ORASECOM Document No. 006/2010

SUPPORT TO PHASE 2 OF THE ORASECOM BASIN-WIDE INTEGRATED WATER RESOURCES MANAGEMENT PLAN

Work Package 3:

Integrated Water Resources Quality Management Plan

Development of Specifications for the Water Quality Model

December 2010

ORASECOM

The *Support to Phase 2 of the ORASECOM Basin-wide Integrated Water Resources Management Plan* Study was commissioned by the Secretariat of the Orange-Senqu River Basin Commission (ORASECOM) with technical and financial support from the German Federal Ministry for Economic Cooperation and Development (BMZ) in delegated cooperation with the UK Department for International Development (DFID) and the Australian Agency for International Development (AusAID). The Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) implemented the study.

giz | On behalf of Federal Republic of Germany The Federal Government | UKaid from the Department for International Development | Australian AID

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ORASECOM Document No.	006/2010
Date of Publication:	December 2010
Authors:	Chris Herold
Status:	Final Report

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Study Name	**Support to Phase 2 of the ORASECOM Basin-wide Integrated Water resources Management Plan**		
Report Title:	***Development of Specifications for the Water Quality Model***		
Submitted by:	WRP Consulting Engineers in association with Golder Associates, DMM, PIK, RAMBOLL and WCE		
REPORTS, WPS AND OTHER DELIVERABLES SUBMITTED		**TYPE**	**No.**
Overall Study			
	Inception Report	Report	004/2010
	Overall Project Executive Summary	Report	013/2011
Work Package 1: WATER RESOURCES MODELLING OF THE ORANGE-SENQU BASIN			
	Strengths and Weaknesses of Existing Models	WP	005/2010
	Setting up and Testing of the Final Extended and Expanded Models; Changes in Catchment Yields and Review of Water Balance	Report & WP	001/2011
	Modelling software and datasets	Software	None
	Capacity Building and Setting up the Models in each Country; Process of Continuous Review	WP	003/2011
Work Package 2: EXTENSION AND EXPANSION OF HYDROLOGY OF ORANGE-SENQU BASIN			
	Improvements to Gauging Network and Review of Existing Data Acquisition Systems	WP	005/2011
	Extension of Hydrological Records	Report	006/2011
	Hydrological Database	Database	None
Work Package 3: INTEGRATED WATER RESOURCES QUALITY MANAGEMENT PLAN			
	Development of Water Quality Monitoring programme and Data Management Framework	Report	007/2011
	Development of Specifications for the Water Quality Model	***WP***	***006/2010***
Work Package 4: CLIMATE CHANGE IN THE ORANGE-SENQU RIVER BASIN			
	Downscaling Methodology and Ongoing Climate Modelling Initiatives	WP	007/2010
	GCC Downscaling for the Orange-Senqu River Basin	Report	008/2011
	Projection of impacts and Guidelines on Climate Change Adaptation Strategies	WP	009/2011
Work Package 5: ASSESSMENT OF ENVIORNMENTAL FLOW REQUIREMENTS			
	Literature survey and Gap Analysis	WP	008/2010
	Delineation of Management Resource Units	WP	009/2010
	Desktop Eco Classification Assessment	Report	016/2010
	Goods and Services Report	WP	010/2010
	Environmental Flow Requirements	Report	010/2011
Work Package 6: WATER CONSERVATION AND WATER DEMAND IN THE IRRIGATION SECTOR			
	The Promotion of WC WDM in the Irrigation Sector	Report	011/2011
	Irrigation GIS Database, Interactive Database and Irrigation Scenario Tools	WP	012/2011
	Irrigation GIS Database and Interactive Classification Tool	Software	None
	Irrigation Scenario Generation Tool	Software	None

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1 INTRODUCTION

1.1 Background and Motivation

South Africa is a water scarce country that is prone to prolonged droughts. This has led to the development of a large number of large dams interlinked in intricate inter-basin transfer systems. Planning and optimisation of these systems has led to the development of sophisticated water resource models, culminating in the Water Resources Yield Model (WRYM) and the Water Resource Planning Model (WRPM) that have been successfully applied for a number of years.

However, a water resource that is too polluted to use is almost as limiting as having no water at all. It is therefore imperative to manage water quality, as well as water quantity.

Water scarcity and aridity has, combined with burgeoning industrial, mining and population growth spawned intensifying water quality problems. From the early 1980s (Herold, 1981a,b,c) hydro-salinity models have been developed and applied to deal with the acute problems that were apparent in the Vaal River System.

The salinity models have been successfully applied in managing the salinity related aspects of water quality in the Vaal River System.

The management of nutrients is the next modelling challenge facing the Orange River Basin. Although nutrient models have been applied to sectors of the Vaal River, there is a need for a planning level nutrient model which can be applied to develop nutrient management strategies for the basin.

1.2 Model Requirements

The roles of water quality models can be divided into the following categories:

- Planning;
- Operation;
- Pollution control; and
- Reservoir dynamics.

1.2.1 Planning

By its nature, the planning process needs to focus on those water quality variables that have the greatest influence on water resource planning, rather than those that only have a peripheral influence. Since water resource planning is already computer intensive, requiring iterative solution of the entire complex system to cover a wide range of climatic conditions. It is therefore desirable to keep water quality modelling requirements to the minimum required to reasonably describe cause-effect relationships and estimate the magnitude of ensuing concentrations.

The water quality variables of concern that commonly affect (or should affect) the large scale water resource planning process in the Southern African context include:-

- Salinity; and
- Eutrophication (as driven by nutrients).

In this regard **salinity** is recognised as an important water quality problem facing South Africa. Salinity is especially significant, since much of the country is semi-arid and large salt-laden pollutant loads enter the system and are concentrated by cascading reuse down the river systems and evaporative concentration in irrigated lands and reservoirs. The Water Resources Planning Model (WRPM) (Van Rooyen, 2000) is used extensively by DWA to simulate the yield of river systems. This model has a powerful facility to simulate salinity in tandem with the water resources systems and has the unique capability to incorporate salinity related operating rules directly in the analyses. This is based on the algorithms of the WQT hydro-salinity model (Allen and Herold, 1988), which is used to calibrate the salinity model parameters. Hence, for the last quarter of a century, salinity has played an integral part in the planning and operation of the Vaal River System.

Eutrophication is now recognised as a critical water quality problem facing South African River systems, including the Orange River System. Many of the potential measures to control eutrophication hold water resources implications and it is therefore desirable to include eutrophication modelling in the system models. To date, such modelling has not been integrated into the DWA's WRPM. This is an important gap that needs to be filled.

A number of other water quality issues face South Africa, including bacterial and other biological contaminants, acid mine drainage (AMD), heavy metals, sediment, pesticides, biocides and radionuclides.

Bacterial pollution, often indicated by *E.coli*, poses a threat to human health, largely due to ineffective sewage treatment and diffuse sources from informal and formal settlements. Although the importance of bacterial pollution cannot be over-stated, it is recognised that its greatest influence is local, close to the pollution sources. Natural in-stream decay processes rapidly break down such pollution, with the result that on the catchment scale normally dealt with in water resource planning, it soon has little or no influence on downstream water quality. This is especially so in South Africa's shallow well aerated rivers and generally warm climate. The influence of bacterial pollution on water resource planning is limited, even close to pollution sources, since dilution has little effect on resource planning (for example, halving the concentration of contaminated water from 100 000 counts per 100 ml to 50 000 will still leave the water unfit to drink or use for contact recreation). Moreover, adequate water purification can still render the water safe for potable use. Finally, source control is undoubtedly the most effective and morally defensible remedy for dealing with bacteria pollution, rather than water resource planning.

Acid Mine Drainage imposes a severe local impact, and is associated with high heavy metal contamination and oxygen deficit. But after a short distance of travel, neutralisation occurs and the water ceases to be acidic, resulting in precipitation of the heavy metals. Re-aeration of the generally shallow streams, where AMD occurs, also rectifies the oxygen sag.

However, the high salinity does remain and strongly influences planning decisions throughout the downstream river system. Hence, at the planning scale, AMD is neutralised and manifests more as a salinity problem, for which tried and trusted planning tools are already in place.

While sediment definitely impairs storage capacity, it has previously proved adequate to make allowance for this separately in the design of dams.

Pesticides and biocides (along with a host of other organic pollutants) and radionuclides can pose significant problems. But they too, like biological contamination, tend to be local problems that either decay directly or mimic decay processes by being removed from the water column by various sedimentation processes. They are seldom amenable to flow regulation and in any event are best dealt with by source control rather than in-stream measures.

Hence, in the wider context of water resources planning there is little point in including more than salinity and eutrophication in the water resources planning models.

1.2.2 Operation

The main purpose of operational models is to facilitate optimal implementation of the water resource plans.

Similar criteria to those for planning apply when selecting water quality variables to be modelled. These should be confined to those most likely to be amenable to manipulation by flow.

In this context, any problematic variable can be diluted by releases of fresh water. This is particularly so for **salinity**, which is a persistent conservative pollutant. However, it is less appropriate for short lived non-conservative pollutants which are better dealt with as pollution control issues. There are also obvious constraints on the amount of fresh water that a water stressed country can afford to release, as conditions favouring options like the Gauteng salinity blending option are not common.

As for planning, **eutrophication** is another water quality problem that could benefit from operational control of water releases. Vaal Barrage and the Middle Vaal River down to Bloemhof Dam are examples of such areas. On the other hand, the severe eutrophication of Hartbeespoort Dam is essentially a pollution control issue that is not amenable to operational measures.

Whereas the WRPM model operates at a monthly time step, operational control of eutrophication in the Middle Vaal River would require a more complex, shorter time step daily dynamic model to take account of the detention time required to convert from nutrients to algae. The application of effective operational eutrophication models represents a gap that needs to be filled.

1.2.3 Pollution Control

Pollution control is an essential function that focuses on reducing pollution at source and, as such, is largely independent of the wider water resource planning and development.

In this context, the role of models is to assist in determining and enforcing waste disposal quality standards to meet in-stream water quality objectives. This involves quantifying pollution loads, testing the effectiveness of control strategies, setting in-stream water quality objectives, linking these to effluent discharge quality requirements, making waste load allocations, assessing permit applications and running waste discharge billing systems.

The emphasis is usually on smaller more developed catchments. Modelling requirements range between simple to use models, such as WQDOWN (Herold and Le Roux, 2010), to sift the effect of numerous permit applications and pollution control options, to a multiplicity of more detailed models, such as QUAL2K (Chapra and Pelletier, 2003), to carry out more rigorous evaluations.

The full range of water quality variables discussed in **Section 1.2.1** are relevant to pollution control and, depending on local conditions, may need to be modelled.

The range and types of water quality model needed to support pollution control are varied and site specific and it would therefore be difficult to be prescriptive and single out specific models. Nor is it relevant in the context of this report, which is aimed primarily at fulfilling the needs for water quality in the wider water resources context.

1.2.4 Reservoir Dynamics

Reservoir water quality is relevant to water resource planning and use. However, detailed reservoir dynamics models have been dealt with separately since they deal with complex and often poorly understood processes, are data intensive and require specialist input to calibrate and run. As such, these limnological models are not amenable to direct inclusion in resource planning or operational models. It must also be admitted that generally they do not display reliable prediction ability (Venter and Herold, 1999), which limits their applicability to water resource planning and operation.

Rather, such models are better suited to research type investigations aimed at gaining understanding of a particular problem or specialist studies to determine the likelihood of a proposed reservoir becoming eutrophic, locating intake towers and designing intake levels to minimise the abstraction of eutrophic water. There are many such models and little consensus on which are the best to use, since site specific topographical and other features often affect the choice.

While detailed reservoir dynamics models undoubtedly have a role to play, more simplified reservoir models are relevant to the water resources planning and operation.

1.3 Objectives

The intention of this report is not to assess the needs for pollution control models or detailed limnological models, but rather to concentrate on the water quality modelling needs for larger scale water resource planning and operation.

In this context, the two primary types of water variables that have been identified include salinity and eutrophication. Models addressing these two water quality problems are needed for planning and river system operation.

1.3.1 Planning Modelling

Salinity modelling has already been integrated with water resource planning in the WRPM. An important gap that needs to be filled is the inclusion of eutrophication modelling algorithms.

1.3.2 Operational Modelling

Salinity and eutrophication need to be integrated into water resources operational models. In the case of salinity, operational modelling needs to be focussed on the Gauteng blending and Vaal Barrage dilution options. Eutrophication modelling is required primarily for regulated river reaches, where the storage states of upstream and downstream dams, the incremental catchment yield and downstream water demands may present opportunities to change the timing and magnitude of releases from upstream dams without compromising system yield. Vaal Barrage and the Middle Vaal River are cases in point. Operational models can also be used to provide warning of unfavourable water quality conditions in a particular river reach

2 SALINITY MODELLING FOR PLANNING

2.1 Introduction

The WRPM incorporates salinity modelling algorithms that allow for the full integration of salinity-triggered operating rules in the water resources planning process. Salinity simulation is supported by the parameters prepared when calibrating the WQT hydro-salinity model. There is no need for further salinity modelling development, since improvements are continually made to WQT and WRPM as the need arises.

The structure and algorithms used in the WRPM are based on those used in the WQT model, hence only the latter model will be described.

2.2 General Description: WQT Model

WQT (Water Quality TDS) is a modular deterministic monthly time step hydro-salinity simulation model. The river system is configured as a series of nodes connected by routes (i.e. flow channels). Penalties are applied to each route to mimic system operating rules.

A versatile feature is that the model can accommodate feedback loops, whereby part of the salt-enriched effluent from a demand centre is returned to its own supply source. WQT is designed to operate seamlessly with the WRPM. As such, it is widely used in water resources planning studies.

WQT is structured to allow multiple cycles of model simulation, view graphs and statistics, adjust model parameters re-simulate and store results, without having to terminate the program and re-enter the input data. This makes it well suited to the calibration process.

A later development (Coleman and Van Rooyen, 2001) included a mining module, and the simulation of sulphate as well as TDS, including sulphate adsorption / desorption processes.

2.3 Model Nodes

The types of node include:

- Catchment Washoff (SW);
- Channel Reach (CR);
- Irrigation (RR);
- Reservoir (RV);
- Demand Centre (DC); and
- Junction (JN).

The **Catchment Washoff** module allows for the accumulation and washoff of conservative soluble pollutants from pervious and paved catchment surfaces, sub-surface storage effects and anthropogenic induced growth in diffuse source salt generation. This sub-model is based on a simplified monthly version (Herold, 1980) of the NACL01 daily time step model (Herold, 1981a), but has been adapted to allow it to use stochastically generated monthly inflow data as input. This is accomplished by using algorithms to split the specified monthly inflow time series into surface and sub-surface discharge components. Paved catchment areas at various dates can be specified with linear or exponential interpolation between the break point dates. Similarly growth in the catchment diffuse source salt generation rate can be specified through the calibration (or simulation) period.

Channel Reach modules can accommodate wetlands, seepage loss, input from upstream modules, point sources and riparian irrigation abstractions and return flows. Growth in wetland areas can be simulated.

Irrigation modules can be specified as riparian, in which case they do not have their own input and outflow routes, but are implicitly connected to a specified channel reach. Alternatively irrigation modules can be separate entities (i.e. nodes) with defined inflow and return flow routes originating from a Junction, Reservoir or Demand Centre node. Return flow is routed to a Channel, Junction or Reservoir node. The Irrigation node takes account of multiple cropping, irrigation efficiency, canal losses and sub-surface storage. Return flow is via direct spillage from canal ends and seepage from two sub-surface zones. Water and salt balances make allowance for both cropped and fallow areas, depending on supply water availability.

The **Reservoir** module allows for commissioning during the simulation period. Multiple dates can also be specified to define changes in reservoir storage capacity. A storage-area curve is specified. The model simulates the water and salt balance taking account of upstream inflow, rainfall and evaporation, abstractions, downstream water demand and spillage.

The **Demand Centre** sub-model simulates fluctuations in percentage effluent return flow driven by climatic change (i.e. net evaporation). The addition of salt load by users in demand centres is also simulated. The proportions of both water and salt discharged to each return flow route are defined. Allowance is also made for salts to be removed by a desalination plant.

Junction nodes are used to collect and mix inputs from upstream reaches and distribute them to abstractions and spillage via downstream routes.

The **Mining** module allows the simulation of both open cast and underground mines, including underground storage, reduction plants and surface pollution control dams.

The WRPM, which incorporates all of the above nodes, includes a **Blending Junction**, which allows simulation of the blending option, whereby raw water from two sources can be blended to prevent the salinity in supply exceeding a prescribed maximum. This option was instrumental in reducing mineralisation costs in the Gauteng region by hundreds of millions of Rands per annum. In times of water excess this option is superseded by the Vaal Barrage dilution option, which holds even greater economic benefit. WRPM also incorporates this option, switching back to blending during times of water stress. (WQT does not include these options, since it is intended for model calibration against observed historical data, for which operating rules are irrelevant.)

A **system command** file defines the system code, input and output directories, debug and summary file options, system nodes (in solution order), observation points and their flow and TDS / sulphate time series files and the routes and nodes where time series data is to be stored.

2.4 Model Routes

A **system network** file is used to define the simulation period, routing option, route and node connectivity, route costs and the summary elements to be written to file.

2.5 Input Data

The model requires parameter files for each node specified in the system layout. This includes both physical data and model parameter values. The input requirements are described in detail in (Allen and Herold, 1988; Coleman and Van Rooyen, 2000).

All of the above values can be entered via pre-prepared files. They can also be entered manually at run time via an interactive menu. Manually entered values can then be stored in files, which can subsequently be used as input to the model.

Time series data includes files of monthly catchment runoff for each Catchment Washoff module, monthly abstractions, monthly flow and TDS / sulphate concentration for external effluent sources and importation inputs, mine discharge, monthly rainfall (used in the Channel Reach, Irrigation, Reservoir and Demand Centre nodes) and data required by mining modules. Demand Centre nodes also require time series of monthly curtailment factors.

Calibration parameters can be changed, and graphical and tabular comparisons made between modelled and observed statistical values and mean monthly values.

2.6 Model Output

A summary file consisting of simulated monthly flows, concentrations and loads can also be generated. A debug file can also be generated.

A number of time series files are also generated. These include simulated monthly flows, TDS concentration and TDS loads in specified reaches. Monthly time series of Catchment Washoff module runoff volume and concentration, urban and pervious surface salt storage, groundwater salt storage; reservoir storage and deficit; irrigation supply and return flow volume, TDS concentration and TDS load and soil moisture storage depth and salt storage can also be stored.

Plots comparing modelled and observed flows, salt concentrations and loads, catchment surface and sub-surface salt storages, reservoir water and salt storages and irrigation storages can be generated. Tabular comparisons can also be made between modelled and observed statistical values and mean monthly values.

3 EUTROPHICATION MODELLING FOR PLANNING

3.1 Motivation

Increasing stress on water resources and catchment development has led to eutrophication steadily gaining in importance, as eutrophic conditions have degraded the quality of water stored in the reservoirs, such as Hartbeespoort Dam, Vaal Barrage and key river reaches, such as the Middle Vaal River between Vaal Barrage and Bloemhof Dam. However, to date, only ad hoc eutrophication modelling has been carried out. None of these models have been linked to system planning to facilitate simulation of eutrophication ameliorative measures. Such measures could vary between the introduction of nutrient controls at source and attempts to dilute or flush rivers.

3.2 Structure

It is proposed that the WRPM and the WQT calibration model provide the basic structure for the nutrient model. Furthermore, salinity and nutrient modelling should be carried out in tandem on a time-step by time-step basis to facilitate the simulation of operating rules that would simultaneously affect salinity and eutrophication. However, a switch should be included to switch off one or both of these water quality variables if so required.

The WQT model structure can be used to add nutrient modelling algorithms to all of the above nodes, routes, data import and export and plotting facilities.

Catchment phosphate export algorithms can be attached to the Salt Washoff module, making use of the simulated surface, sub-surface and paved surface flows. The Channel Reach module provides the river flows needed to drive nutrient river routing and the Reservoir module provides the hydraulic information required for nutrient processes. The Irrigation module provides return flows, to which nutrient values can be assigned and the Demand Centre module generates effluent discharges to which nutrient concentrations appropriate to the treatment of the effluent can be assigned. Nominal nutrient concentrations can be assigned to Mining module outputs. As for salts, the Junction Node module will simply keep a mass balance to mix and redistribute nutrients.

3.3 Choice of Variables

The primary drivers of eutrophication are nutrient enrichment and favourable light and temperature conditions.

In nearly all cases, phosphate is the limiting nutrient. Most troublesome algae can in any case fix nitrogen from the atmosphere. Climate is the driver of temperature and light and is not amenable to practical control. It follows that eutrophication control focuses on the reduction of phosphate concentrations. This is rendered even more plausible by the fact that phosphate is the one persistent nutrient added by anthropogenic point and diffuse sources. (Although human activities add large ammonia and nitrate loads, these soon decay in the natural aquatic environment.)

3.3.1 Phosphorus

Following the discussion above, phosphorus is the first choice of water quality variable required for modelling eutrophication.

Two species of phosphorus are relevant, namely the soluble (SP) and particulate (PP) forms. For a number of reasons SP is considered to have the greatest impact on eutrophication. Moreover, PP records at most sites (if they exist at all) are too short and erratic to provide a valid basis for model calibration.

3.3.2 Chlorophyll-a

One of the most serious manifestations of eutrophication is the proliferation of algal species, some of which are more damaging than others. However, it is considered impractical to develop an eutrophication planning model complex enough to differentiate between the growth of different algal species. Instead a much simpler model is sought. The modelling of chlorophyll-a is therefore deemed a suitable surrogate indicator.

3.4 Choice of Model

There are a number of eutrophication models of varying complexity available. However, few are dynamic and therefore suitable for simulating time series and most are much too complex and data-hungry to consider for large scale planning. It is also apparent that the increasing complexity of these models fails to yield a commensurate improvement in their prediction ability. Moreover, few are designed to operate at a monthly time step.

The dearth of available models that are suitable for planning purposes was also encountered by the Ninham Shand – GIBB consortium that developed the IMPAQ model for the Amatole Water Resources System Analysis (Bath, 1998). Examination of the results shows fits between modelled and observed phosphate and chlorophyll-a that are as good as many more sophisticated models and adequate for the purpose of providing usable indicators of the expected impacts.

IMPAQ is a monthly time step model that simulates TDS, suspended solids, phosphorus (soluble and particulate), chlorophyll-a (in impoundments) and E.coli. It takes account of catchment washoff from rural and urbanised areas, point sources, river transport and assimilation in reservoirs. Phosphate is modelled for all of the elements down to reservoirs and chlorophyll-a is simulated for reservoirs.

Although IMPAQ simulates PP, which it links to sediment processes, there is no provision for the conversion for phosphate from the particulate to the soluble form and only the soluble form is used in the conversion to chlorophyll-a. This is most fortuitous for the planning model that is sought, since it is not necessary to carry out the complex and somewhat data-hungry modelling that is required to simulate catchment sediment export.

The detachment of SP from PP is justified by Bath (1998) by the consideration that “at least 90% of the particulate phosphorus is part of the soil matrix (apatitic phosphorus) and is thus completely unavailable In terms of eutrophication. Even the remaining adsorbed phosphorus (about 5% to 10% of the particulate phosphorus) is unlikely to desorb except possibly under anaerobic conditions at the bottom of dams."

3.5 Algorithms

The algorithms used to include soluble phosphorus and chlorophyll-a in the WQT model (and hence the WRPM) are described in the following section. These are based largely on the modelling of these two variables in the IMPAQ model (Bath, 1998). For the sake of clarity variable names have been changed and minor typing errors have been corrected.

In each case the equations are identified with the WQT model nodes to which they will be added.

3.6 Washoff Module (SW)

Soluble phosphorus (SP) export will be addressed in the WQT's Salt Washoff (SW) module, which handles catchment runoff.

The IMPAQ model simulates export from both rural and urbanised surfaces. However, SP is assumed to be derived only from the rural portion of the catchment. The assumption is that the dry sediment accumulated on urban areas would contain particulate phosphorous, which is tracked separately through the receiving waters and ultimately to reservoirs.

The SW module reads in the monthly runoff volumes from both the paved and pervious portions of the catchment. In the case of WQT, these volumes are based on observed or hydrologically generated data. As used in the WRPM, these flows are stochastically generated. The SW module disaggregates the monthly input flows from the pervious portion of the catchment into a direct surface runoff component and a component passing through the sub-surface storage. This is necessary to facilitate salinity modelling, which tracks changes in the salt load stored in the soil. Since IMPAQ requires both surface and sub-surface runoff components, these same flow components are used in the SP export equations. (Indeed, the write up indicates that WQT's SW module algorithms are actually used in IMPAQ.)

One minor modification in the proposed model is that the urban runoff is added to the pervious surface runoff to derive the total surface runoff used in the following SP export equation. This has been done since IMPAQ does not allow for SP export from paved surfaces, which would lead to the anomalous situation that the SP export would decline as urbanisation increases.

The catchment SP export load is given as:

$$LSPW = (1/AREA)\cdot\sum_{i=1}^{NA}\{A_i\cdot(\alpha_i\cdot QG + \beta_i\cdot[QS + QU])\} \quad (3.1)$$

Where:

LSPW = Soluble phosphorus export load from catchment (t/month)

NA = Number of land use types (-)

A_i = Area of catchment covered by land use i (km^2)

α_i = Groundwater loading coefficient for land use i (mg/l)

QG = Sub-surface flow component of runoff from pervious surfaces as calculated by the SW module (10^6m^3/month)

β_i = Surface flow loading coefficient for land use i (mg/l)

QS = Surface flow component of runoff from pervious surfaces as calculated by the SW module (10^6m^3/month)

QU = Urban runoff component as used in the SW module (10^6m^3)

Table 3.1 gives the suggested SP loading functions derived from IMPAQ for different land uses:

Table 3.1: Soluble Phosphorus Loading Coefficients for Various Land Uses

Parameter	Grass(1)	Forest(2)	Farm(3)	Rural(4)
α (mg/l)	0.01	0.005	0.01	0.05
β (mg/l)	0.01	0.01	0.1	0.1

NOTES:
1. The riparian, grass and bush land uses used in IMPAQ have been combined since they have the same SP loading coefficients.
2. Forest and timber land uses have been combined.
3. Dryland farming and irrigation land uses have been combined.
4. The rural land use is suggested to apply to urban areas.

It is suggested that the SP loading functions given in **Table 3.1** be used as starting values. It will seldom be necessary to change these during calibration since there will always be intervening river reaches ahead of the calibration point at which SP measurements are available. Calibration at these points will be dominated by river transport processes. Any intervening effluent inputs will also tend to dominate, depending on the relative flow rates, since the rural SP loading coefficients are relatively low. If the nearest downstream SP monitoring point is in a reservoir, then sedimentation processes will become the dominant calibration parameter, further reducing the impact of the choice of rural loading coefficients. Only if the calibration results in unrealistic values (e.g. much too little sedimentation), should higher rural loading coefficients be considered.

The SP concentration of the outflow from the Washoff module is then given by:

CSPW = LSPW/(QP + QU) (3.2)

Where:

CSPW = Soluble phosphorus concentration in the catchment runoff (mg/l)

QP = Runoff from pervious portion of catchment ($10^6 m^3$/month)

(= QG + QS)

3.7 Channel Reach module (CR)

A Channel Reach (CR) module actually represents the entire length of the river from the upstream node(s) until the next downstream node. Hence this is the logical node in which to include the river routing SP processes. This implies that care should be taken to ensure that all significant river reaches should be represented by CR modules, rather than by Junction Node (JN) modules that only account for the mixing of flows at a single point. In cases where JN modules are required to handle abstractions, they should be placed in series with a CR module in all reaches where SP river routing processes are significant.

Figure 3.1 defines the structure of Channel Reach module of the WQT model (Allen and Herold, 1988), showing the flows and associated soluble phosphorus concentrations.

The WQT model keeps track of upstream inflows that are dependent on the salinity in a reservoir that forms an integral part of a salinity feedback loop, and inflow sources that are independent of the reservoir quality. While this is important for modelling salinity, it is irrelevant for phosphate since return flow concentrations are independent of the supply water quality. Hence in **Figure 3.1** no such distinction is made and all upstream routes and effluent discharges are treated as being independent.

The inflow to the upstream end of a Channel Reach node is calculated as:

$$QUPo = QMINE + QCAT \cdot PQCAT + \sum_{i=1}^{NR} QR_i + \sum_{i=1}^{NE} QE_i \qquad (3.3)$$

where:

QUPo = Inflow to upstream end of channel reach ($10^6 m^3$/month)

QMINE = Mine discharge to channel reach ($10^6 m^3$/month)

QCAT = Runoff from catchment within which the channel reach is located ($10^6 m^3$/month)

NR = Number of routes entering upstream end of the channel reach (-)

QR_i = Flow from i^{th} upstream route ($10^6 m^3$/month)

NE = Number of external point sources entering the channel reach (-)

QE_i = Flow from i^{th} external point source ($10^6 m^3$/month)

PQCAT = Proportion of catchment runoff entering the channel reach (-)

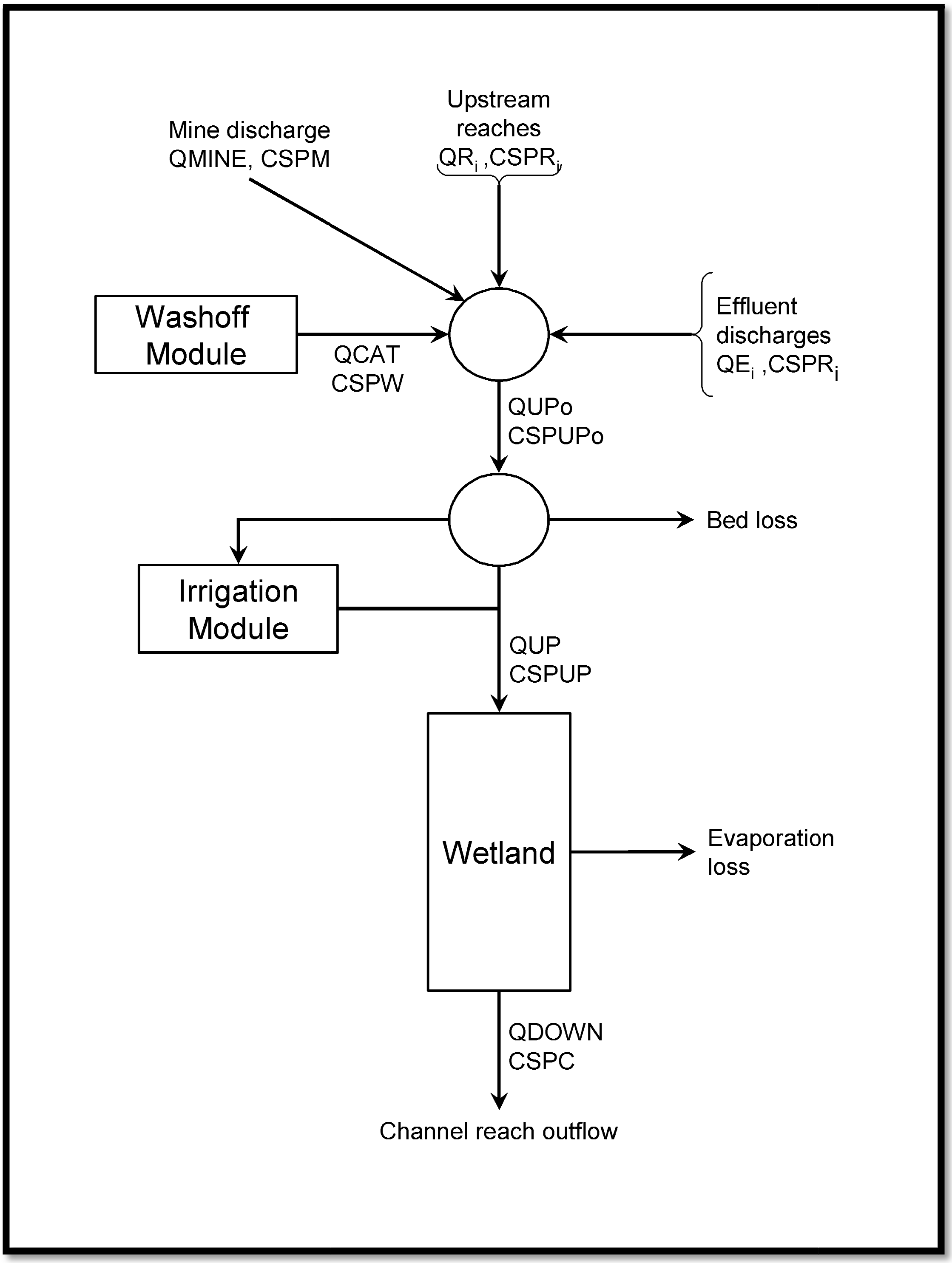

Figure 3.1: Structure of the Channel Reach Module of the WQT Model

The SP load entering the upstream end of the channel reach is calculated as:

$$LSPUPo = \{QMINE \cdot CSPM + QCAT \cdot PQCAT \cdot CSPW + \sum_{i=1}^{NR} QR_i \cdot CSPR_i + \sum_{i=1}^{NE} (QE_i \cdot CSPE_i)\}/QUP \qquad (3.4)$$

Where:

LSPUPo = SP load entering upstream end of channel reach (t)

CSPM = SP concentration of mine discharge into channel reach (mg/l)

CSPW = SP concentration of catchment runoff (mg/l)

$CSPR_i$ = SP concentration of flow from i^{th} upstream route (mg/l)

$CSPE_i$ = SP concentration of flow from i^{th} externally defined point source (mg/l)

The SP concentration of the flow entering the upstream end of the river reach, CSPUPo (mg/l) is given by:

$$CSPUPo = LSPUPo/QUP \qquad (3.5)$$

In keeping with the assumptions of the CR module, the river bed loss and irrigation abstraction are removed at the same concentration and the irrigation return flow enters the channel reach upstream of the wetland area. The SP load entering the wetland is then calculated as:

$$LSPUP = LSPUPo - CSPUPo \cdot (QI + QBLOSS) + QIR \cdot CSPI \qquad (3.6)$$

Where:

LSPUP = SP load entering the wetland section of channel reach (t)

QI = Irrigation abstraction ($10^6 m^3$/month)

QBLOSS = Bed loss from channel reach ($10^6 m^3$/month)

QIR = Irrigation return flow to channel reach ($10^6 m^3$/month)

CSPI = SP concentration of irrigation return defined in Section 3.8 (mg/l)

The flow entering the wetland, QUP ($10^6 m^3$/month), is given by:

$$QUP = QUPo - QBLOSS - QI + QIR \quad (3.7)$$

The SP concentration of the inflow to the wetland, CSPUP (mg/l), is given by:

$$CSPUP = LSPUP/(QUP - QI - QBLOSS + QIR) \quad (3.8)$$

3.7.1 IMPAQ River Transport Algorithms

The river transport algorithms derived from the IMPAQ model relate to the soluble phosphorus concentration at the downstream end of the river channel to that at the upstream end by means of a linear adsorption isotherm, as illustrated in **Figure 3.2.**

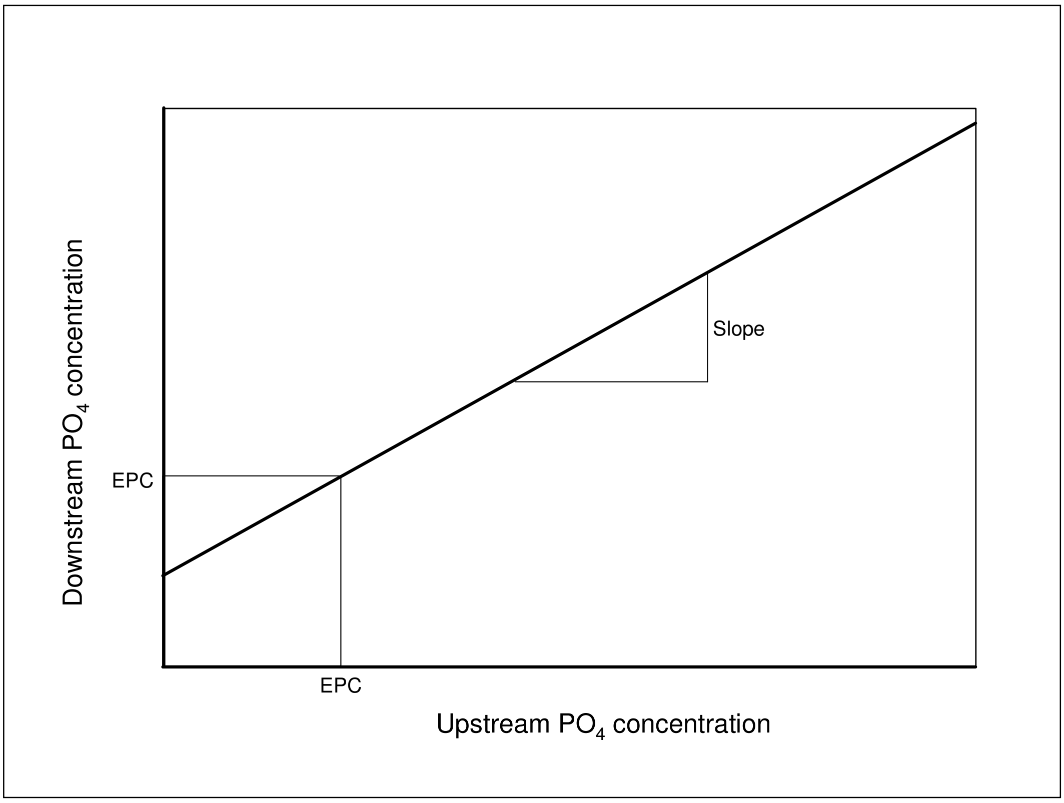

Figure 3.2: Soluble Phosphate Adsorption / Desorption Isotherm

IMPAQ model then calculates the concentration at the downstream end of the river reach by the following equation:

$$CSPC = CSPUP - (CSPUP - EPC) \cdot Islope \qquad (3.9)$$

Where:

CSPC = SP concentration of flow leaving the channel reach (mg/l)

EPC = Equilibrium concentration below which desorption occurs (mg/l)

Islope = Slope of adsorption / desorption isotherm (-)

Although the adsorption/desorption isotherm is linear for a fixed flow rate, a phosphorus transport study of the Berg River by Bath and Marais (1995) found that the slope of the adsorption/desorption isotherm was not constant, but related to the flow rate of the river. For example, during high flow periods with short travel times (and higher velocities), the adsorption rate was found to be low, while during low flow periods the adsorption rate was found to be high.

The following inverse relationship between isotherm slope and flow was derived:

$$Islope = MIR \cdot \{1 - e^{-\varepsilon \cdot (1/Q)}\} \qquad (3.10)$$

Where:

MIR = Maximum isotherm slope (-)

ε = constant

Q = Monthly runoff ($10^6 m^3$/month)

The application of IMPAQ to the Amatole catchment split each of the main river channels into a number of equal length segments, each having identical calibration parameters. Successive solution of the isotherm equations for one segment provided the input to the next downstream segment, and so on to the end of the river reach. This was partially to accommodate the inputs and abstractions of various features and, presumably, to derive calibration parameters that could be comparable between river reaches (provided that the segments of all of the reaches had similar lengths).

3.7.2 Modified River Transport Algorithms

While the isotherm slope described by Equation (3.10) can be calibrated to suit the characteristics of any river reach, it suffers from the problem that calibrated ε values cannot be transferred from one river to another because the value of Q (monthly flow), is open ended and not tied to channel characteristics. Hence the calibrated ε values are likely to differ widely from site to site. (For example the reported values for the constant for the smaller rivers of the Amatole could not to a larger river like the Orange River, since the equation would then grossly under estimate the adsorption.)

Consequently Q was rendered non-dimensional by replacing Q with Q divided by the cumulative MAR at the channel node. This was undertaken in an attempt to narrow the range between the calibrated ε values for different locations within a region. The rationale used was that flow velocity must play a significant role and that since the cumulative MAR drives the channel size, dividing the monthly flow by the MAR should serve to roughly approximate the velocity.

A more rigorous approach would be to use channel slope, channel cross-section shape and estimated friction factor to calculate the velocity directly from the monthly flow. However, this approach was rejected since it would entail exhaustive data collection for every study, which is hard to justify, especially given the inaccuracies inherent in even the best phosphate models. In contrast, the cumulative MAR can easily be calculated from the quaternary MAR data contained in the WR2005 reports (Middleton and Bailey, 2009).

Another disadvantage is that the IMPAQ equations do not take account of river length. Hence the division of a river reach into more segments would result in an ever diminishing MIR value. (For example, using the calibrated MIR and EPC values for the Buffalo River for a fixed flow rate, the slope varied between 0.1 for 6 segments to 0.47 for 1 segment.) Hence Equation (3.10) is unsuitable for systems where the channel lengths vary greatly from one another, as will be the case when applying it to WQT and the WRPM systems. In this application, it is not desirable to split every channel reach into numerous short segments of equal length since it would lead to a proliferation of model elements. Moreover, SP data will not be available for all river reaches. In cases where there is no monitoring data, a means is required to make reasonable estimates of the lumped key river transport calibration parameters without having to resort to multiple small river segments of standard length.

A simple means was therefore sought to account for river length.

Closer examination of the calibration values derived for the rivers of the Amatole system revealed EPC values of 0.020, 0.025 and 0.015 mg/l for the Buffalo, Yellowwoods and Kubusi Rivers respectively. This implies that for all but the cleanest conditions EPC plays little material role in the isotherm defined by Equation (3.9), other than the necessary function of defining a minimum allowable concentration. That being the case, it is justifiable to simplify Equation (3.9) to the following:

$$CSPC = CSPUP \cdot (1 - Islope) \quad (3.11)$$

And instead, treating EPC for what it effectively is, a minimum SP concentration that would arise due to desorption even when the concentration of the incoming water drops below this level.

Hence, whenever the CSPC value calculated by Equation (3.11) drops below EPC, the CSPC value is revised to the minimum value:

$$CSPC = EPC \quad (3.12)$$

This revision of Equation (3.9) will result in a potential discontinuity in the slope of the simulated CSPC curve when the concentration tends towards EPC, but this is considered inconsequential since the observations against which calibrations are made are discrete samples that will be too few in this low concentration region to be noticed. Moreover, the model will be calibrated, which means that the two models would simply exhibit minor changes in the calibration parameters with much the same simulation results.

The big gain in using the modified Equation (3.11) is that it yields a simple relationship between slope and river length of the form:

$$SKM = 1 - (1 - S10)^{KM/10} \quad (3.13)$$

Where:

KM = River length (km)

SKM = Slope applicable to river of length KM (-)

S10 = Slope applicable to a river of length 10 km (-)

A 10 km standard river length has been chosen since the WQT Channel Reach module lengths will typically be quite long. This implies that too short a standard river length would result in a large exponent, which in turn could lead to numerical loss of precision.

Combination of Equations (3.11) and (3.13) and non-dimensionalisation of the flow yields the following slope equation:

$$Islope = 1 – [1 - MIR \cdot \{1 - e^{-\varepsilon \cdot 1/(QUP/MARC)}\}]^{KM/10} \quad (3.14)$$

Where:

MARC = Cumulative Mean Annual Runoff (MAR) at Channel Reach ($10^6 m^3$)

Substitution of Equation (3.14) in (3.12) yields:

$$CSPC = CSPUP1 \cdot \{1 - MIR \cdot (1 - e^{-\varepsilon \cdot MARC/QUP})\}^{KM/10} \quad (3.15)$$

3.7.3 Route Outflow

CSPC, derived from Equations (3.15) and (3.12), defines the SP concentration of the exit route:

$$CSPR = CSPC \quad (3.16)$$

Where:

CSPR = Soluble phosphorus concentration in the downstream route (mg/l)

The same generic symbol is used throughout this report to denote route flows. Naturally each such route has a unique route number, but these are not displayed in order to remove unnecessary complexity from the equations.

3.8 Irrigation Module (RR)

Numerous complex processes take place in irrigated lands. Despite the phosphate contained in the irrigation supply water, the application of fertilizer is commonly required. In a well managed area, most of the phosphate entering via supply water and direct fertilizer application is used by the crop. The SP concentration of the return flow is therefore largely independent of the SP concentration of the supply water.

On this basis, the SP concentration of the return flow is set equal to a constant value, CSPI (mg/l). The SP concentration of the irrigation return flow from the Irrigation (RR) module of WQT is then given as:

$$CSPIR = CSPI \quad (3.17)$$

Where:

CSPI = Average SP concentration of the irrigation return flow (mg/l)

CSPI could be calculated directly from SP measurements of the irrigation return flows. However, this is considered impractical, in the majority of instances, since this is seldom measured. Instead CSPI is deemed a calibration parameter. The phosphorus loading coefficient β (mg/l) for the farm category given in **Table 3.1** is suggested as a starting value for this parameter. Since the calibration parameters controlling river transport and reservoir sedimentation are generally much more dominant, it should seldom be necessary to alter this initial value.

CSPI becomes the SP concentration (i.e. CSPR) entering the downstream route.

3.9 Junction Module (JN)

The junction node carries out simple mixing of the SP loads entering from upstream routes and assigns the resulting concentration to all outflow routes. Unlike salinity, SP is not subject to feedback loops and there is no need to keep track of the inputs and outputs from a dependent reservoir.

The SP concentration of the mixed inputs, CSPR (mg/l), is calculated as:

$$CSPR = \left(\sum_{i=1}^{NR} QR_i \cdot CSPR_i\right) / \left(\sum_{i=1}^{NR} QRi\right) \quad (3.18)$$

3.10 Demand Centre Module (DC)

While the WQT Demand Centre (DC) module is important in simulating the effect of climatic fluctuations on the return flow volume, after water use and effluent treatment, the SP concentration in the effluent bears no resemblance to that of the supply water. For this reason, the SP concentration of the effluent is entered as a model parameter that is related to each effluent treatment works.

The Demand Centre module allows a demand centre to discharge effluent to one or more routes, representing the output from a number of Sewage Treatment Works (STW).

The DC module makes allowance for the direct reclamation of part of the effluent via a demineralisation plant. However, since there is no feedback from water supply to effluent return flow SP, there is no need to take account of the SP concentration of water that is directly reclaimed. All that is necessary is to consider the SP concentration of the final effluent discharge for each STW.

Since the SP concentration of final effluent is an important indicator of plant performance, SP data is readily available and the average SP concentration of each STW can be determined.

The SP concentration in the final effluent discharged to each downstream route is calculated as:

$$CSPR_i = CSPD_i \quad (3.19)$$

Where:

$CSPR_i$ = SP concentration of the outflow via the i^{th} outflow route (mg/l)

$CSPD_i$ = SP concentration of the effluent from the i^{th} STW (mg/l)

3.11 Mining Module (MM)

Various routes discharge water from WQT's Mining Module (MM), from discard heaps, open-cast and underground workings and pollution control dams. The simplifying assumption has been made that the SP concentration of all routes entering the system from mining modules is constant. In some cases, the mining effluent is monitored for phosphate and the observed concentrations can be used to calculate the average. Since the soluble phosphate concentrations associated with these flows are generally low, a nominal low SP concentration is suggested when such data is not available. (For example, the DWA WMS data for the period June 1996 to July 2009 gives the median SP concentration of the discharge from Grootvlei Gold Mine as 0.05 mg/l, with an average of 0.114 mg/l.) The Phalaborwa mining complex represents an exception, since phosphate is mined in this area and a higher effluent flow phosphate concentration is warranted.

The soluble phosphate concentration assigned to each return flow route from the Mining Module is given as:

$$CSPR_i = CSPM_i \quad (3.20)$$

Where:

$CSPM_i$ = SP concentration assigned to Mining Module outflow route i (mg/l)

3.12 Reservoir module (RV)

3.12.1 Soluble Phosphorus

Reservoir processes play a major role in soluble phosphate dynamics.

The SP concentration entering the Reservoir is calculated in IMPAQ by simple mixing with the water already in the dam from the previous time step as:

$$CSPRVo = \{CSPRV_{t-1} \cdot VRES_{t-1} + \sum_{i=1}^{NR}(QR_i \cdot CSPR_i)\}/\{VRES_{t-1} + \sum_{i=1}^{NR}QR_i\} \qquad (3.21)$$

Where:

$CSPRVo$ = Pre mixed SP concentration before sediment interaction (mg/l)

$CSPRV_{t-1}$ = SP concentration of stored water in the dam during the previous time step (mg/l)

$VRES_{t-1}$ = Reservoir storage at end of previous time step ($10^6 m^3$)

QR_i = Inflow to reservoir via route i ($10^6 m^3$/month)

$CSPR_i$ = SP concentration of the in flow via route i (mg/l)

Equation (3.21) implies complete mixing within the reservoir during the monthly time step. This simplifying assumption is considered adequate, since the mixing conditions in most reservoirs will be unknown. At one extreme, density currents might cause incoming cold or salty water to plunge under the stored water and emerge at the outlet with very little mixing. At the other extreme a completely mixed large reservoir will exhibit little change in concentration from one month to another, except during the passage of large floods. In any event, the calibration parameters controlling the sedimentation processes described below will exert by far the biggest influence on SP concentrations near the dam outlet.

Sedimentation processes in the reservoir are described in IMPAQ by the following equation:

$$CSPRV = (CSPRVo + Hp) \cdot (1 - Psed) + CSPRV_{min} \qquad (3.22)$$

Where:

$CSPRV$ = SP concentration at dam outlet during the current time step (mg/l)

Hp = Contribution to SP concentration attributable to the release of phosphate from the anaerobic zone during overturn (mg/l)

Under South African conditions, overturn (vertical mixing) has been found to occur towards the end of summer during April or May. During the overturn month Hp is set to a value ranging from 0.01 to 0.04 mg/l, while for all other months it is set to zero.

Hence, during the overturn month, OM:

$$Hp = Hp1 \qquad (3.23a)$$

During the remaining 11 non-overturn months:

$$Hp = 0 \qquad (3.23b)$$

Where:

OM = Overturn month

Hp1 = Hp value applicable to the overturn month (mg/l)

Psed = Soluble phosphorus sedimentation or adsorption rate (-)

In the IMPAQ model Psed switches between high and low residence times (i.e. monthly inflow divided by storage) with the threshold at approximately 40 to 60 months.

For a short residence time, RT< RTo:

$$Psed = Psed1 \qquad (3.24a)$$

If RT>=RT0:

$$Psed = Psed2 \qquad (3.24b)$$

Where:

RT = Residence time (months)

$$= VRES_{t-1} / (\sum_{i=1}^{NR} QR_i) \qquad (3.25)$$

RTo = Threshold residence time (months)

Psed1 = Short residence time sedimentation rate (-)

Psed2 = Long residence time sedimentation rate (-)

A higher sedimentation rate is applicable to a short residence time since the inflowing water them typically exhibits higher turbidity, thereby providing additional substrate for SP adsorption.

CSPRV = SP concentration at dam outlet during the current time step (mg/l)

$CSPRV_{min}$ = Minimum SP concentration normally found in dams (mg/l)

This value was set to an arbitrary low value in IMPAQ of .002 mg/l, which us below the detection limit of phosphate analyses. Presumably this has been included to prevent numerical underflow during a sequence of zero inflows.

Values of Hp, RTo, Psed1 and Psed2 used in the Amatole study are given in **Table 3.2.**

Table 3.2: SP Reservoir Coefficients used in Amatole Study (Bath, 1998)

Reservoir	Rooikrantz	Wriggelswade	Laing	Bridal Drift	Nahoon	Gubu
Hp (mg/l)	0.03	0.03	0.01	0.03	0.04	0.02
OM	April	May	May	April	May	April
RTo (months)	40	30	60	60	40	40
Psed1	0.60	0.55	0.50	0.83	0.40	0.50
Psed2	0.40	0.30	0.05	0.50	0.25	0.25

NOTE: In the IMPAQ model Psed is defined as the proportion of the SP concentration remaining in solution after sedimentation. In order to clarify the definition (of Psed as the SP deposition rate), Equation (3.21) has been revised by replacing the term Psed with 1-Psed and the Psed1 and Psed2 values in **Table** 3.2 have been adjusted accordingly.

3.12.2 Chlorophyll-a

The last important step is the estimation of the algal response of the reservoir. Chlorophyll-a is used as a surrogate to represent total algal concentration. IMPAQ models this as a function of the monthly soluble phosphorus concentration with temperature limitation:

$$Chl = \{1 - e^{-CSPRV \cdot ALG1}\} \cdot ALG2 \qquad (3.26)$$

Where:

Chl = Chlorophyll-a concentration (µg/l)

ALG1 = Slope of the exponential chlorophyll-a vs SP relationship (l/mg)

ALG2 = Maximum Chlorophyll-a concentration (µg/l)

A growth restricted function was used since at high algal concentrations since self shading can inhibit algal growth. Temperature limitation is achieved by switching the ALG1 and ALG2 parameter values between summer and winter.

Hence for summer months (October to April):

$$ALG1 = ALG1S \qquad (3.27a)$$

$$ALG2 = ALG2S \qquad (3.28a)$$

For winter months (May to September):

$$ALG1 = ALG1W \qquad (3.27b)$$

$$ALG2 = ALG2W \qquad (3.28b)$$

The parameters ALG1 and ALG2 are dependent on a number of site specific characteristics, including the morphology of the reservoir, its size and the nature of the sediment entering it. Hence, they need to be calibrated for each reservoir. In the case of small off-channel reservoirs, such as small farm dams, typical phosphate sedimentation and chlorophyll-a conversion factors should be used, since observed data will not be available. This choice should have little consequence, since both the inflow and outflow SP concentrations from such minor dams will be low. Calibration should rather focus on the main stems of rivers, major tributaries and the more significant reservoirs for which data is available.

Table 3.3 shows the calibrated ALG1 and ALG2 parameter values reported for various reservoirs in the Amatole system.

Table 3.3: Chlorophyll-a Coefficients used in Amatole Study (Bath, 1998)

Reservoir	Rooikrantz	Wriggelswade	Laing	Bridal Drift	Nahoon	Gubu
ALG1S (l/µg)	3.0	3.0	5.1	6.0	3.1	3.0
ALG2S (µg/l)	35	40	35	400	35	35
ALG1W (l/µg)	8.0	10.0	8.0	9.0	8.0	8.0
ALG2W (µg/l)	10	40	10	50	10	10

3.13 General Comment

The IMPAQ model does not include algorithms to simulate chlorophyll-a in river reaches. At this stage it is recommended that important river reaches that experience eutrophication problems, such as the Middle Vaal River, are broken into smaller sections. The swifter flowing reaches should be treated as River Channel modules and the slower moving sections such as reaches backed up by storage weirs (e.g. at Balkfontein) should be modelled as reservoirs.

3.14 Model Calibration

It is not the intention to present exhaustive directions on model calibration since this would require prior model testing and sensitivity analyses. It is desirable, however, to indicate the practicality of calibration.

3.14.1 Calibration Parameters

The model calibration parameters for soluble phosphate include:

Salt Washoff module:

αi = Groundwater loading coefficient for and use i (mg/l)

βi = Surface flow loading function for land use i (mg/l)

Channel Route module:

EPC = Minimum SP concentration in river channel (mg/l)

MIR = Maximum adsorption isotherm slope (-)

ε = Isotherm slope applicable to 10 km river length (-)

Irrigation module:

CSPI = Average SP concentration of the irrigation return flow (mg/l)

Demand Centre module:

CSPDi = SP concentration of the effluent from the ith STW (mg/l)

Reservoir Module:

OM = Overturn month

Hp1 = Hp value applicable to the overturn month (mg/l)

RTo = Threshold residence time (months)

Psed1 = Low residence time sedimentation rate (-)

Psed2 = Long residence time sedimentation rate (-)

The model calibration parameters for chlorophyll-a include:

Reservoir module:

ALG1s = Slope of the exponential chlorophyll-a vs SP relationship for summer

ALG1w = and winter months (l/mg)

ALG2S= maximum chlorophyll-a concentration for summer and

ALG2w = winter months

3.14.2 Initial Selection of Calibration Parameter Values

Salt Washoff module:

Table 3.1 can be used to make an initial selection of the αi and βi loading functions for various catchment land uses. Ideally the areas under each land use cover could be derived from GIS and other sources. Should this data not be available, the dominant land use should be selected (e.g. grassland for a predominantly undeveloped catchment). Further experience with use of the model may eventually lead to revision of the values given in **Table 3.1**

Channel Route Module:

The IMPAQ report used EPC values in the range 0.015 to 0.025 mg/l for various rivers in the Amatole system. This suggests that 0.020 mg/l would be a suitable initial value. Likewise, 0.55 would suffice as an initial starting value for MIR. However, a clear initial value for calibration parameter ε cannot be specified before model testing. This is because the values used in the Amatole study are tied to particular reach segment lengths. The flows had not been non-dimensionalised and the units differ. This is not a serious problem since ε is, in any case, a key parameter that will need to be calibrated. Improved information regarding appropriate initial values will become clear after the model has been applied.

Irrigation Module:

Based on **Table 3.1**, an initial value of 0.1 mg/l is suggested for calibration parameter CSPI.

Demand Centre Module:

It is strongly recommended that CSPDi should not be treated as a calibration parameter. Instead, a representative SP concentration for each STW should be calculated from available data. Failing that, the concentration should be estimated from the nature of the operation. For example, if the STW is complying with the 1 mg/l special standard for phosphate, then a value less than 1 mg/l would be appropriate. If the treatment process is, however, not designed for phosphate removal, or if it is known to be badly run, then higher concentrations would be appropriate.

Mining Module:

Observed phosphate data should be available for most significant mining sources (such as Grootvlei Gold Mine). In such instances, the average of these observations should be used for mining outflow routes (CSPMi). In most instances a relatively low SP concentration is suggested of approximately 0.1 mg/l (based on the Grootvlei Gold Mine data). Even lower values may be appropriate for the outflow from control dams, since phosphate sedimentation could be expected in impoundments. However, care and local knowledge will have to be exercised. There are instances where phosphate may be more prominent (for example phosphate is a mining product at Phalaborwa, although direct point discharges are not recorded).

Reservoir Module:

The overturn month, OM, should be known for most major dams and this could also be applied to other nearby dams. In cases where there is no information, the initial value could be set at April for example. Model calibration against actual data should indicate if this month needs to be adjusted. It should be noted that overturn does not occur in shallow dams, which are usually smaller than the deeper dams. The Amatole system study gives Hp soluble phosphate concentrations ranging from 0.01 mg/l to 0.04 mg/l, with most at 0.03 mg/l. This is suggested as an initial value. The threshold residence time (RT0) for the various dams in the Amatole system range from 30 to 60 months, with an average of 45 months. This is suggested as an initial value. The short residence time phosphate sedimentation rate (Psed1) for the Amatole reservoirs averages at 0.56 mg/l, rounding to 0.6 mg/l, and this is suggested as an initial value. The sedimentation rate for long residence times (Psed2) is about half of that for Psed1. Hence a value of 0.3 mg/l is suggested.

The suggested initial values for the model calibration parameters controlling chlorophyll-a, based on the Amatole study results for various reservoirs, are derived from **Table 3.3.** The ALG1s summer slope values were calibrated at 3.0 for the relatively unpolluted dams and 5.1 to 6.0 for severely polluted reservoirs. These criteria are suggested for selecting initial values. The calibrated winter values (ALG1w) are remarkably consistent, in the range 8.0 to 10.0 with most clustered at 8.0, which is the suggested initial value. The ALG2 maximum chlorophyll-a concentrations are primary calibration parameters that are dependent on the characteristics and pollutant loadings on the individual dams. Accordingly, they show the greatest variation. The summer values (ALG2S) range between 35 µg/l and 400 µg/l, although most are clustered at 35 µg/l, which is suggested as a starting value. The winter values (ALG2w) range between 10 µg/l and 50 µg/l, with all of the smaller reservoirs clustered at 10 µg/l and the two largest reservoirs at 40 µg/l and 50 µg/l. Interestingly, these calibrated winter maxima are not related to the pollution status of the dams.

3.14.3 Calibration Procedure

The following calibration procedure is suggested. Note that this may be revised once the model has been implemented and tested.

Step 1

Select initial values.

Step 2

Run the model and compare modelled with observed phosphate results, starting with the most upstream elements.

Step 2a

If there is a monitoring point in a river reach, first adjust the river transport calibration parameters ε and MIR. MIR should first be used to adjust the simulated maximum SP concentration, and SPC to define the minimum concentration. Thereafter ε should be adjusted to improve the fit. Only as a last resort should any changes be made to the catchment export coefficients α and β, if the channel sedimentation parameters would otherwise result in unrealistically low adsorption.

Step 2b

If the first monitoring station is in a reservoir, then priority should be placed on calibration of the reservoir calibration parameters. The initial catchment export and river routing parameter values should be left unchanged until the reservoir sedimentation parameters have been calibrated. In a severely (or even moderately) polluted reservoir the Hp value will be obscured since the observed SP concentrations will be much higher than the minimum values caused by remobilisation. In such cases Hp should not be changed from the initial values. Hp should only be adjusted in relatively unpolluted reservoirs, where the release of SP from the sediments will contribute to observed minimum concentrations. The overturn month, OM, should only be adjusted if there is a compelling reason to do so. The effect of the threshold residence time, RTo, Psed1 and Psed2 on SP concentrations is expected to be complex and will require trial and error to arrive at the best calibration. Experience with using the model on various reservoirs may yield clearer guidelines.

If the reservoir calibration parameters indicate abnormally low sedimentation, then consideration should then be given to reducing the adsorption of SP in the upstream river reach. Only as a last resort should consideration be given to increase the SP export from the catchment.

Step 3

Step 2 should be repeated for each monitoring point. Thereafter further adjustments should be made to rationalise parameters to achieve consistency between river reaches.

Step 4

After the SP parameters have been calibrated, the chlorophyll-a parameters can be calibrated. The ALG2s and ALG2w parameters should be adjusted to match the maximum summer and winter values. Thereafter the ALG1s and ALG1w values should be adjusted to improve the fit, bearing in mind that the equation controlling this part of the relationship only deals with the relationship between chlorophyll-a and phosphate concentration.

3.15 Data requirements

The data requirements, for the eutrophication model, include the linkages and flow related information normally required by the WQT model. These input requirements are described by Allen and Herold (1988) for the WQT model and the requirements for the mining module are described by Coleman and Van Rooyen (2001). The additional input data required to model SP and chlorophyll-a processes are described in **Table 3.4**.

Table 3.4: WQT Model Input Data Requirements to Model SP and Chlorophyll-a

Data description	Data source
WASHOFF MODULE (SW)	
Areas of land use (km^2)	GIS or other
For each land use: - Groundwater SP loading coefficient, α (mg/l) - Surface flow SP loading coefficient, β (mg/l)	 Table 3.1 / calibration Table 3.1 / calibration
CHANNEL REACH MODULE (CR)	
Time series of monthly mine pumping SP concentrations	Historical records(1)
Time series of monthly effluent SP concentrations	Historical records(1)
Minimum river SP concentration, EPC (mg/l)	Calibration
Maximum SP adsorption isotherm slope, MIR (-)	Calibration
Exponential constant in SP adsorption isotherm (-)	Calibration
Cumulative Mean Annual Runoff ($10^6 m^3$)	WR2005 reports
IRRIGATION MODULE (RR)	
Average SP concentration of irrigation return (mg/l)	Calibration(2)
MINING MODULE	
Average SP concentrations for: - Seepage from each discard heap / slurry pond (mg/l) - Spill from central pollution control dam (mg/l) - Controlled release from central pollution control dam (mg/l) - Surface runoff from each opencast pit catchment (mg/l) - Spill from each opencast pit pollution control dam (mg/l) - Surface runoff from each underground mine catchment (mg/l) - Seepage from each underground storage dam (mg/l)	 Historical records(3) Historical records(3) Historical records(3) Historical records(3) Historical records(3) Historical records(3) Historical records(3)
DEMAND CENTER MODULE	
Average SP concentration of effluent routes, $CSPD_i$ (mg/l)	Historical records(4)
RESERVOIR MODULE (RR)	
SP concentration increase due to sediment release from anaerobic zone during overturn month, Hp1 (mg/l)	Calibration
Overturn month (-)	Limnological experience
Short residence time sedimentation rate, Psed1 (-)	Calibration / Table 3.2
Long residence time sedimentation rate, Psed2 (-)	Calibration / Table 3.2
Threshold residence time, RTo (month)	Calibration / Table 3.2
Nominal minimum SP concentration (mg/l)	.002
Summer slope of exponential chlorophyll-a vs SP curve, $ALG1_s$	Calibration / Table 3.3
Winter slope of exponential chlorophyll-a vs SP curve, $ALG1_s$	Calibration / Table 3.3
Maximum summer Chlorophyll-a concentration, $ALG2_s$ (µg/l)	Calibration / Table 3.3
Maximum winter Chlorophyll-a concentration, $ALG2_s$ (µg/l)	Calibration / Table 3.3
Start and end months of summer (month)	Climatology

NOTE: (1) Gaps in historical point SP records will need to be patched.
(2) An initial irrigation return flow SP concentration of 0.1 mg/l is suggested.

(3) Use any available historical mine records. Otherwise use suggestions in Section 3.14.2.
(4) Calculated from STW SP historical records.

3.16 Soluble Phosphorus and Chlorophyll-a Model Output

The SP and chlorophyll-a model output will comprise:

- Tabulation (files) of simulated monthly time series of:
  - River and dam SP concentration and load
  - Dam chlorophyll-a concentration
- Plots of simulated monthly time series of:
  - River flow, SP concentration and SP load
  - Dam storage, SP concentration and SP load
  - Dam storage and chlorophyll-a concentration
- Plots of seasonal (mean monthly):
  - River flow, SP concentration and SP load
  - Dam SP concentration
  - Dam chlorophyll-a concentration
- Plots of simulated duration curves of:
  - River flow, SP concentration and SP load
  - Dam SP concentration
  - Dam chlorophyll-a concentration
- Plots comparing simulated and observed of monthly time series of :
  - River flow, SP concentration and SP load
  - Dam storage, SP concentration and chlorophyll-a concentration
- Plots comparing simulated and observed seasonal (mean monthly):
  - River flow, SP concentration and SP load
  - Dam SP concentration
  - Dam chlorophyll-a concentration
- Plots comparing simulated and observed duration curves of:
  - River flow, SP concentration and SP load
  - Dam SP concentration
  - Dam chlorophyll-a concentration
- Tabulation of statistical comparison between simulated and observed monthly:
  - River flow, SP concentration and SP load
  - Dam chlorophyll-a concentration

4 OPERATIONAL MODELS

4.1 Purpose

The primary purpose of operational models is to ensure that the operating rules derived at the planning stage are adhered to. Since relatively long lag times exist in storage elements and regulated river reaches, these models are required to adjust releases as day-by-day changes occur in river flows. This implies the need to run at a daily time step, as opposed to the planning model that runs at a coarser monthly time step. Clearly such a model needs to be dynamic, rather than steady state. Optimisation of day by day operation could also lead to improvement of the assumptions made in the planning model. The operational model could also be used to simulate the spread, timing and dilution of pollution plumes arising from accidental spillage. This could be used to develop emergency plans and, in the worst case, track actual events to inform emergency measures.

In terms of those variables that can practically be controlled in the Orange-Vaal system, the operational model needs to simulate the following:

- Flow (and energy);
- Salinity (TDS);
- Soluble phosphorus; and
- Chlorophyll-a (and possibly the constituent algal species).

A wider range of water quality variables is called for to handle the simulation of accidental spills of pollutants that have acute toxicity effects.

The requirements for each of the main categories are discussed in the following sections.

4.2 Flow

Flow control is the most important aspect of an operational model. An obvious example is the need to balance releases from Vaal Dam to satisfy water demands in the regulated Middle Vaal River, while minimising spillage to Bloemhof Dam. Since lag times ranging from days to weeks can arise, it will often occur that the desired release from Vaal Dam will change in step with downstream flow conditions. Even with the best of operation, once water has been released, it may no longer be required by the time it reaches downstream points of abstraction due to the effect of intervening storm events. Hotter than expected conditions may also increase in-stream evaporation loss and the demand at abstraction points, potentially resulting in supply shortfall. Over-reaction to temporary downstream storm runoff could also result in a shortfall trough following the higher runoff, which might in turn force the release of higher than necessary flows to overtake the trough to prevent supply shortfalls.

Areas where flow control is required include:

- Inter-basin water transfers including the Tugela-Vaal, Usutu-Vaal, Slang-Vaal, Orange-Riet, Caledon-Modder, Orange-Vaal and Orange-Fish schemes;

- Hydro power generation, especially in the Orange River scheme;
- Regulated stretches of the Vaal and Orange Rivers, including:
  - Upper Vaal from between the Usutu and Slang River transfers to Grootdraai Dam;
  - Middle Vaal between Vaal Dam and Bloemhof Dam;
  - Irrigation releases from Bloemhof Dam to feed irrigation schemes at Vaal-Harts and down to Douglas Weir and intermediate urban centres;
  - Irrigation releases From Allemanskraal and Erfenis Dams to the Sand and Vet Rivers;
  - Irrigation and urban releases to the Modder and Riet Rivers;
  - Irrigation releases to the Orange River from Vanderkloof Dam.

Flood control is another key operational requirement for all of the regulated river reaches.

Good operation practice taking account of operational procedures, lag times and information phoned in (or obtained by telemetry) to the dam operator can deal with some of these issues and result in efficient system operation. It is recognised, however, that the requisite experience may not always be available. Moreover, many of the systems are complex. A good operational model that encapsulates efficient operating rules is therefore highly desirable.

In some instances flow control is inextricably linked to energy consumption (by pumps), or generation (in hydroelectric schemes), and the associated economic factors. Often this is also linked to long-term yield and related system operating rules. Areas in the Orange River system where flow and energy is linked include:

- Inter-basin water transfers to the Upper Vaal from the Tugela, Slangspruit and Usutu rivers;
- The supply system to Eskom power stations;
- Water transfer to the greater Bloemfontein area from Welbedacht Dam and the Nova pump station;
- Power generation in the Orange River scheme; and
- Power generation in the LHWP and along the Liebenbergsvlei River (although the discharge from LHWP is sustained and hence operational decisions limited).

4.3 Salinity

Operational control is important in the Vaal Barrage – Middle Vaal system, where the Vaal Barrage dilution option is in operation. This reverts to the Rand Water (RW) blending option during periods of drought, when the system water resource is too constrained to support the dilution option.

RW has raw water intakes in Vaal Barrage and in the upstream Vaal Dam. In the past, abstractions from Vaal Barrage were maximised. These were supplemented by withdrawals and releases from Vaal Dam to make up the supply requirements of RW and users in the Middle Vaal River, notably NW Water, Sedibeng Water, Parys, riparian irrigators and intervening transmission losses. This was undertaken to maximise yield. One-third of RW's supply, however, is returned to tributaries of Vaal Barrage, together with saline mine dewatering and saline diffuse sources. Preferential abstraction from Vaal Barrage, therefore, led to a vicious feedback loop with high average salinity and uncontrolled hydrologically induced TDS peaks in RW's supply, with concomitant high mineralisation costs. On the other hand, Vaal Dam is a low TDS water source.

The 600 mg/l Vaal Barrage dilution option is currently used to manage the salinity in the Middle reaches of the Vaal River. Releases are made from Vaal Dam to dilute the higher saline streams entering the Vaal Barrage from the Klyn and Suikerbosrand Rivers.

Daily measurements of flow and salinity in the Klip and Suikerbosrand Rivers, and salinity measurements in Vaal Dam and Vaal Barrage, suffice to operate the dilution option. Releases from Vaal Dam require adjustment to attain the desired level of dilution. In conjunction with this, normal volumetric measurements in the Middle Vaal River, and at the raw water intakes, are required to determine minimum releases from Vaal Barrage. It is necessary for the Vaal Barrage gates to be adjusted to maintain a relatively constant Barrage operating level. An operational model would assist in managing the dilution rule optimally.

4.4 Eutrophication

Initially the control of eutrophication would focus on Vaal Barrage and the Middle Vaal River, from Vaal Barrage to Bloemhof Dam. The lower portion of the Orange River also warrants attention, although the long river length and lag time and limited sources for water releases will reduce the effectiveness of operational control of the latter.

High nutrient loads, particularly phosphate, entering Vaal Barrage are the primary drivers of eutrophication in Vaal Barrage and the downstream Vaal River. Further load is added by the Mooi River. Other factors that promote eutrophication are the naturally warm climate and the slow moving regulated flow, especially behind storage weirs, such as at the Midvaal Water and Sedibeng Water intakes.

Flow control may offer a means of reducing algal blooms, either by flushing nutrients or by reducing residence times.

A comprehensive daily time step dynamic model is required to guide the operation of such measures and to optimise operating rules.

4.5 Suggested Operating Model

An essential requirement is the ability to incorporate quantitative and water quality operating rules, including the salinity dilution option and possible future phosphate control rules, without undue need to reprogram the model. Operational modelling also requires real time simulation with feedback from observed data. A single operating model platform to take account of flow quantity, salinity, nutrients and algal growth is desirable. This would provide the advantage of reducing the need to disperse the limited available expertise in gaining familiarity with using a large number of models. Ideally, this model could also be used to simulate the effect of pollution spills. This would imply the need to also model metals and a range of other toxic substances. While perhaps not essential for operational modelling, GIS and other graphical features are highly desirable for simulating the spread of spills.

An important consideration in acquiring an off-the-shelf operating model is the cost of the package and the ease with which system operating rules can be incorporated. This is particularly relevant for operating rules that integrate water quantity with water quality, such as the RW bending option. Lack of access to the source code could also create a dependency on remote suppliers. This could be even more problematic in instances when access is provided via the internet, since the threat exists that essential services could be suspended by the host country.

It may not be possible to find a single off-the-shelf model that meets all of these requirements. In particular, reservoir modelling differs markedly from river models. In some instances a simple model tailored to the needs of a water bailiff, based on systems that are currently in use, may suffice. This would hold the advantage that updates to the operating rules could be easily updated locally. Therefore, it is not the intention of this report to be prescriptive in singling out a particular model.

Table 4.1 lists, in alphabetical order, a range of water quality models that could be considered for this purpose. Only dynamic unsteady state daily time step models have been considered. The list is by no means exhaustive, as some that already exist may have been overlooked due to insufficient familiarity with their use, and new models are continually being produced. The specific needs arising from local conditions may also point to the requirement for other types of model.

Table 4.1: Operating Models or those that could be Adapted to the Operating Role

Model	River	Reservoir	GIS	Spills	General
Ad hoc	Yes	No	No	No	Simple operation rules to assist water bailiffs for specific systems
CE-QUAL-W2	Yes	Yes	No	Yes	1 and 2 D, rivers, reservoirs and estuaries
EXAMS II	Yes	-	-	Yes	Rapid investigation of transport and decay of organic chemicals
HEC-RAS	Yes	Yes	No	Yes	1-D river flow and water quality
HSPF	Yes	No	No	No	Catchment and river runoff and water quality
ISIS	Yes	Yes	Partial	Yes	1-D river flow, water quality and sediment
MIKE 11	Yes	Yes	Partial	Yes	1-D river flow, water quality and sediment
SAW	Yes	-	-	Yes	Oil spills + dangerous chemicals
WASPS.01	Yes	-	-	Yes	1, 2 or 3 D containment transport and decay in surface water

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

- Satisfactory salinity modelling functions are already integrated into the WRPM and WQT models and improvements are being incorporate as required.
- Algorithms for a river and reservoir phosphate and chlorophyll-a model that are suitable for inclusion in the WQT and WRPM models have been developed.
- The high level requirements for water quality operating models and possible development routes have been considered.

5.2 Recommendations

5.2.1 Incorporate Phosphate and Chlorophyll-a System Modelling

It is recommended that the phosphate and chlorophyll-a modelling algorithms developed in this report be incorporated in the WQT and WRPM models.

5.2.2 Test and Select Water Quality Operational Models

Water quality operating model requirements should be examined in detail and tested on key system elements.

5.2.3 Improve WQT and WRPM Salinity Modelling

Ongoing improvements to the WQT and WRPM salinity modelling routines should proceed.

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