which may be detrimental to farming business profitability. Abatement cost is also highly variable between sub-catchments. None of the gross margins for the three pollution abatement levels follows pollution abatement shown in Figure 5.3 particularly well. For instance, Sub7 and Sub9 have to abate more or less the same amount of pollution to improve water quality by 90%, but Sub7 has a gross margin of about 50% more than baseline level whereas Sub9 has abatement cost of about 50%. Percentage reductions in gross margins are not proportional to pollution abatement because of different pollution baseline levels and the fact that sub-catchment abatement cost is a function of the pollution abatement level and its contribution factor.

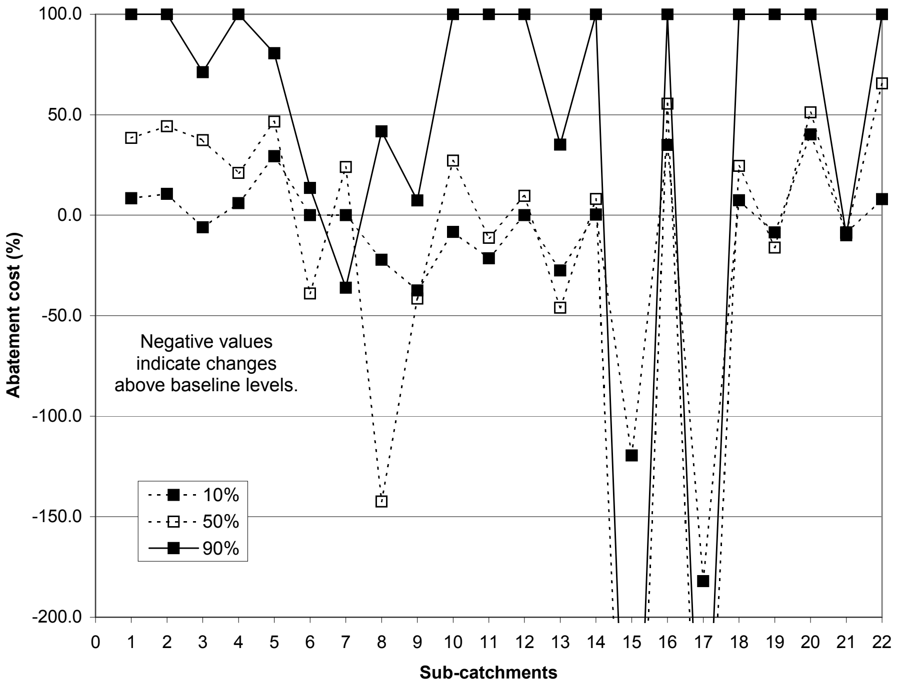

Figure 5.4: Spatial variability of sub-catchment abatement cost when complying to three different water quality abatement levels at the catchment outlet, 2002.

The conclusion is drawn that high abatement cost may cause farming to be unprofitable in some sub-catchments. Furthermore each sub-catchment's baseline pollution levels as well its contribution to the pollution at the outlet of the Gamtoos are important factors determining pollution abatement cost. When interpreted differently the contribution factor means the spatial location of one sub-catchment relative to another.

5.3 POLICY INSTRUMENTS FOR ACHIEVING COST-EFFECTIVE POLLUTION CONTROL

Once the economic environmental tradeoffs are evaluated and a decision is made on the level of pollution abatement that is necessary, the next step is to evaluate alternative instruments that will achieve the pollution standard at minimum cost. Two options that are capable of achieving the specified water quality standard at minimum cost are discussed in this section. The first option involves the spatial regulation of the landuse in the catchment, and the other a tax levied on pollution.

5.3.1 SPATIAL REGULATION OF LANDUSE

Achieving any improvement in the water quality indicator is the result of carefully selected management practices that utilise specific resources (land types and slopes) in specific sub-catchments. Table 5.2 presents the spatial landuse necessary to achieve a water quality improvement of 20% at the outlet of the catchment at least cost.

Table 5.2: Spatial landuse to achieve a 20% improvement in the nitrate water quality indicator at the outlet of the Gamtoos catchment.

Sub-catchment	**HRU**	**Crop**	**Plant date**	**Nitrogen**	**Area planted using irrigation level (ha):**		
					1	**2**	**3**
1	HRU1	pota	Jun	N200		5	
	HRU2	cabg	Nov	N300		2	
	HRU2	pota	Feb	N180		2	
	HRU2	pota	May	N160	2		
	HRU2	pota	Sep	N280			2
2	HRU6	pota	Apr	N120		14	
	HRU7	pota	Feb	N180		28	
	HRU7	pota	Aug	N280			28
3	HRU11	pota	Apr	N120		12	
	HRU12	pota	Jun	N200		47	
	HRU13	cabg	Nov	N300		10	
	HRU13	pota	Feb	N180		29	
	HRU13	pota	May	N160	10		
	HRU13	pota	Aug	N280			19
	HRU13	pota	Sep	N280			10
4	HRU18	pota	May	N160	174		
	HRU18	pota	Jun	N200		353	
	HRU19	cabg	Nov	N300		139	
	HRU19	pota	Feb	N180		341	
	HRU19	pota	May	N160	139		
	HRU19	pota	Jun	N200		202	
	HRU19	pota	Sep	N280			341
	HRU20	pota	Feb	N180		74	
	HRU20	pota	Jun	N200		74	
	HRU20	pota	Sep	N280			74
5	HRU26	pota	Feb	N180		24	
	HRU26	pota	Aug	N280			24
	HRU27	pota	Feb	N180		12	
	HRU27	pota	Mrt	N120	2		
	HRU27	pota	Jun	N200		12	
	HRU27	pota	Aug	N280		1	
	HRU27	pota	Sep	N280			14
6	HRU32	cabg	Sep	N350		37	
	HRU32	pota	Feb	N180		37	
	HRU32	pota	Jun	N200		76	
	HRU33	cabg	Apr	N290		22	
	HRU34	pota	Feb	N180		73	
	HRU34	pota	Aug	N280			73

7	HRU39	cabg	Apr	N290		10	
	HRU40	pota	Feb	N180		12	
	HRU40	pota	Aug	N280			12
8	HRU45	pota	Jun	N200		11	
	HRU46	pota	Feb	N180		65	
	HRU46	pota	Jun	N200		65	
	HRU46	pota	Sep	N280			65
	HRU47	pota	Feb	N180		8	
	HRU47	pota	Aug	N280			8
9	HRU50	cabg	Sep	N350		67	
	HRU50	pota	Mrt	N120	67		
	HRU51	pota	Feb	N180		250	
	HRU51	pota	Aug	N280			250
	HRU52	pota	Mrt	N120	45		
	HRU52	pota	Sep	N280			45
10	HRU55	cabg	Sep	N350		1	
	HRU55	pota	Mrt	N120		1	
	HRU55	pota	Jun	N200		20	
	HRU56	cabg	Sep	N350		5	
	HRU56	pota	Feb	N180		5	
11	HRU61	cabg	Jun	N220	23		
	HRU62	pota	Apr	N120	9		
	HRU62	pota	May	N160	27		
12	HRU66	pota	Jun	N200		14	
	HRU67	cabg	Sep	N350		1	
	HRU67	pota	Feb	N180		3	
	HRU67	pota	May	N160	3		
	HRU67	pota	Sep	N280			3
	HRU68	pota	Mrt	N120		7	
13	HRU72	cabg	Sep	N350		8	
	HRU72	pota	Feb	N180		8	
	HRU73	pota	Feb	N180		33	
	HRU73	pota	Jun	N200		33	
	HRU73	pota	Sep	N280			33
	HRU74	pota	May	N160		15	
14	HRU78	pota	Mrt	N120	755		
	HRU79	pota	Feb	N180		229	
	HRU79	pota	Mrt	N120	168		
	HRU79	pota	Aug	N280		172	
	HRU80	cabg	Apr	N290		23	
	HRU80	cabg	May	N280		1	
	HRU80	cabg	Jun	N220		74	
15	HRU86	cabg	Oct	N350		84	
	HRU86	pota	Mrt	N120	84		
	HRU87	cabg	Apr	N290		100	
16	HRU90	cabg	Apr	N290		20	
	HRU91	pota	Mrt	N120	23		

17	HRU94	cabg	Oct	N350		22
	HRU94	Pota	Mrt	N120	22	
	HRU95	Cabg	Sep	N350		2
	HRU95	Cabg	Dec	N350		2
	HRU95	Pota	Mrt	N120	2	
18	HRU101	Cabg	Sep	N350		29
	HRU101	Pota	Mrt	N120		29
	HRU101	Pota	May	N160		211
	HRU102	Cabg	Jun	N220		23
19	HRU106	Cabg	Jun	N220		33
	HRU107	Cabg	Mrt	N310		14
	HRU107	Cabg	Jul	N300		14
	HRU107	Pota	Apr	N120	368	
20	HRU112	Cabg	Jun	N220	21	
	HRU113	Cabg	Jun	N220	1	
	HRU113	Pota	Mrt	N120	94	
	HRU113	Pota	May	N160	68	
	HRU114	Cabg	May	N280		174
21	HRU118	Cabg	Mrt	N310		161
	HRU118	Cabg	Jul	N300		161
	HRU118	Pota	Jun	N200		159
	HRU119	Cabg	Feb	N320		151
	HRU119	Cabg	Aug	N300	175	
	HRU119	Cabg	Oct	N350		45
	HRU119	Cabg	Dec	N350		149
	HRU119	Pota	Feb	N180		661
	HRU119	Pota	Mrt	N120	27	
	HRU119	Pota	May	N160	124	
	HRU119	Pota	Jun	N200		158
22	HRU125	Pota	Mrt	N120	631	
	HRU125	Pota	May	N160	265	
	HRU126	Pota	May	N160	191	

Although regulating the landuse of a catchment has been proposed in literature as an instrument to comply with water quality standards, implementation maybe difficult. Implementation of this instrument requires regulating areas of the crops grown to specific soils and slopes as well as water and input use spatially over the whole catchment according to Table 5.2. Policing the landcover (crops planted to different soils and slopes) may be feasible, but controlling input use will be much more difficult. The number of entities that needs to be controlled with this alternative is enormous. Furthermore these regulations will infringe on the property rights of farmers.

5.3.2 POLLUTION TAXES

Levying pollution taxes is just as efficient as regulating the landuse spatially in the catchment in terms of achieving a specified improvement in the nitrate water quality indicator. Implementation of this instrument requires the marginal pollution abatement cost, which is the reduction in gross margin due to a one-unit improvement in the water quality indicator. The marginal abatement cost is equal to the shadow price of the water quality constraints in the programming model. Table 5.3 presents the marginal pollution abatement cost and the total amount of taxes used as economic incentive to comply with a 10% and 20% pollution abatement level at the outlet of the Gamtoos catchment.

Table 5.3: Marginal pollution abatement cost and total amount of taxes for two pollution abatement levels at the outlet of the Gamtoos catchment, 2002.

Sub-catchment	**Pollution abatement: 10%**		**Pollution abatement: 20%**	
	Marginal cost	**Total tax**[1]	**Marginal cost**	**Total tax**
1	10 024	186	215 255	2 239
2	71 716	1 714	1 410 048	12 690
3	139 768	0	2 723 285	22 603
4	2 065 551	35 941	38 113 488	236 304
5	78 314	0	1 811 411	0
6	266 965	0	5 725 160	127 671
7	30 807	0	531 368	10 574
8	200 381	0	4 867 697	13 143
9	561 970	3 597	13 562 539	396 026
10	32 777	0	747 826	0
11	64 862	0	942 199	0
12	28 417	0	671 754	0
13	103 686	0	2 770 846	23 829
14	1 388 000	45 110	29 792 947	1 957 397
15	251 008	16 968	3 794 719	541 886
16	52 403	723	596 253	41 082
17	41 160	4 573	897 208	140 592
18	404 976	0	5 927 050	0
19	248 243	0	5 260 529	348 247
20	235 053	0	4 509 903	0
21	1 121 486	6 505	26 867 926	558 853
22	1 027 306	0	15 412 440	288 213
Total	8 069 025	97 635	165 072 671	4 225 860

[1] Total taxes are approximated by multiplying the marginal cost with the pollution abatement.

Pollution taxes can be implemented at the catchment and sub-catchment level. At the catchment level a tax of R165 million per unit pollution is necessary to comply with an improvement of 20% in the nitrate water quality indicator. Since the water quality indicator is measured as a fraction of a full unit of pollution only a portion of the tax is payable. In total R4.2

million is payable if farmers opt not to abate any pollution. Using a catchment level tax will assume that all the farmers in the catchment contribute equally to the pollution at the outlet. Free-riding problems may also exist when such a large number of farmers are held responsible for abating pollution at the catchment level.

Differentiated taxes are necessary to tax each catchment according to its contribution to the pollution level at the catchment outlet. These taxes correspond to the shadow price of the water quality constraints at the sub-catchment level. To comply with the water quality standard at the sub-catchment level a tax per unit of pollution abatement equal to R38 million is levied in Sub4 and R1.8 million in Sub5. These taxes are extremely high due to the scaling[1] of the compliance equations in the programming model. Furthermore the programming model is structured in such a way that the water quality constraint at the sub-catchment level is always binding on the optimal solution. Consequently a shadow price is computed for each sub-catchment even though no pollution abatement at the sub-catchment level is necessary to comply with catchment level water quality standard. The total amount of taxes payable in Sub5 is therefore zero, because no pollution abatement is necessary to comply with the catchment outlet water quality standard. Total taxes in Sub4 are R236 304 if farmers choose not to abate any pollution.

Implementing a pollution tax is difficult because one needs to measure water quality at each sub-catchment as well as at the catchment outlet. Installing measuring devices is expensive, and the additional cost may decrease the feasibility of this policy instrument.

From the above discussion it is concluded that it is very difficult to achieve pollution abatement cost-effectively due to the large number of entities that needs to be controlled and the additional cost of obtaining the necessary water quality data at the sub-catchment level.

5.4 COST-EFFECTIVENESS OF ECONOMIC INCENTIVES APPLIED TO FERTILISER AND WATER

Given the problems associated with achieving cost-effective control of NPS pollution, alternative policies to control NPS pollution should be evaluated. The National Water Act (Act 56 of 1998) provides a means to control pollution using source directed measures. An important source of nitrate pollution is the use of artificial and organic fertilisers. In this section the cost-effectiveness of two alternative economic incentives applied to the source of the pollutant as well as the transport medium is evaluated relative to cost-effective tradeoff curve at total catchment level established in Section 5.2.1 at the beginning of this chapter. In two separate loops the landuse in the Gamtoos catchment is optimised while increasing the price of water

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[1] For example, dividing a resource constraint by a factor of 100 will result in the same optimal solution but the shadow value of the resource when constraining the optimal solution will be 100 times more. Thus it is determined by the units of measurement.

and fertilisers to determine the effect of these price increases on pollution and the resulting gross margins. Figure 5.5 shows the tradeoffs between abatement cost and improving water quality when fertiliser and water costs are increased.

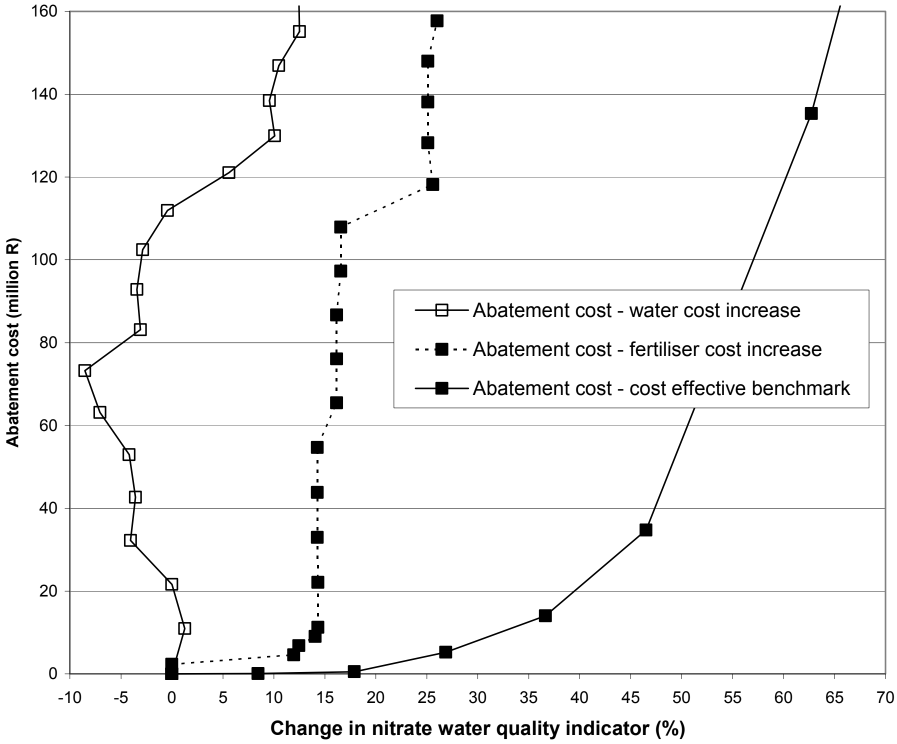

Figure 5.5: Catchment level economic environmental tradeoffs of improving nitrate water quality in the Gamtoos irrigation valley when using fertiliser and water cost increases as economic incentives, 2002.

From Figure 5.5 it is clear that an economic incentive applied to fertilisers is more cost-effective than an incentive applied to irrigation water where cost-effectiveness is measured as the distance between the cost-effective trade-off curve and the alternative evaluated. Increasing fertilisation cost will improve the nitrate water quality indicator by 15% at a cost of R9 million. Improving the water quality indicator by another 1.5 percentage points from 15% to 16.5% will come at an additional cost of almost a R100 million. In comparison the same improvement is achieved, using the cost-effective means whereby the farmers themselves have to choose between different pollution mitigating strategies at a cost of about R0.5 million. Thus, even though a tax on fertilisers is more cost-effective than taxing water, its cost-effectiveness is still very low.

Another important result is that increasing water cost will not necessarily improve water quality, especially if farmers are using water more efficiently without decreasing areas irrigated. Increasing water use efficiency will reduce streamflow via reduced return flows. Reducing the amount of water available to dilute the pollution emissions will increase the concentration of the pollutants, thereby decreasing the quality of the water. Total water cost in the Gamtoos catchment needs to increase to about R112 million before resulting in any water quality improvements. If total water cost is increased above R112 million, reduced areas result in water quality improvements.

5.5 WATER MARKET

Since water is a scarce resource in South Africa, water markets have been proposed as a means of reallocating this scare resource. Many researchers reason that a water market will result in water quality improvements, since it encourages efficient use of water thereby reducing the amount of drainage. Under normal conditions water is not a scarce resource in the Gamtoos catchment mainly due to the Kouga Dam which is used as the main source of irrigation water. To model the impact of a water market, a new baseline was established by re-optimising the baseline model with a 20% reduction in water availability from which the impact of the water market was quantified. With the water market model water use was optimised by reallocating the available water between different sub-catchments. Thereafter pollution information simulated with SWAT was used to determine the pollution impact of a water market. Results of the analysis are given in Table 5.3 as changes relative to the newly established baseline with a water shortage of 20%.

In the presence of a water market the same area is irrigated, but due to the fact that water is allocated to sub-catchments and cropping activities that use water economically, efficient total catchment gross margin increases by R786 263. The nitrate water quality indicator worsens by 0.0074 units mainly due to an increase in total nitrate emissions by 2 934kg and reduced runoff levels of 35820mm.

At the sub-catchment level water is reallocated to sub-catchments 18, 19, 20, 21 and 22 to optimise water use per unit applied water in all the sub-catchments. Only Sub20 and Sub21 uses the water to irrigate 86 ha and 716 ha respectively more than the baseline. The other three sub-catchments use the water to irrigate their crops at higher irrigation levels. Even though three of the sub-catchments did not expand their irrigation areas total nitrate emissions increased for all five the catchments due to a change in the crop mix resulting in an increase in the water quality indicator. What is interesting to note is that the runoff of the sub-catchments to which water is allocated also have significantly higher runoff rates, which culminated into higher pollution contribution rates.

Table 5.4: Effect of a water market on area irrigated, gross margins and nitrate pollution relative to a baseline with a water shortage of 20%, 2002.

Sub-Catchment	**Area (ha)**	**Gross Margin (R)**	**Water Use (m^3)**	**Nitrate Emissions (kg)**	**Runoff (mm)**	**Water Quality Indicator**	**Contribution Factor**
1	-1	-71 748	-5 374	-22	-195	0.0051	-0.0002
2	-28	-1 624 443	-72 907	-104	-1 813	0.0262	-0.0015
3	-22	-911 597	-139 992	-1 088	-6 130	-0.0152	-0.0056
4	-495	-25 162 107	-2 222 558	-14 611	-82 466	-0.0145	-0.0740
5	-50	-3 173 146	-179 329	-862	-5 156	-0.0178	-0.0048
6	-34	-2 975 611	-216 026	-1 635	-2 261	-0.0453	-0.0012
7	-11	-861 217	-49 695	-318	-1 200	-0.0366	-0.0011
8	0	91 693	-158 781	-1 671	-9 251	-0.0551	-0.0087
9	-173	-10 756 177	-606 118	-3 167	-33 505	-0.0019	-0.0313
10	0	-55 899	-28 175	-233	-1 507	-0.0447	-0.0014
11	0	-453 356	-15 620	-102	-293	-0.0104	0.0000
12	0	9 413	-15 857	-131	-836	-0.0177	-0.0008
13	0	551 327	-57 870	-618	-3 239	-0.0349	-0.0029
14	20	-1 021 125	-255 209	-2 730	-29 888	-0.0029	-0.0229
15	-10	-642 482	-15 440	-81	380	-0.0049	0.0014
16	0	-29 176	-1 764	-8	-63	0.0016	0.0001
17	2	-13 141	-12 269	-195	66	-0.0563	0.0002
18	0	-821 816	208 148	1 639	10 490	0.0126	0.0115
19	0	-3 353 046	425 152	4 448	25 135	0.0236	0.0263
20	86	5 640 795	350 997	2 588	13 938	0.0089	0.0155
21	716	46 414 737	3 068 383	21 837	91 997	0.0504	0.0979
22	-1	4 382	305	0	-23	0.0000	0.0037
Total	0	786 263	0	2 934	-35 820	0.0074	-

In general all the sub-catchments from which water is reallocated have reduced emission levels, runoff rates, nitrate pollution indicators and contribution factors.

From the above results it is concluded that although a water market encourages more efficient use of water that results in less drainage, water quality may not always improve due to changes in crop mix with higher nitrate emission. Reallocating water resources in a catchment will change pollution contribution rates, which have already been shown as a very important determinant of abatement cost.

RESEARCH IMPLICATIONS

The research implications are discussed in terms of the implications for policy and further research.

Policy implications

The National Water Act (Act 36 of 1998) provides the legislative means to target non-point source pollution with specific source directed measures (Quibell, 2000). No specific differentiation is made between point and non-point source pollution in the National Water Act (Act 36 of 1998), which allows for the development of source specific procedures which address both point and non-point source pollution from the source. The Act furthermore emphasises the use of economic instruments to achieve its objectives. The waste discharge charge system (WDCS) is one way in which DWAF is implementing the National Water Act (Act 36 of 1998). The basis for this system is the polluter pays principle (PPP). The theory behind polluters paying pollution charges is that the individuals must pay for the cost incurred as a result of their pollution (Taviv, Herold, Forster, Roth and Clement, 1999). However, in order to institute a system of waste charges, the relevant authority must be able to identify who caused the pollution and precisely how much of it. The last mentioned is a necessary condition for any charge system based on the PPP (Taviv et. al, 1999).

Results from this research have some serious implications for combating pollution from non-point pollution sources as described in the policy options above. The main sources of nitrate pollution evaluated in this research were artificial fertilisers. Given source directed measures and the use of economic incentives to control NPS pollution a logical step would be to try to reduce the amount of fertilisers applied through the use of economic incentives. Although more cost-effective than increasing water cost, fertiliser price increases are not very cost-effective in decreasing nitrate pollution. The total cost to improve water quality by 16.5% will amount to approximately R11 000 per hectare planted, taking a land utilisation factor of 1.43 into account.

Another important factor that should be recognised is that abatement cost does not change proportionately to pollution abatement due to changes in each catchment's pollution contribution factor. The sub-catchment trade-offs showed that although total loss of nutrients (kg) in some catchments increased, the pollution indicators did not change due to dilution effects. Thus, each sub-catchment should not be taxed based on pollution emissions, but rather on its contribution to a specific ambient water quality level measured at a specific location in the catchment. Calculation of each catchment's pollution contribution factor is not straightforward because, it depends on the management options taken by irrigators in other sub-catchments. Furthermore reallocation of water rights has a significant effect on pollution contribution factors as is illustrated in the water market analysis.

Water market results further indicate that more efficient use of water may result in increasing pollution concentrations. This result is alarming because government is currently placing high priority on more efficient use of water. If farmers are allowed to use conserved water to irrigate larger areas the total dilution capacity of a given water system will be reduced due to increased water consumption, while fertiliser use will increase due to larger irrigation areas. One can expect that water pollution will increase under these conditions especially under variable weather conditions that might flush excess nutrients into water sources.

Another troublesome fact is that policies are usually formulated based on catchment level trade-offs. However, the sub-catchment level tradeoffs explaining the catchment level tradeoffs are much more important in determining irrigation farming profitability and therefore the impact on the economy of the region. Even quantifying the tradeoffs at the sub-catchment level may not be sufficient. Although catchments and sub-catchments constitute logical planning units from an environmental viewpoint, it does not coincide with the management units and political boundaries. However, water pollution is determined by decisions made within political boundaries and management units. The policy challenge is to harmonise economic development within political boundaries and decisions made at farm level with sustainable environmental protection. Brooks *et. al.* (1994) reasoned that this should be done by realistically integrating these views by adapting catchment management to economic and social realities.

One of the main results from this research is that the pollution contribution factor plays a cardinal role in determining pollution abatement cost and therefore also in ranking alternative instruments to combat pollution relative to each other. Lichtenberg (2000) acknowledged this result and reasoned that ignoring transport linkages to receiving water bodies as well as the link between emitted pollutants and ambient pollution levels and therefore the interrelated linkages between agricultural production practices and pollution damage may stem relative comparisons between alternative policies inappropriate. Thus, in future there will be an increasing demand for catchment scale economically linked NPS pollution models that account for all the NPS pollution processes and their linkages. Only through the application of these types of models in different catchments will a better understanding be gained of changing linkages between institutional settings, irrigation technology, economic efficiency, water pollution and human value systems necessary to advance meaningful water pollution abatement policy.

Further research

A troublesome factor that may hamper NPS pollution policy in future is the level of modelling expertise available in South Africa regarding the application and use of catchment scale NPS pollution models that account for the linkages from the field to catchment scale. Ribaudo *et al.* (1999) argued that it is only through a better understanding of these interrelated linkages that advances in meaningful NPS pollution will occur. Application of catchment scale NPS models may assist in understanding these linkages. However, it is important that these models are able to quantify the impact of alternative management practices implemented at the field scale on water quality indicators measured at the catchment scale. Thus, there is a clear need for more detailed models that may complement modelling procedures used in South Africa to target problem areas.

More detailed NPS modelling to quantify economic and environmental tradeoffs should recognise that although catchments and sub-catchments are logical management units from an environmental viewpoint, decisions made at the farm level actually determine pollution abatement cost. Further research is thus necessary to more closely reflect the farm as management unit when quantifying economic environmental trade-offs of improving water quality, thereby quantifying the impact of pollution abatement policies on irrigation farming profitability.

To advance the application of more detailed economically linked catchment scale NPS models, the development of appropriate GIS data bases cannot be overemphasised. Although GIS soils information is available from the ISCW, the data contained in the database are not suited for direct hydrological modelling. Furthermore, most troublesome is the existence of detailed landuse information within the boundaries of water user associations (WUA) necessary for the evaluation of alternative management practices on pollution loads. In many instances the WUAs only know how much water has been distributed to specific farmers without knowing consumptive use patterns. Thus, basic spatial information on temporal cropping patterns and water use is not available in most catchments. A GIS database of temporal cropping patterns and irrigation technology is essential for model validation and if available may prove to be of benefit to WAUs given they will have to submit water use plans in future proving efficient use of their water supplies.

Among the main outputs from this research are the procedures used to link the spatial use of different management options to the nitrate water quality indicator using a dynamic pollution contribution factor. The pollution contribution factor is based on the dilution capacity of total runoff making the assumption that no degradation takes place while it is transported to the catchment outlet. In many sub-catchments this assumption is not valid and future research should be aimed at incorporating pollutant decay rates into the pollution contribution factors.

The mathematical programming model can be developed further to recognise that pollutant loads are inherently stochastic, and that the risky environment in which farmers produce and market their crops may have a significant effect on pollution abatement cost. Although alternative policy instruments were evaluated to reduce NPS pollution it was assumed that transactions cost is zero. In this research alternative policy instruments were evaluated to reduce NPS pollution assuming transactions cost is zero. Transactions cost include, among others, the costs associated with implementing, administering, and enforcing policies, as well as the costs of obtaining information to design policies. Future research should also include transaction cost when evaluating alternative NPS control policies.

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APPENDIX A

SOILS INFORMATION

Table A1: Hydrological properties of soils included in the land type database of the Gamtoos Catchment (Smithers and Schiulze, 1995).

Soil Form	**Code**	**Soil Series**	**SCS Grouping**	**SCS Adjustment Factor**	**Clay Distribution model**	**Typical Texture Class**	**Interflow Potential**	**Erosion Hazard Rating**
AVALON	Av30	Viljoenskroon	B	+t/-1	1a	LmSa	X	High
	Av33	Bleeksand	B/C	-1	1b	SaLm	X	High
	Av36	Soetmelk	B/C	-1	1c	SaClLm	X	Mod
CARTREF	Cf10	Amabele	B/C	+t	5a	LmSa	0	High
	Cf11	Rutherglen	C		5b	SaLm	0	High
	Cf12	Arrochard	C		5c	SaClLm	0	High
	Cf20	Waterridge	B/C	+t	5a	LmSa	0	High
	Cf21	Cartref	C		5b	SaLm	0	High
	Cf22	Cranbrook	C		5c	SaClLm	0	Mod
	Cf30	Grovedale	B/C	+t	5a	Sa	0	High
CHAMPAGNE	Ch10	Mposa	D		2c	SaLm	0	High
CONSTANTIA	Ct10	Strombolis	B		3a	LmSa	X	High
	Ct11	Tokai	B		3a	Sa	X	High
	Ct14	Noetzie	B		2b	SaLm	0	High
	Ct20	Palmyra	B		3b	LmSA/SaClLm	XX	High
	Ct21	Vlakfontein	B		3b	LmSA/SaClLm	XX	High
	Ct23	Dwesa	B		3e	SaLm/SaClLm	XX	High
	Ct24	Kromhoek	B		3e	SaCl/SaClLm	XX	High
CLOVELLY	Cv20	Tweefontein	A	+t	1a	LmSa	0	High
	Cv21	Sonnenblom	A	+t	1a	LmSa	0	Mod
	Cv30	Sunbury	A/B	+t/-1	1a	LmSa	0	High
	Cv33	Annandale	B	-1	1b	SaLm	0	High
	Cv40	Bleskop	A	+t	1a	LmSa	0	High
	Cv43	Vaalbank	A/B		1b	SaLm	0	High
DUNDEE	Du10	Dundee	B/C		2c	SaLm	0	Mod

Table A1: Continue

ESTCOURT	Es14	Grasslands	D		3e	SaLm/SaClLm	XX	V.High
	Es16	Rosemead	D		3h	SaClLm/SaCl	XX	High
	Es20	Assegaai	D		3c	LmSa/SaClLm	XX	V.High
	Es21	Langkloof	D		3c	LmSa/SaClLm	XX	V.High
	Es40	Beerlaagte	D		3c	LmSa/SaClLm	XX	V.High
	Es41	Heights	D		3c	LmSa/SaClLm	XX	V.High
FERNWOOD	Fw10	Maputa	A		1b	SaLm	0	High
	Fw11	Fernwood	A		1b	SaLm	0	High
	Fw20	Motopi	A		1b	SaLm	0	High
	Fw30	Shasha	B	-w	1b	SaLm	XX	High
	Fw31	Warrington	B	-w	1b	SaLm	XX	High
GLENROSA	Gs10	Martindale	B	+t	5a	LmSa	X	High
	Gs13	Kanonkop	B/C		5b	SaLm	X	High
	Gs14	Platt	B/C		5b	SaLm	X	Mod
	Gs16	Williamson	B/C		5c	SaClLm	X	Mod
	Gs19	Saintfaiths	C	-t	5d	Cl	X	V.Low
	Gs26	Lekfontein	B/C		5a	SaClLm	X	Mod
HOEKHOUW	Hh20	Albertinia	C		2a	LmSa	X	High
	Hh30	Houwhoek	B/C	+t	2a	Sa	X	High
	Hh31	Gouna	B/C	+t	2b	SaLm	XX	High
HUTTON	Hu26	Msinga	A		1c	SaClLm	0	Low
	Hu30	Roodepoort	A	-1/+t	1a	LmSa	0	High
	Hu33	Mangano	A/B	-1	1b	SaLm	0	High
	Hu36	Shorrocks	A/B	-1	1c	SaClLm	0	Mod
	Hu37	Makatini	B	-t/-1	1d	SaCl	0	Low
	Hu43	Maitengwe	A		1b	SaLm	0	High
	Hu44	Malonga	A		1b	SaLm	0	High
	Hu46	Shigalo	A		1c	SaClLm	0	Mod
	Hu47	Hardap	A/B	-t/-1	1d	SaCl	0	Mod

Table A1: Continue

KROONSTAD	Kd10	Rocklands	C/D		3b	LmSa/SaLm	XX	V.High
	Kd11	Velddrif	C/D		3b	LmSa/SaLm	XX	V.High
	Kd13	Kroonstad	C/D		3e	SaLm/SaClLm	XX	V.High
	Kd14	Mkambati	C/D		3b	SaLm/SaClLm	XX	V.High
	Kd16	Bluebank	C/D		3h	SaClLm/SaCl	XX	High
	Kd17	Avoca	C/D		3h	SaClLm/SaCl	XX	High
	Kd22	Katarra	C/D		3c	Sa/SaClLm	XX	V.High
LONGLANDS	Lo10	Orkney	C		1a	LmSa	XX	High
	Lo11	Waaisand	C		1b	SaLm	XX	High
	Lo12	Waldene	C/D	-t	1c	SaClLm	XX	High
	Lo13	Winterton	C	-t	1d	SaCl	XX	Low
	Lo20	Vasi	C		1a	LmSa	XX	High
	Lo21	Longlands	C		1b	SaLm	XX	High
	Lo22	Albany	C/D	-t	1c	SaClLm	XX	Mod
LAMOTTE	Lt14	Chamond	A/B		2b	SaLm	X	High
MISPAH	Ms10	Mispah	C		2c	SaClLm	XX	Mod
	Ms11	Klipfontein	C		2c	SaClLm	XX	Mod
	Ms13	Plettenberg	C		2c	SaClLm	XX	Mod
	Ms20	Muden	C		2c	SaClLm	XX	High
	Ms22	Kalkbank	C		2c	SaClLm	XX	High
OAKLEAF	Oa16	Leeufontein	B		1c	SaClLm	0	Low
	Oa17	Highflats	B/C	+t	1d	SaCl	0	V.Low
	Oa26	Letaba	B		1c	SaClLm	0	Mod
	Oa30	Oakleaf	A/B	+t	1a	LmSa	0	High
	Oa31	Oshikango	A/B	+t	1a	LmSa	0	Mod
	Oa32	Sezela	A/B	+t	1a	Sa	0	Mod
	Oa33	Vaalrivier	B		1b	SaLm	0	High
	Oa34	Levubu	B		1b	SaLm	0	Mod
	Oa36	Jozini	B		1c	SaClLm	0	Low
	Oa37	Koedoesvlei	B/C	-t	1d	SaCl	0	V.Low
	Oa43	Allanridge	B		1b	SaLm	0	High
	Oa46	Limpopo	B		1c	SaClLm	0	Mod

Table A1: Continue

PINEDENE	Pn33	Oewer	B/C	-1	1b	SaLm	X	High
	Pn36	Klerksdorp	B/C	-1	1c	SaClLm	X	High
SHORTLANDS	Sd31	Sunvalley	B/C	-1	1d	SaCl	0	Low
SHEPSTONE	Sp10	Tergniet	A		3a	LmSa	0	High
	Sp11	Bitou	A		3a	LmSa	0	High
	Sp13	Gouritz	A		2b	SaLm	0	High
	Sp14	Robberg	A		2b	SaLm	0	High
STERKSPRUIT	Ss16	Swaerskloof	D		3h	SaClLm	X	High
	Ss26	Sterkspruit	D		3h	SaClLm	X	High
SWARTLAND	Sw11	Skilderkrans	C/D		1d	SaCl	X	Low
	Sw12	Breidbach	D	-t	1e	Cl	X	Mod
	Sw20	Uitsicht	C/D		1c	SaClLm	X	High
	Sw21	Broekspruit	C/D		1d	SaCl	X	Mod
	Sw30	Rosehill	C/D		1c	SaClLm	X	High
	Sw31	Swartland	C/D		1d	SaCl	X	High
VALSRIVIER	Va11	Waterval	C/D		1d	SaCl	0	Mod
	Va21	Craven	C/D		1d	SaCl	0	Mod
	Va41	Lindley	C/D		1d	SaCl	X	Mod
VILAFONTES	Vf10	Moreland	A/B		3a	LmSa	XX	High
	Vf11	Hudley	A/B		3a	LmSa	XX	High
	Vf13	Tinely	A/B		2b	SaLm	XX	High
	Vf24	Chantilly	A/B		3e	ClLm/SaClLm	XX	High
WASBANK	Wa12	Burford	C		2c	SaClLm	XX	High
	Wa20	Rondevlei	B/C	+t	2a	LmSa	XX	High
	Wa21	Warrick	C		2c	SaClLm	XX	Mod
WESTLEIGH	We11	Westleigh	C		1b	SaLm	X	High
	We12	Rietvlei	C		1c	SaClLm	X	Mod
	We13	Sibasa	D	-t	1d	SaCl	X	Low
	We21	Witsand	C		1b	SaLm	X	High

Table A2: Topsoil and subsoil clay percentages of different water retention models (Schiulze, Hutson and Guss, 1985).

Submodel	**Percentage clay**	
	Topsoil	**Subsoil**
1a	2	4
1b	8	12
1c	17	33
1d	36	54
1e	54	66
3a	3	10
3b	3	18
3c	3	28
3d	10	17
3e	10	25
3f	10	35
3g	25	32
3h	25	40
3i	25	50
3j	45	52
3k	45	60
3l	45	70
5a	3	1.5
5b	10	5
5c	25	12.5
5d	45	22.5
5e	60	30

Table A3: Typical particle distributions for different textural classes bulk density and saturated hydraulic conductivity.

	Percentage			Silt coef	Sand coef	Bulk density		SHC
	Clay	**Silt (A)**	**Sand (B)**	**A/(A+B)**	**B/(A+B)**	**Top**	**Sub**	
C	48.3	14.5	35.2	0.291	0.709	1.22	1.37	0.6
ClLm	32.0	22.0	46.0	0.324	0.676	1.22	1.41	2.3
Lm	18.0	32.1	49.5	0.393	0.607	1.26	1.42	13
LmSa	4.6	8.7	86.5	0.091	0.909	1.31	1.51	61
Sa	5.8	5.2	91.1	0.054	0.946	1.32	1.5	210
SaCl	42.2	6.0	54.0	0.100	0.900	1.35	1.53	1.2
SaClLm	27.0	8.0	65.0	0.110	0.890	1.35	1.58	4.3
SaLm	13.5	19.2	65.1	0.228	0.772	1.26	1.46	26
SiCl	50.0	37.0	13.0	0.740	0.260	1.23	1.38	0.9
SiClLm	33.0	46.0	21.0	0.687	0.313	1.25	1.4	1.5
SiLm	17.7	52.5	29.3	0.642	0.358	1.13	1.34	6.8

Table A4: Soil depth, particle distribution, bulk density and saturated hydraulic conductivity of soil families included in the land type database.

Land type	Soil family		Depth (mm)				Clay (Avg%)		Silt (Avg%)		Sand (Avg%)		Bulk density (Avg)		SHC
			Given	Total	Top	Sub	Top	Sub	Top	Sub	Top	Sub	Top	Sub	
Hb83	Cv30Cv40	33%	>1200	600	200	400	2	4	9	9	89	87	1.31	1.51	61
Hb83	Fw10Fw20	67%	>1200	600	200	400	8	12	21	20	71	68	1.26	1.46	26
Hb84	Cf20Cf21	5%	50-150	250	200	50	7	3	15	15	79	81	1.29	1.49	44
Hb84	Kd14Kd21	14%	400-800	600	200	400	14	29	13	11	73	60	1.29	1.48	118
Hb84	Cv20Cv21	16%	>1200	600	200	400	2	4	9	9	89	87	1.31	1.51	61
Hb84	Vf24	33%	>1200	600	200	400	10	25	29	24	61	51	1.22	1.41	2
Hb84	Sp11Sp14	8%	>1200	600	200	400	29	38	10	8	62	54	1.29	1.49	44
Hb84	Hu33Hu36Hu37	14%	>1200	600	200	400	20	33	10	9	70	58	1.30	1.49	149
Hb84	Fw30Fw31	4%	>1200	600	200	400	8	12	21	20	71	68	1.26	1.46	26
Hb84	Ct11Ct14	6%	>1200	600	200	400	29	38	8	6	64	56	1.29	1.48	118
Ia91	R	3%													
Ia91	Du10	4%	900>1200	1050	350	700	54	66	10	8	36	26	1.26	1.46	26
Ia91	Oa26Oa30Oa31Oa36Oa43Oa46	58%	900>1200	1050	350	700	11	20	9	8	81	72	1.31	1.50	130
Ia91	Vf10Vf13	2%	900>1200	1050	350	700	29	38	10	8	62	54	1.29	1.49	44
Ia91	We11We21	2%	300-600	450	200	250	8	12	21	20	71	68	1.26	1.46	26
Ia91	Lo10Lo11	2%	900>1200	1050	350	700	5	8	15	14	80	78	1.29	1.49	44
Ia91	Cv30Cv33Cv40Cv43	0%	900>1200	1050	350	700	5	8	15	14	80	78	1.29	1.49	44
Ia91	Cv30Cv33Cv40Cv43	3%	900>1200	1050	350	700	5	8	15	14	80	78	1.29	1.49	44
Ia91	Sw11Sw21Sw31	0%	600-900	750	250	500	36	54	3	2	61	44	1.32	1.50	210

Table A4: Continue

Land type	Soil family		Depth (mm)				Clay (Avg%)		Silt (Avg%)		Sand (Avg%)		Bulk density (Avg)		SHC
			Given	Total	Top	Sub	Top	Sub	Top	Sub	Top	Sub	Top	Sub	
Ia91	Ss16Ss26	1%	<300	250	200	50	25	40	4	3	71	57	1.32	1.50	210
Ia91	Ms10	2%	<300	250	200	50	54	66	2	2	44	32	1.32	1.50	210
Ia91	Fw11Fw20	6%	>1200	600	200	400	8	12	21	20	71	68	1.26	1.46	26
Ia91	Gs16Gs26	0%	<300	250	200	50	14	7	5	5	81	88	1.32	1.50	210
Ia91	Hu36Hu37Hu47	2%	300-1200	750	250	500	30	47	4	3	67	50	1.32	1.50	210
Ia91	Hu36Hu37Hu47	8%	300-1200	750	250	500	30	47	4	3	67	50	1.32	1.50	210
Ia91	T	6%		250	200	50									
Ia91	S	1%		250	200	50									
Ib63	R	67%													
Ib63	Ms10	2%	<200	250	200	50	54	66	2	2	44	32	1.32	1.50	210
Ib63	Gs10Gs13	3%	<200	250	200	50	6.5	3	15	15	79	81	1.29	1.49	44
Ib63	Cf10Cf20Cf30	15%	200-300	250	200	50	3	2	8	8	89	91	1.31	1.51	111
Ib63	Sw30Sw31	1%	250-300	275	200	75	27	44	4	3	70	53	1.32	1.50	210
Ib63	Es14Es21Es41	4%	300-450	375	200	175	5	27	13	10	82	63	1.29	1.49	49
Ib63	Hh20Hh31	1%	300-450	375	200	175	54	66	7	5	39	29	1.29	1.49	44
Ib63	Kd13Kd21Kd22	6%	300-600	450	200	250	13	31	10	8	77	61	1.30	1.49	149
Ib95	R	69%													
Ib95	Ms10	5%	<100	250	200	50	54	66	2	2	44	32	1.32	1.50	210
Ib95	Gs10Gs13	5%	<200	250	200	50	7	3	15	15	79	81	1.29	1.49	44

Table A4: Continue

Land type	Soil family		Depth (mm)				Clay (Avg%)		Silt (Avg%)		Sand (Avg%)		Bulk density (Avg)		SHC
			Given	Total	Top	Sub	Top	Sub	Top	Sub	Top	Sub	Top	Sub	
Ib95	Cf10Cf20Cf30	17%	<300	250	200	50	3	2	8	8	89	91	1.31	1.51	111
Ib95	Sw30Sw31	2%	300-450	375	200	175	27	44	4	3	70	53	1.32	1.50	210
Ib95	Es14Es21Es41	0%	300-450	375	200	175	5	27	13	10	82	63	1.29	1.49	49
Ib95	Hh20Hh30Hh31	2%	300-600	450	200	250	54	66	6	4	40	30	1.30	1.49	99
Ib95	Kd13Kd22	0%	600-900	750	250	500	7	27	13	11	81	63	1.29	1.48	118
Ib95	Oa34Oa36	0%	600-900	750	250	500	13	23	13	12	75	66	1.29	1.48	118
Ib96	R	67%													
Ib96	Ms10	2%	<200	250	200	50	54	66	2	2	44	32	1.32	1.50	210
Ib96	Gs10Gs13	3%	<200	250	200	50	7	3	15	15	79	81	1.29	1.49	44
Ib96	Cf10Cf20Cf30	15%	200-300	250	200	50	3	2	8	8	89	91	1.31	1.51	111
Ib96	Sw21Sw31	1%	<300	250	200	50	36	54	3	2	61	44	1.32	1.50	210
Ib96	Es14Es21Es41	4%	300-450	375	200	175	5	27	13	10	82	63	1.29	1.49	49
Ib96	Hh20Hh31	1%	300-450	375	200	175	54	66	7	5	39	29	1.29	1.49	44
Ib96	Kd21Kd22Kd13	6%	300-600	450	200	250	13	31	10	8	77	61	1.30	1.49	149
Ib96	Oa34Oa36Oa46	0%	600-900	750	250	500	14	26	10	9	76	65	1.30	1.49	149
Ib96	Du10	0%	600-900	750	250	500	54	66	10	8	36	26	1.26	1.46	26
Ib97	R	67%													
Ib97	Ms10	2%	<200	250	200	50	54	66	2	2	44	32	1.32	1.50	210
Ib97	Gs10Gs13	3%	<200	250	200	50	7	3	15	15	79	81	1.29	1.49	44

Table A4: Continue

Land type	Soil family		Depth (mm)				Clay (Avg%)		Silt (Avg%)		Sand (Avg%)		Bulk density (Avg)		SHC
			Given	Total	Top	Sub	Top	Sub	Top	Sub	Top	Sub	Top	Sub	
Ib97	Cf10Cf20Cf30	15%	200-300	250	200	50	3	2	8	8	89	91	1.31	1.51	111
Ib97	Sw21Sw31	1%	<300	250	200	50	36	54	3	2	61	44	1.32	1.50	210
Ib97	Es14Es21Es41	4%	300-450	375	200	175	5	27	13	10	82	63	1.29	1.49	49
Ib97	Hh20Hh31	1%	300-500	400	200	200	54	66	7	5	39	29	1.29	1.49	44
Ib97	Kd21Kd22Kd13	6%	300-600	450	200	250	13	31	10	8	77	61	1.30	1.49	149
Ib97	Oa34Oa36	0%	600-900	750	250	500	13	23	13	12	75	66	1.29	1.48	118
Ib97	Du10	0%	600-900	750	250	500	54	66	10	8	36	26	1.26	1.46	26
Ae199	R	3%													
Ae199	Ms10	8%	<300	250	200	50	54	66	2	2	44	32	1.32	1.50	210
Ae199	Gs13Gs16	11%	<300	250	200	50	18	9	12	13	70	78	1.29	1.48	118
Ae199	Hu36Hu37Hu46Hu47	56%	450-1200	825	275	550	27	44	4	3	70	53	1.32	1.50	210
Ae199	Sw11Sw21	5%	450-600	525	200	325	36	54	3	2	61	44	1.32	1.50	210
Ae199	Sw11Sw21	0%	450-600	525	200	325	36	54	3	2	61	44	1.32	1.50	210
Ae199	Va21Va41	4%	600-900	750	250	500	36	54	3	2	61	44	1.32	1.50	210
Ae199	Sd31	5%	600-1200	900	300	600	36	54	3	2	61	44	1.32	1.50	210
Ae199	Oa26Oa36Oa37Oa46	4%	600-1200	900	300	600	22	38	4	3	74	58	1.32	1.50	210
Ae199	Du10	3%	600-900	750	250	500	54	66	10	8	36	26	1.26	1.46	26
Ae199	Ss16Ss26	2%	300-600	450	200	250	25	40	4	3	71	57	1.32	1.50	210

Table A4: Continue

Land type	Soil family		Depth (mm)				Clay (Avg%)		Silt (Avg%)		Sand (Avg%)		Bulk density (Avg)		SHC
			Given	Total	Top	Sub	Top	Sub	Top	Sub	Top	Sub	Top	Sub	
Ae200	Hu36Hu37Hu44Hu46Hu47	51%	600-1200	900	300	600	23	37	7	6	70	56	1.31	1.49	173
Ae200	Sd31	12%	600-1200	900	300	600	36	54	3	2	61	44	1.32	1.50	210
Ae200	Sw11Sw21	9%	600-900	750	250	500	36	54	3	2	61	44	1.32	1.50	210
Ae200	Va21Va41	7%	300-600	450	200	250	36	54	3	2	61	44	1.32	1.50	210
Ae200	Oa26Oa46	20%	900-1200	1050	350	700	17	33	5	4	78	63	1.32	1.50	210
Ae200	Du10	2%	900-1200	1050	350	700	54	66	10	8	36	26	1.26	1.46	26
Ah60	Ms22	6%	100-250	250	200	50	54	66	2	2	44	32	1.32	1.50	210
Ah60	Hu33Hu36Hu43Hu46	63%	800>1200	1000	333	667	13	23	13	12	75	66	1.29	1.48	118
Ah60	Fw20	4%	>1200	600	200	400	8	12	21	20	71	68	1.26	1.46	26
Ah60	Cv30Cv40	27%	800>1200	1000	333	667	2	4	9	9	89	87	1.31	1.51	61
Bb82	R	46%													
Bb82	Cf20Cf21	38%	150-350	250	200	50	7	3	15	15	79	81	1.29	1.49	44
Bb82	Lo21Lo22	7%	500-800	650	217	433	13	23	13	12	75	66	1.29	1.48	118
Bb82	Lo21Lo22	4%	500-800	650	217	433	13	23	13	12	75	66	1.29	1.48	118
Bb82	Kd14Kd17	4%	600-900	750	250	500	14	29	13	11	73	60	1.29	1.48	118
Bb82	Fw31	2%	>1200	600	200	400	8	12	21	20	71	68	1.26	1.46	26
Bb84	R	19%													
Bb84	Cf20Cf21Cf22	37%	50-450	250	200	50	13	6	11	12	76	82	1.30	1.49	99
Bb84	Cf20Cf21Cf22	1%	50-450	250	200	50	13	6	11	12	76	82	1.30	1.49	99

Table A4: Continue

Land type	Soil family		Depth (mm)				Clay (Avg%)		Silt (Avg%)		Sand (Avg%)		Bulk density (Avg)		SHC
			Given	Total	Top	Sub	Top	Sub	Top	Sub	Top	Sub	Top	Sub	
Bb84	Lo20Lo21	7%	150-450	300	200	100	5	8	15	14	80	78	1.29	1.49	44
Bb84	Lo20Lo21	5%	150-450	300	200	100	5	8	15	14	80	78	1.29	1.49	44
Bb84	Wa20Wa21	20%	100-800	450	200	250	54	66	3	2	43	32	1.32	1.51	136
Bb84	Wa20Wa21	8%	100-800	450	200	250	54	66	3	2	43	32	1.32	1.51	136
Bb84	Ct11	2%	1000>1200	1100	367	733	3	10	5	5	92	85	1.32	1.50	210
Bb84	Fw31	3%	>1200	600	200	400	8	12	21	20	71	68	1.26	1.46	26
Bb84	Du10	1%	>1200	600	200	400	54	66	10	8	36	26	1.26	1.46	26
Bb85	Ms10	3%	100-250	250	200	50	54	66	2	2	44	32	1.32	1.50	210
Bb85	Cf12Cf21Cf22	10%	100-300	250	200	50	20	10	10	10	70	80	1.30	1.49	149
Bb85	We12We13We21	4%	100-300	250	200	50	20	33	10	9	70	58	1.30	1.49	149
Bb85	Gs19Gs16	5%	150-250	250	200	50	35	18	10	14	55	69	1.27	1.44	105
Bb85	Hu36Hu26Hu37	4%	200-500	350	200	150	23	40	4	3	73	57	1.32	1.50	210
Bb85	Hu36Hu26Hu37	1%	200-600	400	200	200	23	40	4	3	73	57	1.32	1.50	210
Bb85	Lo12Lo13Lo21Lo22	25%	200-500	350	200	150	20	33	8	7	72	60	1.31	1.49	164
Bb85	Lo12Lo13Lo21Lo22	2%	200-500	350	200	150	20	33	8	7	72	60	1.31	1.49	164
Bb85	Sw11Sw12Sw31	2%	300-500	400	200	200	42	58	7	5	51	37	1.29	1.46	140
Bb85	Va11	3%	300-500	400	200	200	36	54	3	2	61	44	1.32	1.50	210
Bb85	Kd16Kd14Kd13Kd20	3%	400-600	500	200	300	16	31	13	11	72	59	1.29	1.48	118
Bb85	Oa16Oa17Oa36Oa37	32%	500>1200	850	283	567	27	44	4	3	70	53	1.32	1.50	210

Table A4: Continue

Land type	**Soil family**		**Depth (mm)**				**Clay (Avg%)**		**Silt (Avg%)**		**Sand (Avg%)**		**Bulk density (Avg)**		**SHC**
			Given	**Total**	**Top**	**Sub**	**Top**	**Sub**	**Top**	**Sub**	**Top**	**Sub**	**Top**	**Sub**	
Bb85	Du10	9%	>1200	600	200	400	54	66	10	8	36	26	1.26	1.46	26
Bb86	Cf12Cf21	35%	20-150	250	200	50	18	9	12	13	70	78	1.29	1.48	118
Bb86	Ms10	35%	20-180	250	200	50	54	66	2	2	44	32	1.32	1.50	210
Bb86	Lo12Lo21	12%	300-500	400	200	200	13	23	13	12	75	66	1.29	1.48	118
Bb86	Wa12	9%	300-500	400	200	200	54	66	2	2	44	32	1.32	1.50	210
Bb86	Kd16	2%	300-600	450	200	250	25	40	4	3	71	57	1.32	1.50	210
Bb86	Lt14	8%	800>1200	1000	333	667	54	66	10	8	36	26	1.26	1.46	26
Ca87	R	12%													
Ca87	Ms10	11%	50-300	250	200	50	54	66	2	2	44	32	1.32	1.50	210
Ca87	Cf12Cf21	20%	50-300	250	200	50	18	9	12	13	70	78	1.29	1.48	118
Ca87	Gs19	4%	150-250	250	200	50	45	23	16	23	39	55	1.22	1.37	1
Ca87	Lo20Lo22	10%	400-800	600	200	400	10	19	7	6	84	75	1.32	1.51	136
Ca87	Es16	5%	600-800	700	233	467	25	40	4	3	71	57	1.32	1.50	210
Ca87	Kd17	1%	600-800	700	233	467	25	40	4	3	71	57	1.32	1.50	210
Ca87	Sw11	9%	600-900	750	250	500	36	54	3	2	61	44	1.32	1.50	210
Ca87	Va11	5%	600-900	750	250	500	36	54	3	2	61	44	1.32	1.50	210
Ca87	Oa16Oa17	23%	>1200	600	200	400	27	44	4	3	70	53	1.32	1.50	210
Ca87	Fw31	2%	>1200	600	200	400	8	12	21	20	71	68	1.26	1.46	26

Table A4: Continue

Land type	Soil family		Depth (mm)				Clay (Avg%)		Silt (Avg%)		Sand (Avg%)		Bulk density (Avg)		SHC
			Given	Total	Top	Sub	Top	Sub	Top	Sub	Top	Sub	Top	Sub	
Ca88	R	6%													
Ca88	Cf20Cf21	20%	150-250	250	200	50	7	3	15	15	79	81	1.29	1.49	44
Ca88	Cf20Cf21	2%	150-250	250	200	50	7	3	15	15	79	81	1.29	1.49	44
Ca88	Lo20Lo21	10%	250-350	300	200	100	5	8	15	14	80	78	1.29	1.49	44
Ca88	Lo20Lo21	3%	250-350	300	200	100	5	8	15	14	80	78	1.29	1.49	44
Ca88	Wa20Wa21	6%	250-600	425	200	225	54	66	3	2	43	32	1.32	1.51	136
Ca88	Kd11Kd14Kd17Kd21	20%	400-800	600	200	400	14	29	10	8	76	63	1.30	1.49	127
Ca88	Ct10Ct11	10%	>1200	600	200	400	3	10	7	7	90	83	1.32	1.51	136
Ca88	Fw31	26%	>1200	600	200	400	8	12	21	20	71	68	1.26	1.46	26
Db160	Cf20Cf21	10%	50-150	250	200	50	7	3	15	15	79	81	1.29	1.49	44
Db160	Es41	5%	150-250	250	200	50	3	28	9	7	88	65	1.31	1.51	61
Db160	Lo10Lo20Lo21Av30	5%	450-900	675	225	450	4	6	12	12	85	82	1.30	1.50	52
Db160	Kd14Kd20Kd21Kd13	74%	700-1000	850	283	567	16	31	13	11	72	59	1.29	1.48	118
Db160	Fw31	6%	>1200	600	200	400	8	12	21	20	71	68	1.26	1.46	26
Fa250	R	8%													
Fa250	Cf21	64%	50-250	250	200	50	10	5	21	22	69	73	1.26	1.46	26
Fa250	Ms10	3%	50-250	250	200	50	54	66	2	2	44	32	1.32	1.50	210
Fa250	Kd14	5%	400-600	500	200	300	3	18	22	19	75	63	1.26	1.46	26
Fa250	Wa21	1%	400-800	600	200	400	54	66	2	2	44	32	1.32	1.50	210

Table A4: Continue

Land type	Soil family		Depth (mm)				Clay (Avg%)		Silt (Avg%)		Sand (Avg%)		Bulk density (Avg)		SHC
			Given	Total	Top	Sub	Top	Sub	Top	Sub	Top	Sub	Top	Sub	
Fa250	Lo21	15%	>1200	600	200	400	8	12	21	20	71	68	1.26	1.46	26
Fa250	Vf24	4%	>1200	600	200	400	10	25	29	24	61	51	1.22	1.41	2
Fa250	Fw31	0%	>1200	600	200	400	8	12	21	20	71	68	1.26	1.46	26
Fa250	Du10	0%	>1200	600	200	400	54	66	10	8	36	26	1.26	1.46	26
Fa251	R	23%													
Fa251	Ms10	23%	50-100	250	200	50	54	66	2	2	44	32	1.32	1.50	210
Fa251	Cf21	41%	50-250	250	200	50	10	5	21	22	69	73	1.26	1.46	26
Fa251	Kd14	3%	500-600	550	200	350	3	18	22	19	75	63	1.26	1.46	26
Fa251	Es14	1%	500-600	550	200	350	10	25	21	17	69	58	1.26	1.46	26
Fa251	Lo21Lo22	7%	500-800	650	217	433	13	23	13	12	75	66	1.29	1.48	118
Fa251	Oa36	4%	>1200	600	200	400	17	33	5	4	78	63	1.32	1.50	210
Fa252	R	40%													
Fa252	Ms10	9%	100-250	250	200	50	54	66	2	2	44	32	1.32	1.50	210
Fa252	Cf11Cf21	38%	100-450	275	200	75	10	5	21	22	69	73	1.26	1.46	26
Fa252	Cf11Cf21	6%	100-450	275	200	75	10	5	21	22	69	73	1.26	1.46	26
Fa252	Lo22	0%	250-650	450	200	250	17	33	5	4	78	63	1.32	1.50	210
Fa252	Ct11	4%	>1200	600	200	400	3	10	5	5	92	85	1.32	1.50	210
Fa252	Fw31	3%	>1200	600	200	400	8	12	21	20	71	68	1.26	1.46	26

Table A4: Continue

Land type	Soil family		Depth (mm)				Clay (Avg%)		Silt (Avg%)		Sand (Avg%)		Bulk density (Avg)		SHC
			Given	Total	Top	Sub	Top	Sub	Top	Sub	Top	Sub	Top	Sub	
Fa253	R	2%													
Fa253	Ms10	0%	50-200	250	200	50	54	66	2	2	44	32	1.32	1.50	210
Fa253	Cf12Cf21	93%	50-200	250	200	50	18	9	12	13	70	78	1.29	1.48	118
Fa253	Lo12Lo21	5%	150-200	250	200	50	13	23	13	12	75	66	1.29	1.48	118
Fa254	R	2%													
Fa254	Ms10	1%	50-250	250	200	50	54	66	2	2	44	32	1.32	1.50	210
Fa254	Cf12Cf21	61%	50-250	250	200	50	18	9	12	13	70	78	1.29	1.48	118
Fa254	Cf12Cf21	4%	50-250	250	200	50	18	9	12	13	70	78	1.29	1.48	118
Fa254	Wa12	1%	200-300	250	200	50	54	66	2	2	44	32	1.32	1.50	210
Fa254	Lo12Lo21	9%	200-600	400	200	200	13	23	13	12	75	66	1.29	1.48	118
Fa254	Ct24	6%	1000>1200	1100	367	733	10	25	5	4	85	71	1.32	1.50	210
Fa254	Kd16	11%	1000-1100	1050	350	700	25	40	4	3	71	57	1.32	1.50	210
Fa254	Fw31	6%	>1200	600	200	400	8	12	21	20	71	68	1.26	1.46	26
Fa256	R	23%													
Fa256	Ms10	23%	50-100	250	200	50	54	66	2	2	44	32	1.32	1.50	210
Fa256	Cf21	41%	50-250	250	200	50	10	5	21	22	69	73	1.26	1.46	26
Fa256	Kd14	3%	500-600	550	200	350	3	18	22	19	75	63	1.26	1.46	26
Fa256	Es14	1%	500-600	550	200	350	10	25	21	17	69	58	1.26	1.46	26
Fa256	Lo21Lo22	7%	500-800	650	217	433	13	23	13	12	75	66	1.29	1.48	118

Table A4: Continue

Land type	**Soil family**		**Depth (mm)**				**Clay (Avg%)**		**Silt (Avg%)**		**Sand (Avg%)**		**Bulk density (Avg)**		**SHC**
			Given	**Total**	**Top**	**Sub**	**Top**	**Sub**	**Top**	**Sub**	**Top**	**Sub**	**Top**	**Sub**	
Fa256	Oa36	4%	>1200	600	200	400	17	33	5	4	78	63	1.32	1.50	210
Fa260	R	20%													
Fa260	Ms10	6%	<300	250	200	50	54	66	2	2	44	32	1.32	1.50	210
Fa260	Cf10Cf20	27%	300-450	375	200	175	3	2	9	9	88	90	1.31	1.51	61
Fa260	Kd10Kd20Kd21	14%	600-1200	900	300	600	18	33	6	5	77	63	1.32	1.50	160
Fa260	Es20Es21	5%	300-400	350	200	150	3	28	9	7	88	65	1.31	1.51	61
Fa260	Sw31	5%	300-600	450	200	250	36	54	3	2	61	44	1.32	1.50	210
Fa260	Ct10Ct20Ct21Ct23Ct24	12%	600-1200	900	300	600	6	19	10	9	84	72	1.30	1.50	84
Fa260	Ct10Ct20Ct21Ct23Ct24	1%	600-1200	900	300	600	6	19	10	9	84	72	1.30	1.50	84
Fa260	Sp10Sp13	2%	600-1200	900	300	600	29	38	10	8	62	54	1.29	1.49	44
Fa260	Av33Av36	2%	600-1200	900	300	600	13	23	13	12	75	66	1.29	1.48	118
Fa260	Av33Av36	0%	600-1200	900	300	600	13	23	13	12	75	66	1.29	1.48	118
Fa260	Pn33Pn36	2%	600-1200	900	300	600	13	23	13	12	75	66	1.29	1.48	118
Fa260	Pn33Pn36	0%	600-1200	900	300	600	13	23	13	12	75	66	1.29	1.48	118
Fa260	Cv30Cv33	2%	600-1200	900	300	600	5	8	15	14	80	78	1.29	1.49	44
Fa260	Hu30Hu33Hu36	2%	600-1200	900	300	600	9	16	11	11	80	73	1.30	1.49	99
Fa260	Hu30Hu33Hu36	1%	600-1200	900	300	600	9	16	11	11	80	73	1.30	1.49	99
Fa260	Oa33	1%	600-1200	900	300	600	8	12	21	20	71	68	1.26	1.46	26
Fa260	Vf10	2%	600-1200	900	300	600	3	10	9	8	88	82	1.31	1.51	61

Table A4: Continue

Land type	Soil family		Depth (mm)				Clay (Avg%)		Silt (Avg%)		Sand (Avg%)		Bulk density (Avg)		SHC
			Given	Total	Top	Sub	Top	Sub	Top	Sub	Top	Sub	Top	Sub	
Fa260	Ch10	0%	600-1200	900	300	600	54	66	10	8	36	26	1.26	1.46	26
Fa260	Du10	1%	600-1200	900	300	600	54	66	10	8	36	26	1.26	1.46	26
Fa261	R	25%													
Fa261	Ms10	6%	<300	250	200	50	54	66	2	2	44	32	1.32	1.50	210
Fa261	Cf10Cf20Cf30	53%	<300	250	200	50	3	2	8	8	89	91	1.31	1.51	111
Fa261	Kd10Kd20Kd21Kd22	10%	300-600	450	200	250	14	32	6	4	80	64	1.32	1.50	173
Fa261	Es20Es21	3%	300-400	350	200	150	3	28	9	7	88	65	1.31	1.51	61
Fa261	Sw31	2%	300-400	350	200	150	36	54	3	2	61	44	1.32	1.50	210
Fa261	Vf10Vf11	0%	600-900	750	250	500	3	10	9	8	88	82	1.31	1.51	61
Fa261	Oa30Oa32Oa33	0%	600-900	750	250	500	4	7	12	11	84	82	1.30	1.49	99
Fa261	Du10	1%	600-1200	900	300	600	54	66	10	8	36	26	1.26	1.46	26
Fa262	R	49%													
Fa262	Ms10Ms13	6%	<250	250	200	50	54	66	2	2	44	32	1.32	1.50	210
Fa262	Cf10Cf20	26%	<350	250	200	50	3	2	9	9	88	90	1.31	1.51	61
Fa262	Gs13Gs14	6%	<350	250	200	50	10	5	21	22	69	73	1.26	1.46	26
Fa262	Es20Es21Es40Es41	3%	200-800	500	200	300	3	28	9	7	88	65	1.31	1.51	61
Fa262	Es20Es21Es40Es41	2%	200-800	500	200	300	3	28	9	7	88	65	1.31	1.51	61
Fa262	Kd13Kd14Kd20Kd21	3%	400-1000	700	233	467	16	31	13	11	72	59	1.29	1.48	118
Fa262	Kd13Kd14Kd20Kd21	3%	400-1000	700	233	467	16	31	13	11	72	59	1.29	1.48	118

Table A4: Continue

Land type	Soil family		Depth (mm)				Clay (Avg%)		Silt (Avg%)		Sand (Avg%)		Bulk density (Avg)		SHC
			Given	Total	Top	Sub	Top	Sub	Top	Sub	Top	Sub	Top	Sub	
Fa262	S	2%		250	200	50									
Fc377	R	20%													
Fc377	Ms10	20%	<300	250	200	50	54	66	2	2	44	32	1.32	1.50	210
Fc377	Gs13Gs16Gs26	36%	300-450	375	200	175	13	6	10	11	77	83	1.30	1.49	149
Fc377	Sw11Sw20Sw21Sw31	9%	300-600	450	200	250	31	49	4	3	65	48	1.32	1.50	210
Fc377	Sw11Sw20Sw21Sw31	2%	300-600	450	200	250	31	49	4	3	65	48	1.32	1.50	210
Fc377	Hu36Hu46	8%	600-900	750	250	500	17	33	5	4	78	63	1.32	1.50	210
Fc377	Oa26Oa46	4%	600-1200	900	300	600	17	33	5	4	78	63	1.32	1.50	210
Fc377	Va21Va41	1%	300-600	450	200	250	36	54	3	2	61	44	1.32	1.50	210
Fc377	Du10	0%	600-900	750	250	500	54	66	10	8	36	26	1.26	1.46	26
Fc378	Ms10Ms11	1%	50-150	250	200	50	54	66	2	2	44	32	1.32	1.50	210
Fc378	Cf12Cf20Cf21	36%	50-150	250	200	50	13	6	11	12	76	82	1.30	1.49	99
Fc378	Va21	4%	300-400	350	200	150	36	54	3	2	61	44	1.32	1.50	210
Fc378	Sw21	4%	300-400	350	200	150	36	54	3	2	61	44	1.32	1.50	210
Fc378	Es41	6%	400-500	450	200	250	3	28	9	7	88	65	1.31	1.51	61
Fc378	Kd14Kd21	10%	400-800	600	200	400	14	29	13	11	73	60	1.29	1.48	118
Fc378	Lo21	4%	400-800	600	200	400	8	12	21	20	71	68	1.26	1.46	26
Fc378	Hu33Hu36Hu43Hu46	19%	500>1200	850	283	567	13	23	13	12	75	66	1.29	1.48	118
Fc378	Hu33Hu36Hu43Hu46	5%	500>1200	850	283	567	13	23	13	12	75	66	1.29	1.48	118

Table A4: Continue

Land type	Soil family		Depth (mm)				Clay (Avg%)		Silt (Avg%)		Sand (Avg%)		Bulk density (Avg)		SHC
			Given	Total	Top	Sub	Top	Sub	Top	Sub	Top	Sub	Top	Sub	
Fc378	Oa16Oa26Oa33Oa36Oa43Oa46	6%	800>1200	1000	333	667	16	30	7	6	77	64	1.31	1.49	179
Fc378	Oa16Oa26Oa33Oa36Oa43Oa46	4%	800>1200	1000	333	667	16	30	7	6	77	64	1.31	1.49	179
Fc378	Sp11Sp13	4%	>1200	600	200	400	29	38	10	8	62	54	1.29	1.49	44
Fc379	Ms20Ms22	2%	150-250	250	200	50	54	66	2	2	44	32	1.32	1.50	210
Fc379	Gs16Gs19Gs26	2%	200-600	400	200	200	24	12	8	11	67	77	1.29	1.46	140
Fc379	Va21	4%	400-500	450	200	250	36	54	3	2	61	44	1.32	1.50	210
Fc379	Hu36	35%	400>1200	800	267	533	17	33	5	4	78	63	1.32	1.50	210
Fc379	Oa16Oa26	59%	1000>1200	1100	367	733	17	33	5	4	78	63	1.32	1.50	210

Table A5: Soil depth, particle distribution, Permanent wilting point (PWP), field capacity, available water (AW), bulk density and saturated hydraulic conductivity and soil erodibility factors for the land types in the Gamtoos catchment.

Land type	**Depth**		**Clay(%)**		**Silt(%)**		**Sand (%)**		**PWP**		**FC**		**AW**		**BD**		**SHC**	**USLE K**	
	Top	Sub	Top	Sub	Top	Sub	Top	Sub	Top	Sub	Top	Sub	Top	Sub	Top	Sub		Top	Sub
Hb83	200	400	6	9	17	16	77	74	0.102	0.112	0.224	0.234	0.123	0.122	1.277	1.477	38	0.154	0.156
Hb84	200	384	13	24	17	15	70	62	0.129	0.161	0.251	0.281	0.121	0.120	1.270	1.462	62	0.160	0.149
Ia91	337	635	15	25	9	9	75	66	0.109	0.143	0.231	0.264	0.122	0.121	1.301	1.492	121	0.132	0.130
Ib63	200	107	11	18	9	8	80	74	0.091	0.114	0.214	0.236	0.123	0.122	1.305	1.498	113	0.120	0.128
Ib95	200	74	16	19	8	8	76	73	0.106	0.115	0.228	0.237	0.122	0.122	1.309	1.500	121	0.123	0.125
Ib96	200	110	12	18	9	8	80	73	0.092	0.115	0.215	0.237	0.123	0.122	1.305	1.498	113	0.121	0.128
Ib97	200	111	12	18	9	8	80	73	0.092	0.115	0.215	0.237	0.123	0.122	1.305	1.498	112	0.121	0.128
Ae199	256	438	30	43	5	4	65	52	0.146	0.196	0.267	0.315	0.121	0.119	1.315	1.497	194	0.109	0.096
Ae200	300	591	26	41	6	5	68	54	0.135	0.191	0.256	0.310	0.121	0.119	1.313	1.495	188	0.116	0.101
Ah60	320	619	12	20	11	11	77	70	0.103	0.130	0.226	0.252	0.122	0.121	1.296	1.489	104	0.137	0.140
Bb82	207	171	8	9	14	14	77	76	0.100	0.104	0.223	0.227	0.123	0.122	1.285	1.483	63	0.146	0.148
Bb84	203	150	25	27	9	9	65	64	0.146	0.153	0.267	0.273	0.121	0.121	1.300	1.493	102	0.132	0.130
Bb85	226	290	28	39	7	6	65	55	0.147	0.186	0.268	0.305	0.121	0.119	1.304	1.487	164	0.121	0.111
Bb86	211	134	36	41	8	7	56	52	0.182	0.198	0.301	0.317	0.119	0.119	1.301	1.488	153	0.119	0.114
Ca87	210	284	28	35	7	7	66	58	0.146	0.175	0.266	0.294	0.121	0.120	1.307	1.489	167	0.121	0.115
Ca88	200	272	11	16	14	13	75	71	0.108	0.126	0.231	0.248	0.122	0.122	1.287	1.483	71	0.148	0.149
Db160	263	474	13	25	13	11	74	63	0.114	0.155	0.236	0.276	0.122	0.120	1.289	1.482	99	0.147	0.139
Fa250	200	140	11	10	20	20	68	69	0.134	0.132	0.256	0.253	0.121	0.121	1.261	1.460	33	0.168	0.169
Fa251	201	113	23	26	14	14	63	60	0.155	0.168	0.276	0.288	0.120	0.120	1.283	1.475	96	0.147	0.145

Table A5: Continue

Land type	Depth		Clay(%)		Silt(%)		Sand (%)		PWP		FC		AW		BD		SHC	USLE K	
Fa252	200	110	16	15	17	17	67	68	0.139	0.137	0.260	0.258	0.121	0.121	1.274	1.469	67	0.159	0.161
Fa253	200	50	17	10	12	13	70	77	0.127	0.100	0.249	0.223	0.122	0.123	1.290	1.480	118	0.145	0.142
Fa254	227	198	18	16	11	12	71	73	0.124	0.119	0.246	0.240	0.122	0.122	1.294	1.483	130	0.142	0.142
Fa256	201	113	23	26	14	14	63	60	0.155	0.168	0.276	0.288	0.120	0.120	1.283	1.475	96	0.147	0.145
Fa260	248	375	13	22	8	8	78	70	0.096	0.127	0.219	0.249	0.123	0.122	1.308	1.502	103	0.121	0.126
Fa261	201	90	10	14	7	7	83	80	0.078	0.091	0.201	0.214	0.123	0.123	1.314	1.505	127	0.103	0.111
Fa262	212	127	12	16	10	10	78	74	0.096	0.112	0.219	0.234	0.123	0.122	1.302	1.499	81	0.128	0.133
Fc377	211	213	26	32	6	6	67	62	0.139	0.159	0.261	0.279	0.121	0.120	1.311	1.494	182	0.119	0.115
Fc378	232	309	15	21	11	10	74	69	0.113	0.134	0.235	0.255	0.122	0.121	1.296	1.487	114	0.139	0.138
Fc379	321	628	18	34	4	4	77	62	0.101	0.158	0.224	0.278	0.123	0.120	1.320	1.499	209	0.103	0.098

APPENDIX B

WXGEN INPUT PARAMETERS

Table B1: WXGEN input parameters based on weather data from Patensie weather station.

	Temperature				Precipitation							SOLAR	DEWPT	Wind
	Max	**Min**	**STD(Max)**	**STD(Min)**	**Total**	**STD**	**Skew**	**Prob(dry)**	**Prob(wet)**	**Days**	**Max(hour)**			
Jan	29.06	16.86	4.60	2.85	37.37	34.60	0.98	0.08	0.28	3.31				2.48
Feb	29.38	17.31	4.78	2.95	37.98	30.89	1.04	0.12	0.33	4.31				2.30
Mar	28.09	16.04	4.85	2.77	44.62	72.24	3.74	0.12	0.36	4.54				2.06
Apr	25.78	12.96	5.21	3.28	34.10	36.35	1.14	0.09	0.35	3.50				1.86
May	23.95	10.04	3.98	3.11	18.16	23.75	2.31	0.06	0.31	2.46				1.82
Jun	22.07	7.67	3.78	3.47	21.39	27.47	1.81	0.06	0.33	2.46				2.02
Jul	21.71	6.92	4.10	3.72	21.37	30.24	2.67	0.04	0.42	2.00				2.03
Aug	22.26	8.05	4.68	3.50	38.12	46.71	1.95	0.10	0.31	3.81				2.01
Sep	23.74	10.08	5.10	3.04	23.61	27.17	1.80	0.08	0.39	3.23				2.15
Oct	25.14	11.93	5.37	3.11	38.87	41.69	1.09	0.10	0.42	4.42				2.40
Nov	26.28	13.79	5.02	3.14	41.95	54.82	2.10	0.10	0.38	4.23				2.49
Dec	27.93	15.90	4.71	2.98	34.47	32.95	0.94	0.10	0.35	4.19				2.52