ASSIGNMENT OF A FINANCIAL COST TO POLLUTION FROM SANITATION SYSTEMS, WITH PARTICULAR REFERENCE TO GAUTENG

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WRC Report No 631/1/01

Water
Research
Commission

ERRATUM

Research report:
Van Ryneveld, M B, Marjanovic, P D, Fourie, A B and Sakulski, D (2001) Assignment of a Financial Cost to Pollution from Sanitation Systems, with particular reference to Gauteng, Water Research Commission Report No. 631/1/01, xix+165pp.

The summarised costs of water supply and sanitation in Gauteng, given in Table 5.11 (p.117) are correctly stated, but were incorrectly carried through to the chapter conclusions (**Section 5.6 Preliminary conclusions on costing**, point 7, p.118), which should read as follows:

7 *Costs of provision (i.e. construction, operation and maintenance) of the different levels of service of water supply and sanitation* in Gauteng (2000 costs) are:
- Stand-pipe and VIP (basic) R130/cap.a
- Yard tap and aquaprivy (intermediate) R240/cap.a
- House connection and water-borne sanitation (Full; *essential* use) R390/cap.a
- House connection and water-borne sanitation (Full; *convenience* use) R530/cap.a

These corrections also need to be carried through to the associated comparisons in points 12 and 13 (p.119) as follows:

12 By comparison with the costs of a higher level of service of water supply and sanitation, the maximum additional costs of treatment are small. For surface water, the additional cost of treatment (R20/cap.a) is only about 7.5% of the difference in cost between a basic and a full level of service (*essential* use) (R260/cap.a). If water usage for the full level of service increases towards *convenience* use, then the relative cost of treatment will drop even more. For groundwater, the additional cost of treatment (R50/cap.a) is about 20% of the level of service cost difference.

13 In summary, even *conservative* estimates of additional treatment costs (either surface water or groundwater), *fully* (i.e. very conservatively) assigned to pollution from sanitation systems are still *only about a fifth* of the cost difference between basic and full (essential use) levels of service of water supply and sanitation (based on the particular catchments used in the analysis).

In addition, the above corrections need to be carried through to the *Costing* section of section **8.1 Conclusions** (same point numbering; p.146 and 147), as well as to the *Costing* section of the **EXECUTIVE SUMMARY** (again, same point numbering; p.v and vi).

While these corrections do make a material difference to the conclusions of the study, they in fact *strengthen* the argument rather than weaken it.

M B van Ryneveld
May 2003

ASSIGNMENT OF A FINANCIAL COST TO POLLUTION FROM SANITATION SYSTEMS, WITH PARTICULAR REFERENCE TO GAUTENG

Report to the Water Research Commission

by

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WRC Report No: 631/1/01
ISBN No: 1 86845 717 6

EXECUTIVE SUMMARY

Various studies have suggested that in order to ensure access to adequate sanitation facilities for all in the country within the constraints of the country's financial resources, it will be necessary to use a mix of levels of service[1], an option which (ignoring costs of pollution[2]) is significantly cheaper than high levels of service throughout: At the Water and Sanitation 2000 workshop in 1991 a scenario was proposed in which some 50% of sanitation systems in the urban areas of the country by the year 2000 would be ventilated improved pit (VIP) latrines (Jackson, 1991). Subsequently, the Municipal Infrastructure Investment Framework (MIIF) study (Ministry in the Office of the President and the Department of National Housing, 1995) proposed a programme of infrastructure provision that would eliminate much (but not all) of the backlog within 5 to 7 years and would match service levels with predicted household income levels in 10 years (i.e. by the year 2005). This programme would result in a 55:25:20 distribution nationally between full, intermediate and basic levels of service.

Both studies therefore have envisaged a significant amount of on-site sanitation in use in the urban areas of South Africa for the foreseeable future. However, a concern that is often raised in relation to the use of on-site sanitation is the potential pollution of water resources that is associated with these systems. This concern about environmental impact of on-site sanitation systems appears to be serious enough to persuade some decision-makers in the urban areas of the country to opt for the provision of full water-borne sanitation where, but for this concern about environmental impact, on-site sanitation might have been used, thereby foregoing the significant potential cost saving in the construction, operation and maintenance of the service.

There is therefore a need to translate the environmental impact of sanitation systems (and on-site sanitation in particular) into financial terms so as to enable a comparison of these systems to be made, which includes not only the cost of the construction, operation and maintenance of the systems, but also the cost of their respective environmental impacts.

This study:

- provides a methodology for assigning a financial cost to the environmental impact of different sanitation systems;
- provides a first estimate of the comparative costs of pollution from different sanitation scenarios in Gauteng, as well as a very rough first estimate of the comparative costs of pollution from different sanitation systems in general.

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1 A *basic* level of service for sanitation would comprise on-site sanitation (e.g. a VIP latrine), while an *intermediate* level of service would comprise simple water-borne sanitation. Simple water-borne sanitation may include on-site systems such as the LOFLOS (low flush on-site sanitation system, also referred to by some as an aquaprivy). A *full* level of service would comprise full water-borne sanitation. A *basic* level of service is sometimes referred to as a *low* level of service, while a *full* level of service is referred to as a *high* level of service. Lower levels of sanitation service therefore tend to be on-site services, whereas higher levels of service tend to be off-site services.

2 The term 'pollution' or 'pollutant' is used where the concentrations exceed acceptable levels. Otherwise the term 'contamination' or 'contaminant' is used.

is the fact that the concentration of PO_4-P entering Hartbeespoort Dam at weir A2H012 was virtually the same as the concentration of effluent leaving the Northern works (WWTW) some 30km away.

3 The *effect of the wetlands on the Klip River* was not investigated in depth in this study. The effect of wetlands on the nutrient loading on the Vaal Barrage - certainly compared with Hartbeespoort Dam - may be very significant.

4 The *existing* (REM) models for both nutrient budget and nutrient-algae poorly described lake response in Hartbeespoort Dam over the past 10 years.

5 Accounting only for phosphorus, a (modified) nutrient-algae model adequately (for the purposes of this study) described the lake response. This implies that even if the lake is nitrogen-limited at certain select times, the effect of phosphorus is overriding.

6 By comparison with water-borne sanitation discharges - even from well-functioning WWTW meeting the special standard of 1mg/l PO_4-P - pollution from on-site sanitation is negligible. The 'wild card' is grey water; although the effect is not completely random in that if the contaminants remain in the subsurface, it isn't a problem. It needs some serious attention. A controlled experiment may be the best approach to further investigation. Pillay by her assumptions suggested that it was negligible. Ashton and Grobler in their Botshabelo study identified it as a critical question, and presented a range of scenarios.

7 Nitrate contamination of groundwater *will* occur. In Gauteng, contamination of groundwater has *already* occurred (e.g. in Soshanguve). Groundwater is certainly a strategic resource. Dolomitic areas need special consideration. However, fractured rock aquifers are small.

8 It has been assumed in this study that one is only concerned with human wastes i.e. that one is able to address the problem of inorganic salts, refractory organics, heavy metals etc by other means - and at source.

9 Because WWTW effluent standards are concentration-related (e.g. 1mg/l PO_4-P), one needs to keep an eye on growth of household water consumption (and hence sewage flow) for the full water-borne (WB) LOS. The reason is that if the flow volume doubles (for the same concentration of contaminants), then the *mass load* doubles (while still meeting the effluent standard). That can have a serious effect on the receiving impoundments. *Mass load* may well be a more appropriate measure for monitoring contaminant levels than *concentration*.

10 In terms of environmental impact, there is little difference between basic (e.g. the VIP) and intermediate on-site sanitation systems (e.g. the LOFLOS).

Costing

1 For all water treatment - both surface water and groundwater - the cost is a *step-wise function* as one moves to new processes in the treatment train, with deteriorating raw water quality.

2 *Costs of surface water treatment:* For the smaller sized - i.e. 50Ml/d - plant capacity (2000 costs) the cost sequence for different process combinations is estimated as follows:

- conventional (settling and filtration) 30c/kl
- conventional + flotation 37c/kl
- conventional + PAC 36c/kl
- conventional + GAC 50c/kl
- conventional + flotation + GAC + ozone 65c/kl

For a large capacity works (i.e. 200Ml/d) water treatment costs are about 20-25% lower than the above figures.

3 *Maximum* additional cost of surface water treatment to deal with poor quality raw water roughly *doubles* the costs of conventional treatment. For a relatively small works (50Ml/d) the magnitude of the increase (from 30c/kl to 65c/kl) amounts to about 35c/kl. For a larger works (200Ml/d), the proportional increase would remain about the same, but the magnitude of the increase would be somewhat less - about 30c/kl.

4 *Costs of groundwater treatment:* Treatment of groundwater resources is considerably more expensive than the treatment of surface water resources - with groundwater treatment ranging between R1.60/kl and R3.15/kl depending on plant capacity and process.

5 Because groundwater is generally not treated before use (in certain cases, it may be disinfected), the *additional* cost of treatment due to poor raw water quality for groundwater is suggested to be the *full* cost of treatment. This may not be entirely reasonable, but is suggested as a *very worst case* scenario for the purposes of this study.

6 Assuming this to be the case, the *additional* cost of groundwater treatment is somewhere between 4 and 9 times the *additional* cost of surface water treatment (30-35c/kl).

7 *Costs of provision (i.e. construction, operation and maintenance) of the different levels of service of water supply and sanitation* in Gauteng (2000 costs) are:

- Stand-pipe and VIP (basic) R130/cap.a
- Yard tap and aqua-privy (intermediate) R160/cap.a
- House connection and water-borne sanitation (full; *essential* use) R260/cap.a
- House connection and water-borne sanitation (full; *convenience* use) R530/cap.a

8 Assuming a maximum yield (assumed to be natural MAR) for the Gauteng portion of the catchment of the Vaal Barrage downstream of Vaal Dam - essentially consisting of the catchments of the Suikerbosrant River (C21) and the Rietspruit/Klip River (C22) - of 275Mm^3/a at an additional unit cost of treatment of 30c/m^3, the total *additional* cost of treatment will amount to R82.5, say R83million/a. For a population of 4.5 to 5million people in the catchment (in 2000), this translates to only R18, say R20/cap.a. At the lower concentrations of contaminants, it will increase the use of PAC (say 7c/kl), which amounts to less than R4/cap.a.

9 A key requirement is that the (clean) water imported from Lesotho Highlands should not be mixed with (contaminated) water from the Vaal Barrage (requiring more sophisticated treatment processes).

10 Similar calculations to those for surface water can be made for the use of groundwater resources. Assuming a maximum yield (assumed to be the Groundwater portion of the Groundwater Harvest Potential) for the Gauteng portion of the catchment of the Vaal Barrage downstream of Vaal Dam - essentially consisting of the catchments of the Suikerbosrant River (C21) and the Rietspruit/Klip River (C22) - of 125Mm^3/a at an additional unit cost of treatment of R1.90/m^3, the total *additional* cost of treatment will amount to R237.5, say R238million/a. For a population of 4.5 to 5million people in the catchment (in 2000), this translates to only R53, say R50/cap.a.

11 For the Gauteng portion of the catchment of the Vaal Barrage downstream of Vaal Dam, the sustainable yield of groundwater is about *half* that of the surface water. The additional cost of treatment of groundwater due to deteriorated raw water quality is about *five* times

the equivalent additional cost of treatment for surface water. Translated to a cost per person per year, the additional cost of treatment of groundwater is therefore about 2.5 times the equivalent cost for surface water treatment. However, with current utilisation of groundwater of this catchment only about 6% (7.5Mm^3/a) of the maximum yield, this cost is still far from being realised.

12 By comparison with the costs of a higher level of service of water supply and sanitation, the maximum additional costs of treatment are small. For surface water, the additional cost of treatment (R20/cap.a) is only about 15% of the difference in cost between a basic and a full level of service (*essential* use) (R130/cap.a). If water usage for the full level of service increases towards *convenience* use, then the relative cost of treatment will drop even more. For groundwater, the additional cost of treatment (R50/cap.a) is about 40% of the level of service cost difference.

13 In summary, even *conservative* (i.e. high) estimates of additional treatment costs (either surface water or groundwater), *fully* (i.e. very conservatively) assigned to pollution from sanitation systems, are still *well less than half* the cost difference between basic and full (essential use) levels of service of water supply and sanitation (based on the particular catchments used in the analysis).

Application of model to Hartbeespoort Dam

1 From 1990 sanitation figures, there are not that many people with inadequate sanitation in Gauteng. Most are in the 'fringe' areas. These will start to be included in the cross-boundary municipalities; but if one is looking at Gauteng only, there isn't a massive problem. 90% have full water-borne sanitation.

2 Based on estimated population figures and effluent flows from WWTW, water usage for sanitation in the Hartbeespoort Dam catchment appears to be considerably higher than (about double) the figures originally estimated for that level of service. The variation in flow is large enough to warrant more than one level of service for water-borne sanitation (e.g. low level use and high level use); although it is likely that there will be less variation in per capita contaminant loads than in per capita flows. It is unclear whether these changes in water usage occur evenly, in which case more than two (say three i.e. low, medium and high) levels of service for water-borne sanitation may be necessary, or whether there is a step-wise change, in which case the two levels of service may suffice.

3 A not unreasonable flow/TP relationship, which *aggregated* both point and non-point sources, could be identified at weir A2H012. Such a flow/load relationship could *not* be established for Northern works alone; nor could it be established for weir A2H012 minus Northern works. This is anomalous. A possible explanation is that there is in-stream sedimentation of P, and transport of this P into Hartbeespoort Dam is more dependent on general stream flow than on discharge from the WWTW. This is also supported by the fact that spikes of PO_4-P discharged from WWTW are not evident in the flows entering Hartbeespoort Dam; neither is any clear lag evident between discharge from WWTW and entry into Hartbeespoort Dam (in contrast to what Pillay found for Inanda Dam). To draw any further conclusions would require more detailed analysis.

4 The response of the lake to contaminant loads is not static. In particular, it appears that either an algal species shift or a change in the response of the algae to nutrient load can be triggered by events such as floods or droughts. These changes in lake response overshadow any changes in nutrient loading. The increased incidence of algal blooms in Hartbeespoort Dam since February 1996 has not been as a result of increased

contaminant loading, but rather as a result of changed lake response, which appears to have been triggered by the high flows and contaminant loads of February 1996. Once the shift had occurred, the lake did not revert to its earlier response characteristics.

5 In terms of allocation of the cost of pollution, approximately *half* of the increased cost of surface water treatment as a result of deteriorated water quality could be attributed to sanitation systems, and most of this to full water-borne sanitation.

General comments + conclusions

1 While in themselves, most of these findings are not entirely new (virtually all of them are based on *existing* data), it is the *implication* or *significance* of a finding in one area (e.g. planning) for another area (e.g. water quality) that is particularly noteworthy.

2 Water-borne sanitation (WB) discharges directly to the surface watercourses. It is currently the major contributor to pollution (primarily phosphorus) from sanitation systems in Gauteng.

3 Even effluents meeting the effluent quality standards have a major impact on water bodies; and, added to that is the fact that a number of the sewage treatment works do not meet the standards at all times.

4 The situation in Gauteng with respect to sanitation provision and consequent pollution over the next 10 years appears to be slow to change: It appears that it is water-borne sanitation that is - and will continue - to have the major effect on lakes in Gauteng (with a bit of a 'wild card' being diffuse load washed off the *surface*). Although one can get significant changes in demographics, settlement patterns and LOS at a local (i.e. municipal) level in a relatively short space of time (say, of the order of two or three years), it takes a fairly extended period of time (say, of the order of a decade or two) to change the overall patterns of a large area such as Gauteng.

5 Unless the 'polluter pays' principle is established, there is little incentive to use a cheaper system than full water-borne systems.

6 With return flows from WWTW making up such a large proportion of the flow into impoundments such as Hartbeespoort Dam, it is becoming difficult to separate out issues of quality from issues of quantity. More specifically, some service providers may prefer to use (and treat) return flows of poor quality rather than import expensive but excellent quality water through inter-basin transfer schemes.

7 Environmental impact is one of several factors to be considered in the choice of level of service of sanitation. It is important not to confuse these different factors. Environmental impact should *not* be given as the reason for not using a particular system, when in fact the reason is motivated by other considerations, such as promotion of equity among users.

In the light of the above conclusions, the following recommendations are made:

1 That the method of pollution costing proposed in this study be *adopted* as an input to deciding whether or not to use on-site sanitation;

2 That policy regarding sanitation use be set at *provincial level - or higher* i.e. at national level - and that DWAF (as custodian of the country's water resources) issue permits for the use of on-site sanitation;

3 That a *workshop* be held to publicise the results of this work, and to identify priority areas for implementation and further development of the principles proposed in this study.

Critical issues that require further investigation include the following:

1 The environmental impact of grey water discharged to the ground surface;
2 The mechanisms surrounding changes in the response of algae to nutrient loads - and possible interventions to control this;
3 The stages at which new water treatment processes need to be introduced to deal with deteriorating raw water quality;
4 Quantitative estimates of the costs of loss of recreation and property value as a result of deteriorated impoundment water quality;
5 Clearer identification of the characteristics of natural resources (including both quantity and quality) and the 'ownership' of these.

ACKNOWLEDGEMENTS

The research in this report emanated from a project funded by the Water Research Commission and entitled:

"Assignment of a financial cost to pollution from on-site sanitation, with particular reference to the PWV"

The Steering Committee responsible for this project consisted of the following persons:

Dr NP Mjoli	Water Research Commission (Chairperson)
Mr ME Mosia	Water Research Commission (Secretary)
Dr G R Backeberg	Water Research Commision
Dr J Howard	Umgeni Water
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Mr HC Chapman	Water Research Commission (Chairman)
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The financing of the project by the Water Research Commission and the contribution of the members of the Steering Committee is gratefully acknowledged.

This project made use of data from a range of individuals and institutions, for which the authors would like to express their sincere thanks:

- Department of Water Affairs and Forestry, for flow and water quality data;
- Department of Planning and Local Government, Gauteng Province, for digital planning data;
- Council of Geosciences, for geotechnical data;
- Rand Water, for literature and water quality data;
- Greater Johannesburg Metropolitan Council, Wastewater Department, for flow and water quality data for their wastewater treatment works, as well as access to technical reports, and to their technical library;
- Stewart Scott Inc. for access to technical reports.

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GLOSSARY OF ABBREVIATIONS

AGP	Algal Growth Potential
APHA	American Public Health Association
Chl *a*	Chlorophyll *a*
CPA	Cape Provincial Administration
CPI	Consumer Price Index
CVM	Contingent Valuation Method
DAF	Dissolved Air Flotation
DBSA	Development Bank of Southern Africa
DIB	Development Information Bureau
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
GAC	Granular Activated Carbon
GIS	Geographic Information System
GSDF	Gauteng Spatial Development Framework
GWS	Government Water Scheme
HRI	Hydrological Research Institute
LOFLOS	Low Flush On-Site Sanitation system
LOS	Level of Service
MAE	Mean Annual Evaporation
MAP	Mean Annual Precipitation
MAR	Mean Annual Riverflow
MCL	Maximum Contaminant Level
MIIF	Municipal Infrastructure Investment Framework
NIWR	National Institute for Water Research
OECD	Organisation for Economic Co-operation and Development
O&M	Operation and Maintenance
PAC	Powdered Activated Carbon
PPI	Producer Price Index
PWV	Pretoria-Witwatersrand-Vaal
REM	Reservoir Eutrophication Model
RLDP	Rapid Land Development Programme
RO	Reverse Osmosis
RSA	Republic of South Africa
RSEM	Reservoir Specific Eutrophication Model
SRP	Soluble Reactive Phosphorus
THM	Trihalomethane
TOC	Total Organic Carbon
TPA	Transvaal Provincial Administration
UF	Urban Foundation
UF	Ultrafiltration
UK	United Kingdom
VIP	Ventilated Improved Pit latrine
WATERTEK	Division of Water Technology, CSIR
WB	Water-borne (sanitation system)

WHO	World Health Organisation
WRC	Water Research Commission
WR90	Water Resources 90
WRSM90	Water Resources Simulation Model 90
WW	Waterworks
WWTW	Wastewater Treatment Works
WTW	Water Treatment Works

1 INTRODUCTION

1.1 Motivation

Various studies have suggested that in order to ensure access to adequate sanitation facilities for all in the country within the constraints of the country's financial resources, it will be necessary to use a mix of levels of service[3], an option which (ignoring costs of pollution[4]) is significantly cheaper than high levels of service throughout: At the Water and Sanitation 2000 workshop in 1991 a scenario was proposed in which some 50% of sanitation systems in the urban areas of the country by the year 2000 would be ventilated improved pit (VIP) latrines (Jackson, 1991). Subsequently, the Municipal Infrastructure Investment Framework (MIIF) study (Ministry in the Office of the President and the Department of National Housing, 1995) proposed a programme of infrastructure provision that would eliminate much (but not all) of the backlog within 5 to 7 years and would match service levels with predicted household income levels in 10 years (i.e. by the year 2005). This programme would result in a 55:25:20 distribution nationally between full, intermediate and basic levels of service.

Both studies therefore have envisaged a significant amount of on-site sanitation in use in the urban areas of South Africa for the foreseeable future. However, a concern that is often raised in relation to the use of on-site sanitation is the potential pollution of water resources that is associated with these systems. This concern about environmental impact of on-site sanitation systems appears to be serious enough to persuade some decision-makers in the urban areas of the country to opt for the provision of full water-borne sanitation where, but for this concern about environmental impact, on-site sanitation might have been used, thereby foregoing the significant potential cost saving in the construction, operation and maintenance of the service.

There is therefore a need to translate the environmental impact of sanitation systems (and on-site sanitation in particular) into financial terms so as to enable a comparison of these systems to be made, which includes not only the cost of the construction, operation and maintenance of the systems, but also the cost of their respective environmental impacts.

This study:

- provides a methodology for assigning a financial cost to the environmental impact of different sanitation systems;
- provides a first estimate of the comparative costs of pollution from different sanitation scenarios in Gauteng, as well as a very rough first estimate of the comparative costs of pollution from different sanitation systems in general.

---

3 A *basic* level of service for sanitation would comprise on-site sanitation (e.g. a VIP latrine), while an *intermediate* level of service would comprise simple water-borne sanitation. Simple water-borne sanitation may include on-site systems such as the LOFLOS (low flush on-site sanitation system, also referred to by some as an aquaprivy). A *full* level of service would comprise full water-borne sanitation. A *basic* level of service is sometimes referred to as a *low* level of service, while a *full* level of service is referred to as a *high* level of service. Lower levels of sanitation service therefore tend to be on-site services, whereas higher levels of service tend to be off-site services.

4 The term 'pollution' or 'pollutant' is used where the concentrations exceed acceptable levels. Otherwise the term 'contamination' or 'contaminant' is used.

The key starting principles inherent in this study are as follows:

- *Environmental impact is a major consideration* in the choice of level of service (LOS) of sanitation.
- The disbenefits of environmental impact need to be *formulated in the same terms* as the cost saving of lower vs higher LOS.
- In dealing with a problem of this magnitude, a *pilot study* is required that develops the arguments, obtains the best answer possible with available data, and identifies those areas that required further investigation. The reasons for undertaking a pilot study in this instance are two-fold: Firstly, it is considered that one can get a *reasonably good answer* on such a basis. Secondly, there has been little work done which *integrates* the various discipline-specific components. It was considered that the integration of the topics could provide useful insight into where more work was required. In some areas, the data already obtained would be sufficient (in some areas, more than sufficient); in others, there would be insufficient data; in other areas still, there would be virtually no data at all.
- A central question is used as a *focus* for the study, irrespective of the disciplinary boundaries that it crossed, namely 'How can one assign a cost to the pollution from different levels of service of sanitation, so as to be able to combine the cost of pollution with the cost of construction, operation and maintenance of the facilities'. The question was directed towards supporting a *decision* on whether - and under what conditions - the large-scale use of on-site sanitation in Gauteng might be permitted.
- If a decision on whether - and under what conditions - the large-scale use of on-site sanitation in Gauteng might be permitted is a policy decision made at provincial level - or higher i.e. at national level - then it needs to be investigated at that level i.e. *at least at provincial level* (hence Gauteng).
- There is a need for *application and illustration* of principles.
- The project therefore sets out to see firstly whether this approach is *feasible at all*; secondly, whether it can *deliver any useful results.*

1.2 Summary of previous work

This study leads on from earlier work by Fourie and Van Ryneveld (1994) and others which sought to provide a better understanding of the environmental impact of on-site sanitation systems in South Africa, and of the range of guidelines for the control of such impacts. This earlier work by Fourie and Van Ryneveld (1994) covered 2 main areas:

- Literature review of the fate in the subsurface of contaminants from on-site sanitation
- Guidelines/strategy for evaluating the environmental impact of on-site sanitation

The conclusions of the work were as follows:

With respect to the *fate in the subsurface of contaminants from on-site sanitation,* the following conclusions were drawn (Fourie and Van Ryneveld, 1995):

Contamination from on-site sanitation is not a single entity, but has a number of components, which may be divided into two broad categories:

- Microbiological contaminants: viruses, bacteria, protozoa and helminths.

- Chemical contaminants: of primary significance, nitrogen and phosphorus, in the form of nitrate and phosphate respectively.

There are different mechanisms of movement of the contaminants and the contaminants themselves are subject to alteration. There are different processes which affect these changes, which are usually temporal in nature:

- Movement takes place primarily by advection, with little diffusion occurring.
- There are numerous other processes which retard or reduce mobility. The following processes affect specific contaminants:
    - *Physical filtration* removes helminths and protozoa very effectively. This factor is of course very dependent on the particle size distribution of the soil, with a well-graded soil (i.e. a soil with a wide and evenly distributed particle size distribution) being the most effective.
    - Phosphate is removed by *adsorption*; although this process is usually extremely effective, the mechanisms of release are not clear. The soil has a certain adsorption capacity and will not adsorb phosphate beyond that limit.
    - Nitrate appears to act like an ideal tracer, but the effects of *denitrification* are not clear.
- The movement of viruses and bacteria is retarded by various processes, including filtration, adsorption and complexation.

Certain clear statements may be made concerning pollution risk in specific hydrogeological conditions:

- Firstly, there is a major difference between the vadose or unsaturated zone and the saturated zone. The hydraulic conductivity in the vadose zone is usually substantially less than in the saturated zone. The rate of movement of contaminants through an unsaturated soil may be several orders of magnitude slower than through a saturated profile of the same soil.
- Secondly, one may make certain limited comments about different subsurface geological conditions:
    - Dolomitic/fractured bedrock close to or at the ground surface is problematic for <u>all</u> contaminants.
    - By contrast, sandy soils are not a problem for microbiological contamination, unless the hydraulic conductivity is extremely high (e.g. a coarse gravel). However, even in sandy soils nitrate contamination remains a potential risk.

With respect to the quality of the data, there is a lack of good-quality long-term data, in which the movement of all the contaminants of concern (e.g. indicator bacteria and viruses, and nitrates) has been simultaneously monitored.

Since the seminal work of Lewis et al. (1980) 20 years ago on the risk of groundwater pollution by on-site sanitation, there has been no research that advances this particular topic. There have been a number of projects that address one or other aspect of the problem, but there has been no concerted effort to establish unequivocally the health and environmental risks associated with on-site sanitation.

With respect to *guidelines/strategy*, it was concluded that simplistic guidelines that consist of a few, easy-to-follow rules are unable to take account of the multitude of variables that influence the potential environmental effect of on-site sanitation. The following strategy was therefore suggested (Van Ryneveld and Fourie, 1997):

- Define compliance requirements that must be met, in terms of both physical location (point of compliance) and allowable contaminant concentration; in other words, what contaminants are allowed where and in what concentration.

  Of particular importance to note here is that compliance requirements may vary, depending on the objectives of these requirements. If groundwater is to be used for drinking purposes, then there will be a particular compliance requirement, whereas if surface water resources are the primary concern, and protection of the groundwater is not a consideration, some other compliance requirement will prevail. Existing guidelines generally restrict their attention to the protection of the groundwater for drinking purposes. Recent formulation of the three-tier approach to the protection of groundwater in South Africa (Xu and Braune, 1995: 6 to 8; Xu and Reynders, 1995) does appear to recognise the dependance of compliance requirements on the use to which the resource will be put in the second and third tiers of the guidelines. Nevertheless, more explicit provision needs to be made for other situations, where protection of groundwater may not be an issue, but where protection of surface water may be important.

  A key consideration in the determination of a point of compliance is the identification of possible contaminant pathways (see also Figure 4.2). The point of compliance may then be viewed as a point along the pathway of a contaminant between a source and a receptor, a specific example being the intersection of the contaminant pathway and the boundary of the water resource being protected. In the case of groundwater at some depth below the base of a pit latrine, the point of compliance could be the intersection of the pathway and the water table; alternatively the point of compliance could be a tap or point of delivery from a hand-pump. To take a different example, a possible pathway from a source consisting of a pit or soakaway of an on-site sanitation system discharging to the subsurface is as follows: travel in the subsurface for a distance; then surface and discharge into a surface watercourse; travel along the watercourse to an impoundment. The point of discharge of the watercourse into the impoundment could be the point of compliance.

- Estimate the risk of pollution of water resources by viruses or bacteria using the 'residence time' approach. This entails a calculation of how long it would take a 'particle' of water to travel from a latrine to the point of compliance. If the latrine is situated above the water table, then this residence time might include time spent in both the vadose and the saturated zones. Techniques for doing this could vary from simple, hand calculation techniques, to sophisticated finite element computer analyses, depending on the complexity of the hydrogeological conditions underlying the latrine. If the travel time exceeds about 150 to 200 d, then according to survival times recorded in the literature, microbiological contamination should be eradicated in all but exceptional circumstances.

- To estimate the risk of pollution of water resources by nitrates, use a mass balance approach. This approach requires knowledge of a number of factors, including the proportion of nitrogen leached from the on-site sanitation system, the amount of rainfall that infiltrates the subsurface, and the rate of denitrification in the subsurface. Very rough estimates of these factors have been made by various authors, which require further investigation.

- For both microbiological and chemical contaminants, use a probabilistic approach (as far as the available data allows), allowing appropriate margins of safety in design. What constitutes an appropriate margin of safety is still to be determined. In the absence of more detailed information and analysis, it remains simply a matter of judgment, erring on the conservative side.

- Until such time as adequate data relating to the input parameters that are required for the above approach become available, it will be necessary to carry out field monitoring of at least selected on-site sanitation schemes if the water resources are to be protected (as suggested by Ward and Foster, 1983; Ward and Schertenleib, 1982; Ward, 1989). This approach is necessary to provide an early warning system that contaminant levels may build up to hazardous levels at some time in the future, and to allow alternative sanitation strategies to be implemented, or remedial measures to be taken.

Following on from the above conclusions, Van Ryneveld and Fourie (1997) asserted that while conservative assumptions based on the available data (together with monitoring of at least selected on-site sanitation schemes to provide an early warning of contaminant build-up and to confirm the validity of such assumptions), may be adequate as a first estimate to address most of the uncertainties in the factors used in the strategy set out out above, there is one issue for which such assumptions cannot as easily be made. This is the choice of compliance requirements (i.e. what contaminants are allowed where and in what concentrations); and it is probably the most critical issue to be addressed in implementing the strategy set out above.

Inherent in this choice are decisions as to which water resources (be they surface water or ground water resources) one wishes to protect and what levels of contamination one is prepared to permit. Such decisions are likely to vary from resource to resource. There is therefore an urgent need for a set of general principles for the determination of compliance requirements, and for the application of such principles to the different water bodies (both surface water and groundwater) in South Africa. The establishment and application of such a set of principles could be seen as an extension of the higher tiers of the three-tier approach to the protection of groundwater in South Africa (Xu and Braune, 1995; Xu and Reynders, 1995). Such principles will need to have a three-fold basis:

- the first is that the understanding of the contaminants, their characteristics and their impact on human health and the natural environment must be technically sound;
- the second is that some value must be assigned to the resources, to any possible damage caused and to possible remedial measures, using environmental economics principles;
- the third is that a policy decision regarding appropriate compliance requirements must be made, to which technical and economic principles can lend support but cannot fully guide.

Until such compliance requirement principles have been established, it will be difficult to make any consistent and comprehensive decisions as to what sanitation systems may be permitted in which areas, particularly in the urban areas of the country.

It was further concluded that in the light of available evidence, evaluation of environmental impact of sanitation systems should not be confined to on-site sanitation alone, but should be extended to *all* forms of sanitation system, including water-borne sanitation systems as well.

Other work carried out by Fourie and Van Ryneveld included a field study on the *fate in the subsurface of contaminants from LOFLOS sanitation systems in Ivory Park, Gauteng* (Fourie and Van Ryneveld, 1993). This work complemented work by Palmer Development Group, including work by them on the characterisation of the effluent from LOFLOS sanitation systems as well as a simple model for the assessing the environmental impact of different sanitation systems (Palmer Development Group, 1992b).

1.3 Relationship between previous work and this study

With respect to the *relationship between the earlier work described above and this study*, the following comments may be made:

Earlier work by Fourie and Van Ryneveld (1994) has largely established a sound technical understanding of the contaminants, their characteristics and their impact on human health and the natural environment: the first component of the basis for the establishment of a set of principles for compliance requirements.

In the light of the fact that sanitation systems are being installed on an ongoing basis and the need for some policy/guidelines with regard to environmental impact of these systems, DWAF has, within a short time frame, developed a groundwater protocol for immediate implementation, to be reviewed after a year: the third component of the basis for this set of principles. One of the key elements of the groundwater protocol is that it provides a simple basis for distinguishing between instances of higher risk and instances of lower risk of groundwater pollution, and sets out responsibilities and procedures for investigation of each level of risk (requiring more detailed investigation for high risk instances, and decision-making by higher level personnel). While the protocol does not fully resolve the question of whether on-site sanitation can be used in any particular instance, it does give a framework within which such decisions can be made.

This study addresses a number of aspects of the second component of the basis for compliance requirement principles set out above, namely the assignment of value to the resources, to any possible damage caused and to possible remedial measures, using environmental economics principles.

The establishment of compliance requirements is an iterative process: While it is difficult to make any consistent and comprehensive decisions as to what sanitation systems may be permitted in which areas in the absence of compliance requirements, so too it is difficult to establish compliance requirements in the absence of an understanding of the implications of different sanitation scenarios in terms of their costs and their environmental impacts. In other words, one cannot set compliance requirements until one knows what the broad social and economic implications of these requirements for the country are likely to be; neither can one make any progress with deciding what levels of service to provide where until one has set appropriate compliance requirements. The two issues need to inform one another.

This point was made by Briscoe et al. (1986) when they pointed out that water quality standards (and hence any environmental regulations) were based on social and economic considerations rather than simply technical considerations; and therefore needed to take cognisance of the social and economic conditions prevailing in a particular country. The principle was further illustrated in a slightly different context by Cotruvo (1989) when he set out the criteria for the setting of maximum contaminant levels (MCLs) for carcinogenic substances in the United States of America, which were based on what was technically possible and affordable for the country.

While much of the work on environmental impact of sanitation systems to date has centred on technical considerations and on making policy decisions in order to allow the installation of sanitation systems to proceed in a reasonable manner, this study makes a link between the technical and social or economic considerations, in order to better inform the policy decisions that need to be made. One specific objective of this study has been to relate issues of environmental impact of sanitation systems back to the debate concerning level of service. The methodology followed in achieving this is the subject of the next chapter.

2 A METHODOLOGY FOR ASSIGNING A FINANCIAL COST TO POLLUTION FROM SANITATION SYSTEMS

As stated in section 1.1, this study:

- provides a *methodology* for assigning a financial cost to the environmental impact of different sanitation systems;
- provides a *first estimate* of the comparative costs of pollution from different sanitation scenarios in Gauteng.

There are two key components to this, as follows:

- *identification (and quantification) of impacts* of contaminants from sanitation systems;
- *assignment of a financial cost* to those impacts.

2.1 Identification of impacts of contaminants from sanitation systems

While the objective is to assign a cost to the *contamination*, it is the *impact* rather than the contamination itself that needs to be costed. Contamination is therefore costed at *receptor*, where the impact is felt, rather than at the *source*. This has a number of implications:

- The receptor may be separated by some *distance* from the source.
- In travelling (along a pathway) from source to receptor, there is generally *degradation or removal of contaminants*, so that the contaminants reaching the receptor are different in amount - and sometimes in form as well - from what they were at source.
- There is a *time lag* between contaminants being discharged at source and arriving at the receptor, which can be considerable.

There are three further consequences to this:

- It is *more difficult to measure contaminant loads at the receptor than at source* - or to allocate the loads at receptor to a particular source;
- Contamination from sanitation systems are generally *not internalised* in the cost of provision of these facilities i.e. they are externalities. The case does exist where contamination from a sanitation system contaminates the water resource used for the same individual's water supply; which means that the cost of contamination will be borne by that individual in the cost of the water supply; but in Gauteng, this is not the norm.
- Because of the time lag between contaminant discharge and its impact being felt, one *may be able to permit pollution (and degradation of the resource) for a limited period of time, and then clean up later*. The cost of the pollution would then be the cost of clean-up in the future (discounted to the present) plus the value of the loss of amenity etc for the period for which that loss applied.

As the survival times of most micro-organisms are not particularly long and filtering/removal mechanisms in the subsurface generally efficient, they do not as a rule affect water resources in a substantial and long-term manner; but more importantly, even if they do, they are relatively easily removed by conventional water treatment processes, and therefore do not have a significant cost attached to them. Chemical contaminants (particularly nitrogen and phosphorus) on the other hand, can have a significant and long-term impact (in different ways) on both surface and groundwater resources, and are therefore the primary focus of this study. For groundwater resources, high nitrates are a direct problem for drinking water; for surface water resources, nitrogen and phosphorus cause eutrophication of the water bodies, particularly man-made reservoirs and lakes.

Major negative impacts of eutrophication can be summarized as follows:

- *Increased primary productivity* in the lake/reservoir with an accompanying shift towards dominance of green algae and frequent occurrence and dominance of blue green algae.
- *Significant increase in the concentration of suspended solids* in the lake/reservoir water mainly due to increased concentrations of algae, zooplankton, bacteria and detritus.
- *Increased occurrence of taste and odour causing organic substances.* These substances are either a result of biological metabolism (excretion products and leaching) or byproducts of breakdown of metabolic products and dead microorganism cells.
- *Leaching out and release of organic substances which* under certain environmental conditions *can form complexes with other substances* present in lake/reservoir water.
- *Formation of humic substances* in the process of natural conversion of organic substances.
- *Occurrence of coloration* of water as a result of biological formation and release of pigments (chlorophyll, carotine etc.)
- *Reduction in water transparency* due to increased suspended solids concentration (algae etc.)
- *Occurrence of intensive infestations by higher aquatic plants* both rooted and floating with emphasis on littoral and shallow zones.
- *Increased pH of lake/reservoir water to alkaline range* due to consumption of aqueous CO_2 by photosynthetic organisms.
- *Changes in the oxygen regime of the water body* with possible creation of anaerobic conditions in deeper water layers and especially at the sediment water interface due to the consumption of oxygen by the degrading organic matter.

Reducing conditions which occur as a result of changes in the oxygen regime can lead to:

- *Incomplete mineralization of organic substances and release of undesirable gases* (H_2S, CH_4 etc.) with resulting increases in the convective vertical transport of other substances, nutrients especially from the deeper unproductive layers into a productive zone of the lake /reservoir.
- *Reduction of nitrates to ammonia and N_2 gas and reduction of sulphates to H_2S*
- *Release of metals, iron and manganese specifically from the sediments* and a corresponding increase of their concentration in the water column.
- *Formation of iron sulphides at the bottom of the lake and the sediments.*
- *Release of phosphorous from the sediments* and increased concentration in the water column.

Man-made lakes and reservoirs are usually constructed for multiple purposes. As is the case in other water scarce countries where a significant amount of water is recycled in one form or another, eutrophication of these lakes and reservoirs in South Africa has been a major problem. In South Africa water supply (domestic, industrial and agricultural) is the dominant reason behind the construction of dams and the formation of lakes and reservoirs; and it is for water supply purposes (much more so than for recreational, fisheries and similar uses) that eutrophication as a process has a most significant negative impact on the use of lake/reservoir water.

Impacts of eutrophication of specific importance to water supply are as follows:

- *Formation of trihalomethanes (THMs):* When eutrophic water bodies are used as a source of raw water for water supply it often becomes necessary to implement pre- chlorination in order to control negative influences on coagulation and filtration processes and in order to ensure adequate levels of residual chlorine during the disinfection process. Such a practice leads to the formation of THMs which have been declared to be carcinogenic and which are not removed in the conventional drinking water treatment processes. This problem can be partially solved by modification of the treatment process (introduction of additional processes for the removal of THMs) or by the introduction of measures to control the productivity of the raw water source. Additionally, chlorination and disinfection processes can be changed to preclude the formation of THMs.
- *Interference with the process of flocculation:* One of the basic processes used in water treatment is flocculation. By addition of Fe^{3+} and/or Al^{3+} ions to water, positively charged polynuclear hydroxy complexes are formed and are responsible for flocculation and subsequent removal of suspended particles. The formation of the positively charged polynuclear hydroxy complexes is interfered with by the presence of low concentrations of certain algal organic substances and products of their degradation if they possess complexing characteristics. These substances can act as protective colloids for the suspended particles or can prevent the formation of hydroxy complexes. The end result is a reduction in the efficiency of the flocculation process, its possible total collapse or at least an increase in the consumption of flocculants with the resulting decrease in the length of filter runs, increased consumption of wash water and increased production of sludge at the treatment plant.
- *Interference with the algal removal processes:* It is the rule rather than the exception that additional processes for the removal of algae from raw water are necessary when using raw water from eutrophic systems. It should be remembered that some algae are removed more easily than others. For example only 90% of the relatively large algal species *Oscillatoria Rubescenes* can be removed by a multiple flocculation process. Maximum removal efficiency for algae under conventional coagulation, flocculation, filtration process is 99.9%. At times of massive algal blooms in eutrophic systems this efficiency is often not sufficient. The residual algal cells that end up in the distribution network serve as a food web base for the development of micro-zoo benthos, snails etc. Only the use of slow sand filters or infiltration (bank filtration) can achieve 99.99% algal reduction. These processes are, however, sensitive to other organic and inorganic substances usually present in eutrophic raw waters.
- *Decrease in filter performance:* Algal blooms, especially larger diatoms, block filters rapidly. This is valid for both rapid and slow sand filters. Since blooms occur rapidly we are most often not in a position to implement any remedial measures and in order to ensure continuous operation of the treatment plants microstrainers are typically installed and used only at the time of algal blooms with additional cost implications, while still not providing a fool-proof solution.
- *Taste and odour problems:* Taste and odour problems are a normal occurrence when raw water is from eutrophic systems. These are usually caused by *Actynomicetes* which typically follow a blue green algal bloom. The problem is usually solved by the addition of powdered activated carbon prior to the filtration process. The results are nevertheless not always satisfactory.
- *Biological growth in a distribution network:* Even small concentrations of organics of

algal origin in the treated water can cause significant, sudden and unpredictable bacterial growth in the distribution network. The only successful solution to these problems is the disinfection of the distribution network.

- *Interference with disinfection:* The presence of ammonia in raw water which often characterizes eutrophic systems reduces the efficiency of the disinfection process due to the formation of chloroamines. It is not unusual for the formation of nitrites from ammonia to occur also with potential public health hazards if the nitrite concentrations are in excess of 5µg/l. To maintain this standard is very difficult when eutrophic systems are used as a source of raw water.
- *Increased concentrations of Fe and Mn:* The drinking water standards for Fe and Mn are relatively low. In eutrophic water bodies it is usual for Fe and Mn concentrations to be in excess of this standard and additional processes for Fe and Mn removal become necessary, otherwise other operational and technical problems can be experienced.

Bruwer (1979) has provided a similar list of problems caused by eutrophication as follows, which additionally includes a number of problems relating to matters other than water supply:

- Increased costs of water treatment (increased use of chemicals and shorter filter runs);
- Taste and odour problems in drinking water, caused by blue-green algae;
- Extensive anaerobic hypolimnia in lakes with the resultant adverse effects on lake biota such as oxygen-dependent organisms and lake chemistry such as increased concentrations of iron and manganese (Stumm and Morgan, 1970);
- Aesthetic problems associated with massive growth of algae and aquatic macrophytes or both, and when these decay;
- Interference with the recreational uses of water bodies such as swimming, boating, fishing and waterskiing;
- Skin irritations in swimmers;
- Loss of livestock as a result of algal toxins produced by certain algae;
- Fish deaths in saline lakes due to toxin producing algal blooms;
- Adverse effect on adjacent real estate development.

So as to reflect cause and effect more clearly, the above problems can be grouped and explained as follows:

Excessive nutrients (specifically nitrates) cause problems in themselves in that high nitrates can cause health problems for young infants; alternatively, together with sunlight and other environmental conditions, they cause excessive growth of algae (some species of which may in turn produce algal toxins) and macrophytes, causing problems for:

- Various uses of the water itself:
    - drinking water: either toxicity (health) or taste and odour (aesthetics) for humans; toxicity for livestock and other agricultural/industrial uses;
    - use of the water for irrigation/agricultural purposes (not mentioned in the initial list by Bruwer, 1979).
- Uses of the water body or aquatic ecosystem as a whole:
    - recreational use of the water body (swimming, boating, fishing, and waterskiing), including skin irritations in swimmers);
    - the natural resource (fish deaths);
    - aesthetics (how the lake looks and smells).

These problems in turn may have an effect on:

- any areas making use of the water for drinking, agricultural or industrial use;
- adjacent real estate development;
- tourism/use of hotels, casinos etc.

2.2 Principles of assigning a financial cost to the impact of contamination from sanitation systems

In assigning a financial cost to the impacts described above, a number of principles need to be recognised:

Where impact or damage is reversible, the cost of the impact is simply the cost of remedial measures (plus the cost of the lost utility while the remediation takes place); however, where impact is for practical purposes irreversible, the cost of the impact has to consist of a valuation of the resource loss. *Remediation* is more straightforward to assign a cost to e.g. the additional cost of water treatment as a result of deteriorated water quality (of either surface water or groundwater) or the additional cost of control measures to keep lakes clear of macrophytes such as water hyacinth. *Loss of amenity or utility* (e.g. use of the facility for drinking water, boating, skiing, swimming, fishing) as a result of deteriorated water quality of the lake, on the other hand, is much more difficult to assign a cost to. There may be a direct loss of revenue (from entrance fees, permits etc) which is easily quantifiable. One may also measure substitute or surrogate variables e.g. the amount of money invested in recreational equipment, such as boats, fishing gear; however neither of these methods may adequately reflect the true value of the loss.

None of the above measures are likely to measure loss of *non-use value* (consisting of existence, bequest and option value - as against utility value). Existence value is the value that people may assign to a facility simply because it is there, rather than for any use that they may derive from it. Bequest value is value placed on future generations being able to use the facility. Option value is the value placed on the possibility or option of using the facility at a future stage. All three values are real, but subjective and difficult to quantify. A way of quantifying these and other losses is by asking people how much they would be prepared to pay to retain these facilities. Alternatively one can compare the cost of property values in the vicinity of the resource with and without the facilities; however, these methods in turn pose a number of further difficulties in ensuring that the values obtained accurately reflect the value of the loss.

The loss itself may be difficult to define. For example, what part of the resource has been lost if the Vaal Barrage or Hartbeespoort Dam goes eutrophic? Certain characteristics of the lakes may have been lost, but not all characteristics have been lost in their entirety. There may also be alternative places where one can pursue recreational activities, although the scarcity (and therefore the demand for the remaining resources) may be greater.

Other measurement problems include:

- *Difficulty of determining an accurate value in a highly diverse society:* Within a society, total value of a resource or facility is the sum of values placed on that resource or facility by all the individuals in the society. Where income levels vary considerably in a society, priorities may be very different. One portion of the society may value a resource or facility very highly, whereas another portion may assign a very low value to it, making the result difficult to interpret e.g. those benefiting from recreational use may value the resource very highly, but constitute a small proportion of the society.

- *The use of money as a measure of value* can be inadequate e.g. for loss of human life.
- *The choice of discount rate* by which to translate costs or values at different times into present values for comparative purposes can affect relative costs significantly.
- *Whether a loss can be considered a loss at all:* man-made reservoirs are built primarily for the purposes of drinking water. Once built, they may perform an additional function of providing recreation. However, the loss of recreation is not necessarily a loss, because it was never built for that purpose in the first place.

Several of these aspects have been addressed by Green and Tunstall (1991). They raise the question as to whether:

- environmental theories and economic theories of value and choice are compatible for the economic values to be meaningful;
- existing economic theory is adequate to encompass and incorporate such evaluations in a theory of social choice.

The principle reason for arguing for the economic evaluation of environmental resources is that if it is not done, then when the consequences of any decision are compared in monetary terms, if the environmental consequences are not evaluated in similar manner, then the latter will be treated as of no value.

In response to the question that they have posed above, Green and Tunstall (1991) make the point first of all that *economic evaluation is not about money*:

> "Money is only used as a yardstick with which to compare the relative values of different goods. In economics, all values of all goods are treated as subjective. What the economist seeks to do is derive a rigorous method of measuring the values different individuals place upon different goods in order that these values can be compared."

In order for a monetary value to be placed on goods, they need to be marketable, and there needs to be a *market* for them:

> "To be a marketable good, or a private good, it must be possible for the seller to be able to prevent those who do not pay for the good from consuming and using the good. Similarly the use of a particular unit of that good by one consumer must prevent another consumer from using that same unit; it must be consumed rather than used (Samuelson, 1958). For a large range of goods, these conditions do not hold and so there cannot be a perfect market in those goods. The classic example of such public goods is a lighthouse: a shipowner who wishes to warn his ships of a rock by erecting a lighthouse cannot prevent other shipowners from benefiting from the warning given, nor does the warning gained by one ship reduce the value of the warning available to other ships."

In considering contamination from sanitation facilities, it is useful to note that *while sanitation facilities are priced goods (leaving aside considerations of public health), the contaminants from sanitation facilities impact on environmental goods.* Environmental goods generally possess one or more of a number of characteristics, namely (Arrow and Fisher, 1974, quoted by Green and Tunstall, 1991):

- they are public goods;
- the good is available only in discrete lumps;

- reductions in the availability of the good are more or less irreversible.

In this study, we are therefore comparing different sorts of goods. We need to make sure that the methodology that we use in this evaluation is consistent. Green and Tunstall (1991) go on to explain this matter as follows:

> "Where values cannot be estimated from market prices, values must be estimated by other means. For environmental goods, the most widely applicable approach is to ask respondents, through a carefully structured *social survey*, what value they place on a good, how much they are willing to pay for some quantity of that good: the contingent valuation method (CVM) (Cummings et al, 1986; Peterson et al, 1988; Tunstall et al, 1988) For a *public good*, the social value of that good is simply the sum of the amounts that each individual in society is willing to pay for that good....The functional role of values in economics is to enable choices to be made which yield the highest gain for the least sacrifice of resources, where resources are seen as intrinsically limited. Thus the purpose of values is to enable the rate to be determined at which trade-offs are to be made for goods and for priorities to be set. Values are, therefore, in no sense absolute but relative and measure the rate at which we are prepared to sacrifice one good for another, and prefer one good to another."

Green and Tunstall (1991) point out that economic theory has developed on the analysis of the demand for private goods; theory about the demand for public goods has, to date simply been extrapolation from that existing theory. Thus, public goods have been regarded as essentially equivalent to private goods.

Green and Tunstall (1991) also go on to highlight the difference between user and non-user (or intrinsic) value. They point out that:

> "Whilst the evaluation of user, and particularly the recreational and amenity aspects of environmental goods, is proving relatively straightforward, it is argued that there remain a number of theoretical as well as methodological problems before valid and reliable measurement of the non-use values of environmental goods can be achieved."

This study concentrates on user costs, includes the recreational and amenity values of environmental goods, and simply flags the non-user or intrinsic values of the goods.

In this study the methodology has been applied to a real situation i.e to a large metropolitan area in order to *illustrate* the application of the methodology, and to provide a first estimate of the comparative costs of contamination from different sanitation scenarios in the province. More importantly, however, it needs to be recognised that *cost is location-specific*. The reason for this is that while certain matters can be generalised (i.e. made independent of location), others cannot be. To be more specific, the following can be generalised:

- pollution load per capita from different sanitation systems;
- different possible pathways of contaminants to groundwater or surface water;
- cost of treatment for different levels of contamination of raw water.

whereas the following are site-specific and *cannot* be generalised:

- type of water resource (surface water or groundwater);
- response of the resource to contaminant loads e.g. the relationship between nutrient loading and algal production for an impoundment;
- *size* (potential utilisation i.e. what *can* be utilised), *purpose* (irrigation or drinking water) and *extent* of utilisation of the water resource (both the water and water body - which might be utilised for recreation etc).

The resource to which the contaminant loads is discharged is in turn determined by:

- settlement patterns; and
- point of discharge of contaminant load.

These two factors determine the catchment in which the contaminant load will be discharged, and therefore the impoundment to which the contaminant load will be discharged. (Note that it is possible for contamination to be discharged to both surface and groundwater resources).

As a result of this, there is no *unique* cost of contamination from a particular level of service of sanitation. In other words, if the contaminant load from a household using a particular level of service of sanitation is discharged into one impoundment (say the Vaal Barrage), it will have one cost, whereas if the *same* contaminant load is discharged into another impoundment (say Hartbeespoort Dam), it will have a *different* cost.

The allocation of the cost of impact back to the source is not as direct as it might be expected to be: Firstly, contamination (or pollution) damage is incurred only to the extent of *use* of polluted resources. There is not some inherent cost. Where a water resource is little utilized - or not utilized at all - the cost of contamination will be very small. While this may be a true reflection of the damage actually incurred, it is not very instructive from a planning point of view. There is, however, a *cost ceiling* (or maximum cost) which is related to the *firm yield* of each catchment. Provisionally, the firm yield of a groundwater resource is suggested as the recharge less the base flow (otherwise the resource is non-renewable). Similarly, for surface water the firm yield of a resource is suggested as the average flow. Certain reserves may additionally need to be set aside from these yield values to make provision for hydrological variability. Nevertheless, these values represent the opportunity cost of the damage, representing the damage caused assuming *optimum* use of the resource.

Once a ceiling cost has been determined and related to the firm yield of the resource, it is then possible to translate the cost back into a *cost per household*, which is dependant on the number of households contributing the contaminant loads (and dependant on their level of service of sanitation); and it is further possible to compare the cost of different levels of service, including the cost of contamination as well as the cost of the construction, operation and maintenance of the facilities.

2.3 Possible remedial measures for costing purposes

In the application of the methodology to Gauteng in this particular study, remedial measures that might be taken need to be realistic and need to be related to the kind of impact that is expected. These impacts are not the same for all impoundments or water resources. Possible remedial measures may be categorised as follows:

- *Larger dams for water supply as well as recreation* (Hartbeespoort Dam, Roodeplaat Dam, Rietvlei Dam and Vaal Barrage):
  - ponds, aerated lagoons and wetlands on the river or stream flowing into the dam;
  - wastewater treatment works at the inflow to the dams;
  - additional treatment technologies required for treatment of water to potable standards;

  - remedial measures in the dam (e.g. hyacinth removal) for exceptional conditions.
- *Small essentially recreational lakes* (Centurion Lake, Emmarentia Dam):
  - ponds, aerated lagoons and wetlands on the river or stream flowing into the dam;
  - remedial measures in the dam itself (e.g. hyacinth removal) for exceptional conditions.
- *Dolomitic groundwater resources* (Klip River Basin, Atteridgeville, Centurion, East Rand, far West Rand areas):
  - treatment of the water to potable standards, when pumped out for use.
- *Other groundwater resources* (Soshanguve - and Winterveld areas, although just outside Gauteng):
  - treatment of the water to potable standards, when pumped out for use.
- *Streams and rivers:*
  - wetlands to treat the flow in-stream.
- *Other on-site remedial measures:*
  - glucose addition at source.

It should be noted that not all measures in the above list are probable e.g. putting a wastewater treatment works at the entrance to important lakes. While it may be the only way to clean up water to its original quality once is has been contaminated, it is almost certainly cheaper to fix it up by preventing contamination at source. The reason for this is that a large amount of clean water will be added to the flow by the time that it reaches the entrance to the lake, which will offset any natural treatment or degradation of contaminants that may occur in the stream en route. It is left on the list as an option nevertheless.

For the purposes of this study, two remedial measures are considered for quantitative analysis:
- Treatment of water for water supply purposes;
- Remedial work on the impoundments themselves e.g. removal of algal growth and other aquatic plants e.g. water hyacinth.

This study identifies all possible costs, concentrates first on quantifying those costs that are easy to quantify, and makes a very rough first estimate of those costs that are more difficult to quantify. The study also concentrates on the major impoundments where the impact is greatest. Very small impoundments have not been considered.

2.4 Other principles

A number of other technical points should be borne in mind at this stage:
- If water is not to be used for drinking purposes, then it would be treated to a standard appropriate to its use (say for recreational purposes).
- We need to make it clear that it is *not* the case that on-site sanitation *does* pollute and that water-borne sanitation *does not* pollute. Both systems pollute to a greater or lesser degree.
- The principle of making rough theoretical estimates of pollutant loading etc, and then following them up with monitoring in order to confirm them, as suggested by Ward et al. (1982, 1983) and Ward (1989) is suggested again in this study (and its applicability broadened).
- It is important to recognise that a soakaway is a *form of conveyance and treatment*. We are simply using a natural, uncontained form of conveyance.

2.5 Steps in the detailed application of the methodology

Following the broad methodology for the assignment of costs to the impact of contaminants from sanitation systems, it was found to be useful to split the application of this to the particular situation of Gauteng into three sectors:

- planning
- water quality
- costing

Input and output data from each of the sectors are as follows:

- *Planning sector*
  input=demographics and settlement patterns in different unit areas over time;
  output=sanitation by level of service in different unit areas over time.
- *Water quality sector*
  input (output of planning sector)=sanitation by level of service in different unit areas over time;
  output= impact of sanitation on water resources, (i.e. changes in water resource quality) in terms of physical phenomena such as algal blooms or nitrate in groundwater for particular water resources (i.e. surface or groundwater resources).
- *Costing sector*
  input (output of water quality sector)= impact of sanitation on water resources, (i.e. changes in water resource quality) in terms physical phenomena such as algal blooms or nitrate in groundwater of particular water resources (i.e. impoundments or groundwater resources);
  output=cost of pollution assigned to individual sanitation levels of service in different unit areas;
  which in turn provides input to the planning sector.

More detailed aspects covered under each sector are as follows:

Planning sector

- *definition of the study area* (also explaining the differences between Gauteng, PWV or Pretoria-Witwatersrand-Vaal and Development Region H);
- *choice of unit area* for planning and modelling purposes (magisterial district, local authority and surface and groundwater catchments);
- *demographics and settlement patterns*, including natural increase and migration patterns, and assigning these to unit areas;
- *sanitation levels of service* i.e. choices between different levels of service starting with existing sanitation coverage figures for the unit areas, and looking at possible future sanitation scenarios.

Water quality sector

- different possible *pathways* for contaminants on the surface or in the subsurface to surface or groundwater resources;
- *rates of movement of contaminants* in the sub-surface in different unit areas;
- *contaminant loads discharged to and from different levels of service of sanitation*;

- *lake response* to contaminant concentrations in terms of algal growth;
- some comment on the approach of *Water Resources 90*[5] in the determination of catchment hydrology.

Costing sector

- Costing of *surface water treatment* (Unit cost at different capacities for different sets of processes);
- Costing of *ground water treatment* (Unit cost at different capacities for different sets of processes);
- Costing of *other impacts and remedial measures* (recreation, land values, agriculture)
- Relationship between trophic status of an impoundment and the set of treatment processes required;
- *Translation of costs per unit volume of water treated to a cost for the resource*;
- Cost of provision (construction, operation and maintenance) of different levels of service of water supply and sanitation (for comparative purposes).

While applying the model to Gauteng, *4 case studies* were carried out (Ivory Park,Soshanguve, Orange Farm and the Vaal Barrage) to illustrate particular situations, which can be replicated in other areas. The Vaal Barrage study is useful in that it illustrates a 'worst case' scenario (of septic tanks discharging directly into an impoundment). Soshanguve illustrates the use of VIPs in an area where groundwater use may be a possibility. (See set of 4 diagrams in Figure 2.1)

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5 Water Resources 90 - or WR90 - refers to *Surface Water Resources of South Africa 1990* by Midgley et al., 1994a - User's Manual, and 1994b - Volume I: Drainage Regions A and B: Limpopo-Olifants, 1994c - Volume II: Drainage Region C: Vaal.

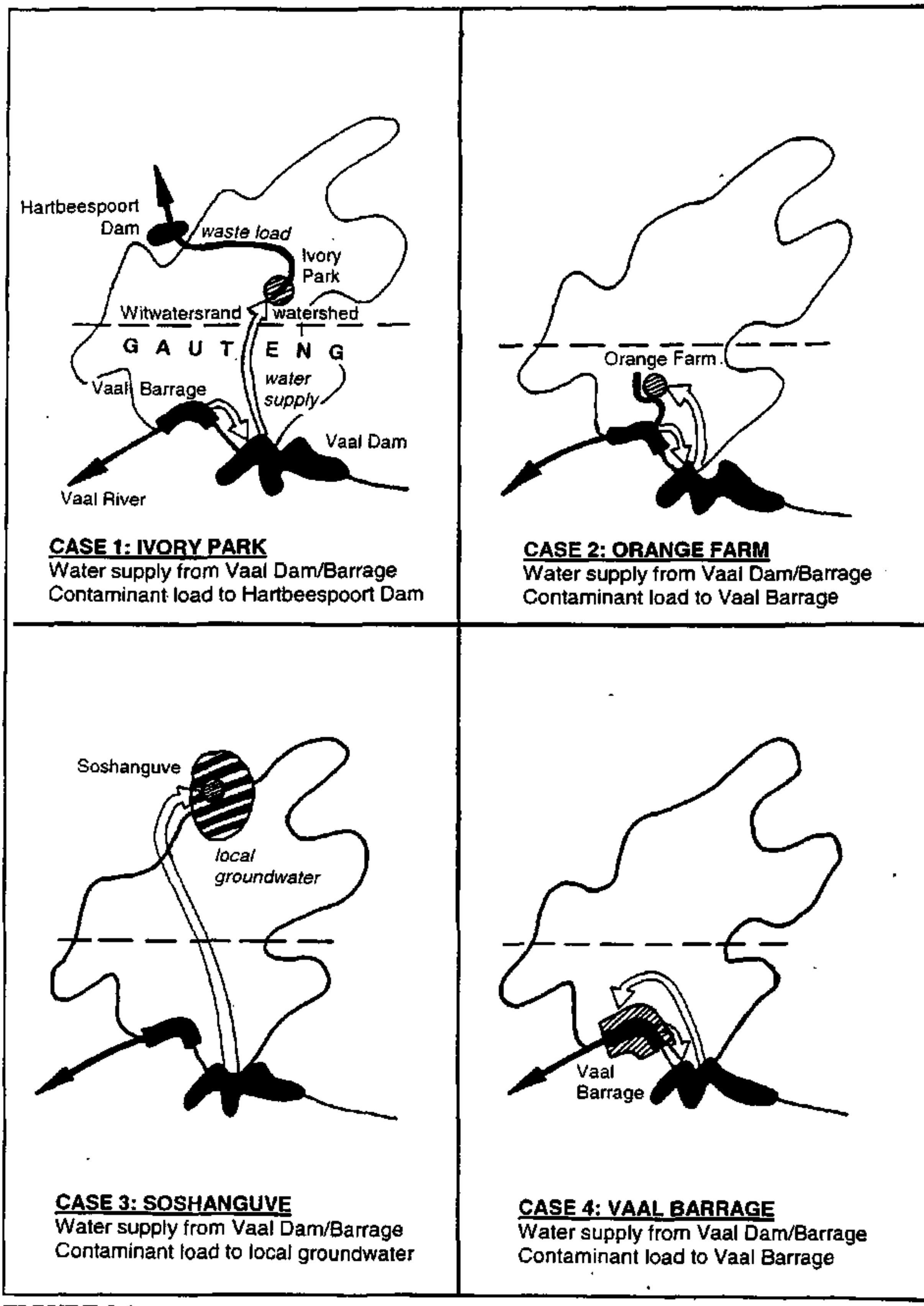

FIGURE 2.1:
FOUR CASE STUDIES IN IMPACT OF ON-SITE SANITATION IN GAUTENG

2.6 Modelling principles

Key principles followed in the modelling were as follows:

- *Internal consistency:* Characteristics of particular levels of service of sanitation must be consistent through all sectors of the model.
- *Facility to construct a range of different scenarios:* It is as important to investigate different scenarios as to get exactly correct figures for contaminant loads, subsurface permeabilities etc.
- *Describe as accurately as possible the form of the relationships* (even if their quantification contains large ranges/uncertainty): Even if the magnitude of particular changes are not entirely clear, identification of factors affecting different parameters should be as clear as possible.
- *Distinguish between those matters that are unambiguous* (despite uncertainties in input data) and *those that require more detailed data in order to resolve them*: Alternatively, provide a good enough answer for the purposes of decision-making at a policy level.
- *Answers to be good enough for decision-making at a policy level* (even though they may not be good enough for a full understanding from a scientific point of view); alternatively, a good enough answer to tell one where to investigate in more detail.

These principles are extended and expanded upon later in the application of the model to Gauteng Province. It is an iterative process in that the very 'shape' and emphasis of the model is determined by the results that it produces in its application to a case study such as Gauteng Province. The intention really has been to provide a first estimate for the method; to see where there is sufficient data and where there are gaps.

This model has relied on data from a number of other sources, and in the water quality sector has used the 'simple model' by Palmer Development Group et al. (1992b). The numbers from this and other earlier studies have been refined somewhat; however, these have been relatively minor adjustments. Where this study has significantly extended the 'simple model' has been in assigning a *value* to these contaminant loads. In order to do this, the following steps have been added to the 'simple model': This study has:

- been more explicit about contaminant pathways from sanitation system to water resources;
- added lake dynamics and additional costs of water treatment of poor water quality;
- related these components to actual settlement patterns and sanitation scenarios in Gauteng in a spatial and temporal manner;
- compared the estimated contaminant loads with actual measured contaminant loads in the various watercourses;
- allocated these costs back to household sanitation systems;
- added the cost of contamination to the cost of provision of the sanitation levels of service, to assist in policy decision about choice of level of service of sanitation in Gauteng.

At an earlier stage in the project, as a result of the limited availability of data together with the complexity of the problem, the emphasis of the study shifted from actual determination of costs of pollution from different sanitation systems in Gauteng to a *modelling tool* (comprising a

Stella[6] systems model, together with GIS) that could be used to test a range of scenarios. Expectations of getting firm 'numbers' for the cost of pollution from different sanitation systems were thus lowered. However, after significant further attention had been given to developing the lake response models for Hartbeespoort Dam, it was possible for the project to return again to an approach which, although simpler than had been developed earlier, gave more definite, robust results - providing comparative cost of pollution from different sanitation systems, and giving more specific indication of unresolved matters which required further investigation. The emphasis has therefore returned to that of a *report* containing a number of *selected scenarios* 'bracketing' the range of possibilities, which essentially obviated the need for the systems model. The final product is therefore *not* primarily an interactive model that can display various scenarios. If the model is further developed, then GIS and systems modelling may well be appropriate e.g. for exploring exact location of new settlements or more detailed water demand and sewage flow characteristics. At the level of detail at which this study was pitched, however, the upper and lower bound scenarios provided sufficiently clear answers so as not to require the facility to test a range of intermediate scenarios. Furthermore, the data was not (yet) sufficiently comprehensive to lend itself to modelling at such a level.

The spreadsheet model that has been developed - and used - in the study has been constructed at the level of an impoundment catchment (in this case, specifically, Hartbeespoort Dam). It can be extended in two (opposite) directions of detail:

- to Gauteng as a whole;
- to an individual settlement.

Spatial data are given in the format of a number of figures in the report: Figure 3.1 (magisterial districts), Figure 3.2 (impoundments catchments) and Figure 3.4 (present and future settlement patterns).

Each of the sectors (planning, water quality and costing) are addressed in turn in the following chapters.

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[6] Stella II software from High Performance Systems Inc., New Hampshire, USA (1994)

3 PLANNING SECTOR

As indicated in the Methodology chapter, the following topics are addressed in the Planning sector:

- *definition of the study area* (also explaining the differences between Gauteng, PWV or Pretoria-Witwatersrand-Vaal and Development Region H);
- *choice of unit area* for planning and modelling purposes (magisterial district, local authority and surface and groundwater catchments);
- *demographics and settlement patterns*, including natural increase and migration patterns, and assigning these to unit areas;
- *sanitation levels of service* i.e. choices between different levels of service starting with existing sanitation coverage figures for the unit areas, and looking at possible future sanitation scenarios.

3.1 Definition of the area of study

There are three slightly different definitions of the metropolitan area that is the subject of this study:

- PWV (Pretoria-Witwatersrand-Vaal) metropolitan area;
- Development Region H;
- Gauteng Province.

The PWV metropolitan area was formally defined and used in the demographic (and other related) studies carried out by the Urban Foundation (UF) in the late 1980s/early 1990s (Urban Foundation, 1990a: p20-21; 1990b: p.2-3,8,12). It did not coincide with political boundaries, but defined an area than formed an economic unit. In particular, it included both 'homeland' and 'white RSA' portions. The PWV coincided largely with Development Region H, a similar economic definition (Urban Foundation, 1990a: p20-21; Office for Regional Development and Regional Development Advisory Committee H, 1991). PWV/Region H was used by Palmer Development Group et al. in their sanitation studies (Palmer Development Group et al., 1993b: Map H1, p.1). Gauteng Province, on the other hand, is a political - and therefore administrative - definition, with somewhat different objectives from the previous two definitions. While the previous two definitions attempted to encapsulate the metropolitan area as a whole, the demarcation of the province attempted to meet other national objectives, such as 'balancing' the strengths (and weaknesses) of the country's provinces. This meant exchanging certain areas with neighbouring provinces.

While there has been considerable change in provincial and local authority boundaries in the transformation of local government which has occurred since the 1994 elections, magisterial district boundaries have remained essentially unchanged, and have formed the basic units for the definitions set out above. The following table gives a comparison of Development Region H/PWV and Gauteng Province:

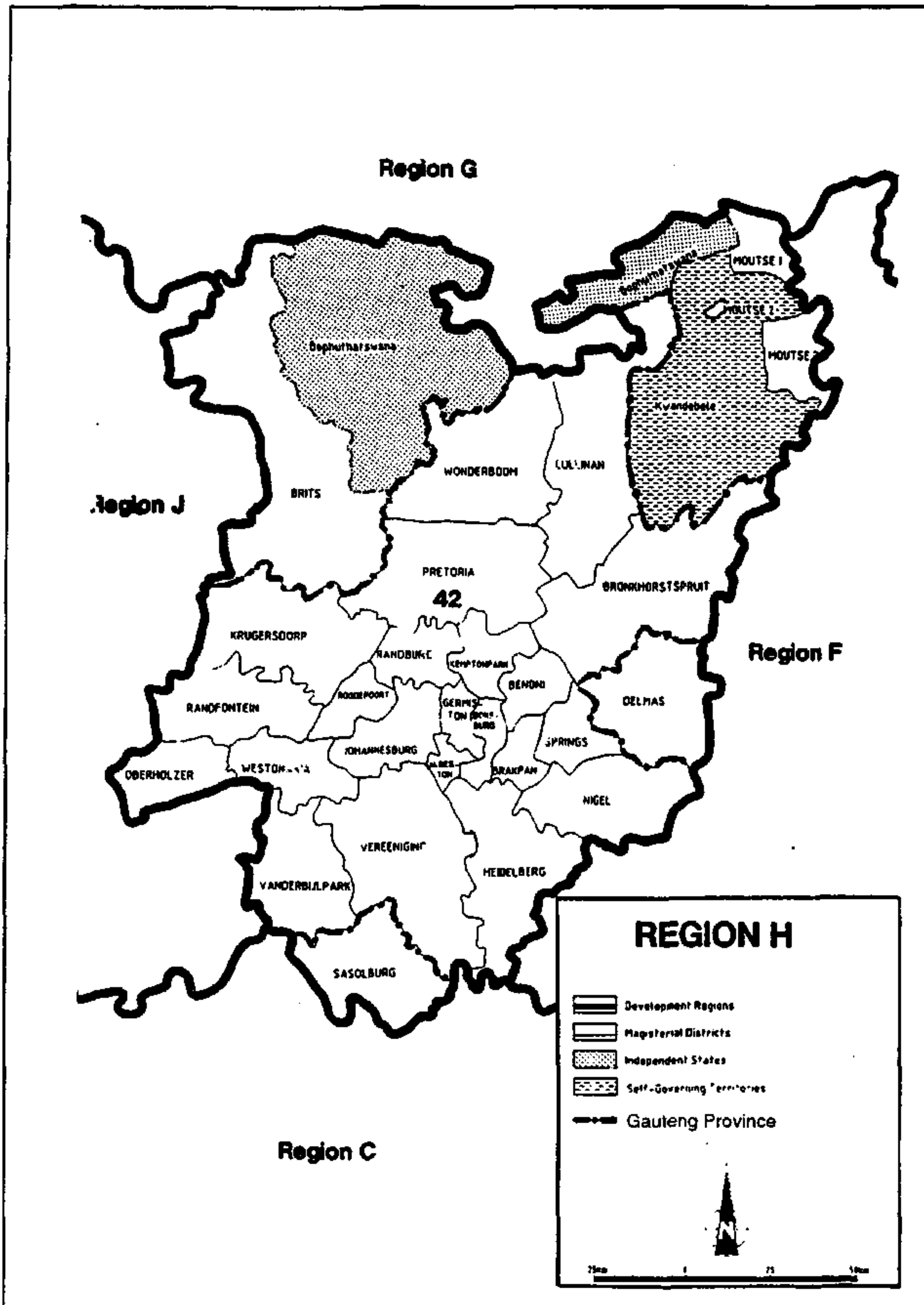


FIGURE 3.1: DEVELOPMENT REGION H (after Office for Regional Development and Regional Development Advisory Committee H, 1991)

TABLE 3.1:
COMPARISON OF PWV/DEVELOPMENT REGION H AND GAUTENG PROVINCE

PWV/ Region H (sub-region)	*PWV/ Region H (magisterial districts)*	*Gauteng Province (sub-region)*	*Gauteng Province (magisterial districts)*	*comment*
Johannesburg (H0M1)	Johannesburg Randburg	Greater Johannesburg	Johannesburg Randburg *Roodepoort* [a]	
East Rand (H0M2)	Alberton Benoni Boksburg Brakpan Germiston Kempton Park Springs	Greater East Rand	Alberton Benoni Boksburg Brakpan Germiston *Heidelberg* [c] Kempton Park *Nigel* [c] Springs	*Heidelberg* and *Nigel* - as is *Delmas* - are included in region F0U2 of Eastern Transvaal in the UF model. All three are in Region H, although excluded from the UF definition of the PWV. *Delmas* is excluded from Gauteng.
West Rand (H0M3)	Krugersdorp Randfontein *Roodepoort* [a] Westonaria	West Rand	Krugersdorp *Oberholzer* [c] Randfontein Westonaria	*Oberholzer* is included in region J0U1 of Western Transvaal in the UF model. It is also in Region H, although excluded from the UF definition of the PWV.
Pretoria (H0M4)	 Pretoria Soshanguve Wonderboom	Greater Pretoria	*Bronkhorstspruit* [a] *Cullinan* [a] Pretoria Soshanguve Wonderboom	
Vereeniging (H0M5)	*Sasolburg* [b] Vanderbijlpark Vereeniging	Vaal	 Vanderbijlpark Vereeniging	
North West (H0M6)	*Brits* [b]			
North West A (HSM6)	*Bafokeng* [b] *Odi II* [b]			
North West B (HSM7)	*Moretele I* [b] *Odi I* [b]			
North East (H0M8)	*Bronkhorstspruit* [a] *Cullinan* [a]			
North East A (HWM7)	*Kwandebele* [b]			
North East B (HSM8)	*Moretele II* [b]			

Note:

a common to both PWV/Region H and Gauteng, but in different sub-regions

b included in PWV/Region H but not in Gauteng

c included in Gauteng, but not in PWV/Region H

The sub-regions (together with codes in brackets) referred to in the PWV/Region H are taken from the Urban Foundation Demographic Projection Model (Urban Foundation, 1990a: pp.20-23). Key differences between the two definitions are:

- Sasolburg (in the south) and Brits (in the north west) are included in the PWV, but excluded from Gauteng Province;
- The various homeland regions of the Bophutatswana and Kwandebele (in the north/north west and north east respectively) are included in the PWV, but excluded from Gauteng.

Region H fell under three regional authorities: the Transvaal Provincial Administration (TPA), the self-governing state of Kwandebele, and the independent state of Bophutatswana.

There were previously 5 Regional Services Councils in Region H: Pretoria, Central Witwatersrand, West Rand, East Rand and the Vaal Triangle. In Gauteng the number of administrative units initially remained the same with names slightly changed (shown as such in Table 3.1), but has subsequently been increased to 6, with the formation of the Kyalami Metropolitan Council. (The additional metro council has not been used in the model as data have only recently been assigned to it).

3.2 Choice of unit areas

Spatially-related data in Gauteng, e.g. demographic data, Statistics SA data, various spatial development studies such as the Land Availability Study for the Witwatersrand (Witwatersrand Metropolitan Chamber, 1991) and the more recent Gauteng Spatial Development Framework (Planafrica Inc. et al., 1996), have been collected using a number of different sets of unit areas. Some data have been collected according to local authority (whose boundaries have been under revision); some have been collected according to magisterial district; and others have been collected under completely different unit areas. Quite apart from such discretionary differences, physical boundaries such as catchment areas have completely different boundaries. Some of the possible 'sets of unit areas' include:

- areas of *water supply*: areas are supplied from different *water resources* - determined by bulk water suppliers (such as Rand Water) or by local authorities (for those that mix their supplies e.g. Pretoria mixing water from Rietvlei Dam and from Rand Water);
- areas of *sewer drainage*: areas are drained to different *wastewater treatment works* - determined by wastewater treatment works operators or utilities;
- areas of *stormwater drainage*: areas are drained by different *natural watercourses* (standard tertiary and quaternary catchments are given in Water Resources 90 (WR90) (Midgley et al., 1994a, 1994b, 1994c))
- *Water quality monitoring points and their corresponding catchments* (for checking of pollutant mass flows) - determined by those responsible for monitoring (such as Rand Water or DWAF); location of monitoring points is also strongly determined by topography, which determines where flow gauging weirs can be constructed.

This poses difficulties where, for example, sanitation coverage is by local authority, whereas population projections are by magisterial district. Similar difficulties arise where contaminant mass flows are measured by catchment area, whereas administration/management takes place by local authority. (This is the very nature of externalities, where the impact takes place beyond the boundaries of the source).

For modelling purposes, it is necessary to assign data to a common set of unit areas. With the data available, the most appropriate approach for this study was considered to be a two stage approach: Two sets of unit areas were selected for this purpose:

- magisterial districts (being the most stable units at present);
- surface water catchment areas, following the Water Resources 90 (WR90) definitions (Midgley et al., 1994a, 1994b, 1994c), grouped together according to major impoundments.

Planning data was first assigned to the one set of unit areas (namely the magisterial districts), and then re-allocated to the second set of unit areas (namely catchment areas of major impoundments) to be combined with the water quality data.

The following impoundments are considered in this study, together with catchments according to WR90:

In the north-west:

- Hartbeespoort Dam;
- Rietvlei Dam;
- Bon Accord Dam;
- Roodeplaat Dam.

In the north-east:

- Rust der Winter Dam;
- Bronkhorstspruit Dam;
- Loskop Dam.

In the south-east:

- Vaal Barrage (Suikerbosrant River and Rietspruit/Klip River sub-catchments).

In the south-west:

- Boskop Dam.

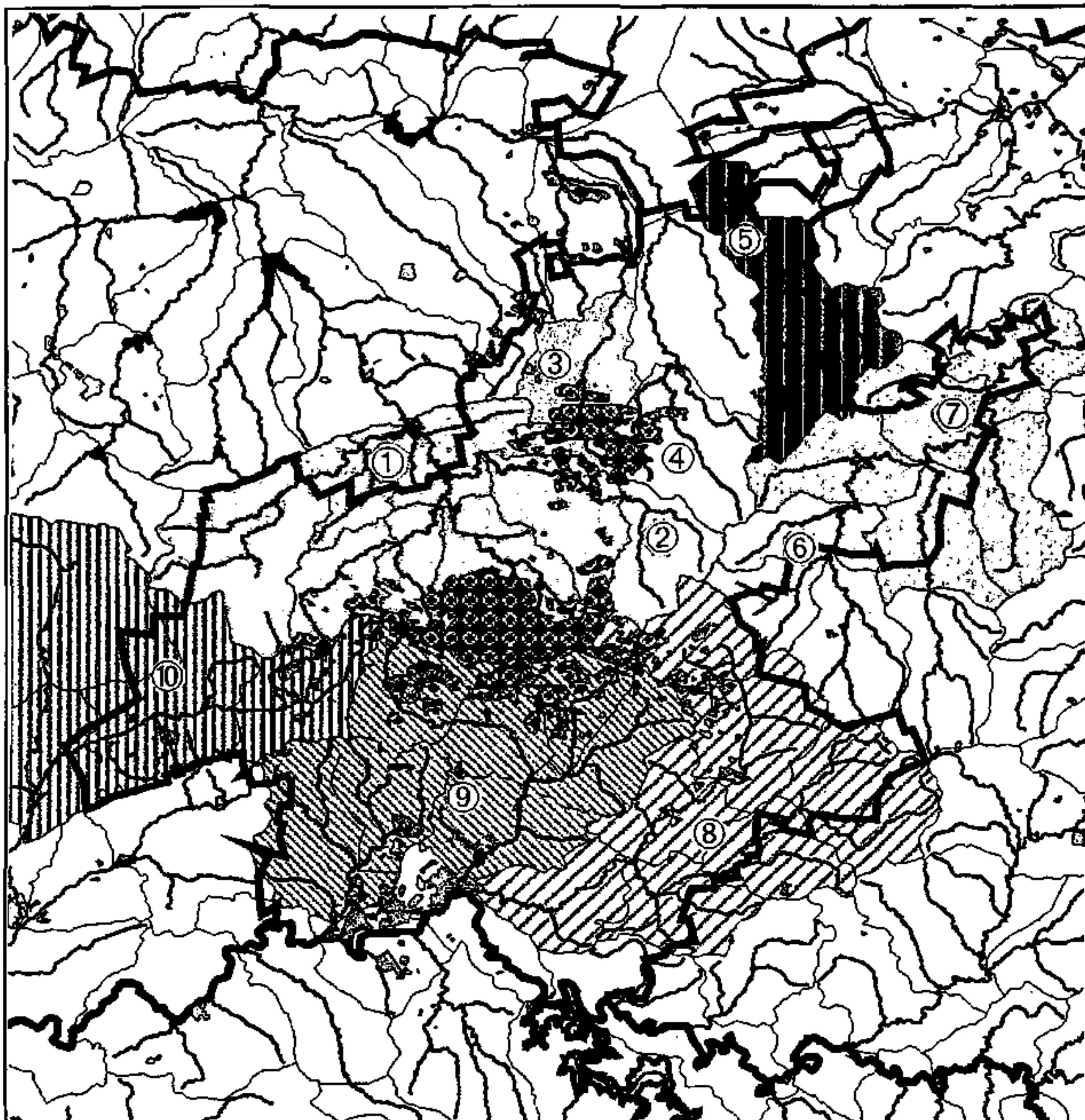
Further details of the catchments are as follows:

<u>TABLE 3.2</u>:
ALLOCATION OF GAUTENG TO IMPOUNDMENT CATCHMENTS

dam	*tributary*	*catchment*	*Magisterial district*
Hartbeespoort	Magalies (west)	A21F A21G	Krugersdorp (west) Randfontein (north)
	Crocodile (south)	A21D A21E A21C	Krugersdorp (east) Roodepoort (north) Johannesburg (north) Randburg Kempton Park (small portion on the west) Pretoria (small portion on the south-west)
	Hennops (east)	A21B	Kempton Park (central) Pretoria (south)
	dam environs	A21H	Wonderboom (south west) Pretoria (north west)

dam	*tributary*	*catchment*	*Magisterial district*
Rietvlei (continues into Hartbeespoort)	Rietvlei	A21H	Pretoria (small portion in the north-western corner) Wonderboom (south-western corner)
Bon Accord	?	A23D A23E (southern parts)	(dam capacity <10Mm^3)
Roodeplaat	?	A23A	Pretoria (north-east) Wonderboom (south-east) Cullinan (south-west)
Rust der Winter	?	B31A B31B B31C	Cullinan (possibly a small portion of Bronkhorstspruit (north))
Bronkhorstspruit (continues into Loskop)	?	B20A B20B B20C	Bronkhorstspruit
Loskop	Wilge?	B20D B20F B20G B20H B20J (small *portion?*)	Bronkhorstspruit
Vaal Barrage	Suikerbosrand	C21A C21B C21C C21D C21E C21F C21G	Benoni Springs Brakpan (east) Nigel Heidelberg (most) Vereeniging (south)
	Klip	C22A C22B C22C C22D C22E	Roodepoort Johannesburg (south) Alberton Germiston Boksburg Kempton Park (small portion in south) Benoni (small portion) Brakpan (most) Heidelberg (north east corner) Vereeniging (north; most)
	Rietspruit	C22H C22J	Westonaria (south) Vanderbijlpark (most)
Boskop	?	C23D C23E C23F C23G	Oberholzer Westonaria (north west) Randfontein (south)

For modelling purposes, both population and sanitation type need to be allocated to both surface water and groundwater resources, (although groundwater resource catchments are far less clearly distinguishable). Figure 3.2 shown the allocation of Gauteng to the various surface water impoundment catchments.



Impoundment catchments:

①	Hartbeespoort Dam	⑥	Bronkhorstspruit Dam
②	Rietvlei Dam	⑦	Loskop Dam
③	Bon Accord Dam	⑧	Vaal Barrage (Suikerbosrant River)
④	Roodeplaat Dam	⑨	Vaal Barrage (Rietspruit, Klip River)
⑤	Rust der Winter Dam	⑩	Boskop Dam

<u>FIGURE 3.2</u>:
ALLOCATION OF GAUTENG TO IMPOUNDMENT CATCHMENTS

3.3 Demographic data

Sources of data
Population coverages were obtained from the following sources:

- 1985-1996 census data (Central Statistical Service, 1986, 1992; Statistics SA, 1998)
- Urban Foundation (1990a);

Data from Development Bank of Southern Africa (DBSA)(1996) - also used in the Gauteng Spatial Development Framework report (Planafrica Inc. et al., 1996) - were also consulted, but not used.

The most up to date figures for *current* population figures are the 1996 census figures. These figures are available by enumeration area or by magisterial district. The enumeration areas provide figures at a very fine resolution, which would be most appropriate for re-allocation to catchment areas. Development Information Bureau (DIB) has also gathered good primary data on the micro movements of population between different local authority areas in Gauteng (Jordaan, 1999). On the basis of these micro studies, they have constructed small-scale projections of likely future settlement patterns (and income levels). Although this data - either from Statistics SA or DIB - could be purchased, copyright restrictions are likely to prevent its inclusion in the study report (except at significant cost). A further difficulty, however, is that any projections that *are* readily available are still provided by much larger units, and it therefore is of limited use to have extremely accurate *current* population figures, but considerably less accurate *projected future* population figures. For the purposes of this study, it was therefore decided to use *the census data at the coarser resolution (i.e. magisterial district) as a baseline*, and apply the *projected growth rates from earlier studies* to these figures to produce future projections of population. Comments on demographic projections are as follows:

Censuses were conducted in 1980, 1985, 1991 and 1996. The 1996 census data have been released relatively recently, but there has been insufficient time to produce new projections based on these most recent figures.

The census data do not appear to be realistic in all respects. Over and above any adjustments made in the original determination of the 1985 census data, further correction factors proposed by Urban Foundation (1990a) have been applied to the 1985 census data, to address the problem of under-enumeration. The relatively low overall growth rates (i.e. natural increase plus migration) for the period 1985-1991, certainly compared with the overall growth rate for the period 1991-1996, appear to indicate one (more probably a combination) of the following:

- over-correction of the 1985 census data by Urban Foundation, particularly for black people;
- slight under-enumeration of the 1991 census data; and
- overall exaggeration of the 1996 census data. This is slightly more complex as the 1996 census figures for white people seems to be at odds with the 1991 census figures.

With respect to the 1996 census data, the fact that there are reported to be 170 000 (which is 25%) fewer white people in Greater Johannesburg in 1996 than 1991 is a concern, and requires further investigation (See Table 3.2). It should be noted, however, that even census figures are considered to be estimates.

The Urban Foundation Demographic Projection model provides detailed figures for 1985 to 1995 (population distributions every year), then less detailed figures for 1995 to 2000, and even less detailed figures from 2000 to 2010. For *Black* people, net migration, total increase, migration percent and growth rate (%pa) are given for all unit areas) from 1980 to 2000 in 5 year intervals (p49-51); population distribution annually 1985-1995, then 2000, 2005 and 2010. For *Asians, Coloureds* and *Whites* it is the same.

The UF Demographic Projection Model was constructed, based on a number of assumptions, which included the following for projections to 2010:

- '...that the *White* population in the towns, on the farms and in the homelands would remain at the same absolute level from 1985 to 2000. All metropolitan populations were adjusted upwards by a constant factor so as to reproduce the estimate of total population. This implies a slight rise in the percentage urban.'
- '...that urbanisation [of *Coloured* people] would proceed at the same rate between 1985 and 2000 as it did between 1980 and 1985. This implies that 87% of the coloured population will be urbanised in the year 2000. 12% will remain rural and 1% in the homelands.'
- assumptions for *Asians* are as for Whites
- '[for *Blacks*]...[i]ndividual growth rates were applied to the 1985 estimates for metropolitan areas and the masculinity ratios were reduced...Details are set out in Appendix 6...', which is given in Table 3.3 below (data for all metropolitan areas given for completeness).
- 'For the remaining years, interpolation and extrapolation from the 1985 and 2000 estimates were used.'

TABLE 3.3:
ASSUMED BLACK POPULATION GROWTH RATES FOR THE METROPOLITAN AREAS 1980 to 2000 (Urban Foundation, 1990a: Appendix 6, p.31)

Metropolitan area	*Population growth [% p.a.]*			
	1980-85	*1985-90*	*1990-95*	*1995-2000*
Cape Town	12.0	5.4	5.0	5.0
Bloemfontein	15.3	3.2	3.2	3.2
OFS Goldfields	4.3	4.0	4.0	4.0
Port Elizabeth	6.0	5.4	5.0	5.0
East London	1.0	4.1	3.8	3.8
Durban	8.4	4.1	4.5	4.5
Pietermaritzburg	2.1	3.5	3.5	3.5
PWV	3.9	5.4	4.3	4.3

A growth rate of 3.0%pa was applied to the towns outside the homelands. The rural population was kept constant in absolute terms. The homeland urban and dense settlement populations were assumed to grow by 4.75%pa and 3.0%pa respectively. The balance of the population was allocated to homeland rural areas. Under these assumptions, the homeland rural population rises by about 1 850 000 between 1985 and 2000. The proportion of the population in the homelands in 2000 is 57%, marginally lower than the 1985 percentage. The middle measure of urbanisation increases quite rapidly from 46% in 1985 to 56% in 2000.'

The *location* of future population increases also depends significantly on spatial development frameworks. While demographic projections may give an *indication* of increase in magisterial districts, this is not necessarily a good indication of where people are likely to remain, nor is it an indication of where new housing (and sanitation provision) is likely to be provided. Demographic projections cannot therefore really be separated from spatial development frameworks. The extent to which the demographic projections have taken account of the spatial development frameworks is, however, difficult to ascertain.

TABLE 3.4:
GAUTENG PROVINCE CENSUS DATA BY MAGISTERIAL DISTRICT AND RACE GROUP 1980-1996: TOTAL POPULATION

District	1985 total total	1991 total total	1996 total total	1985 white total	1991 white total	1996 white total	1985 coloured total	1991 coloured total	1996 coloured total	1985 asian total	1991 asian total	1996 asian total	1985 black total	1991 black total	1996 black total
total Gauteng	5818830	6458332	7348422	1961220	2080199	1702344	230452	262516	278695	118460	147611	161288	3508698	3969007	5147444
Greater Johannesburg	**2125699**	**2135210**	**2306777**	**654741**	**659317**	**487415**	**132127**	**137442**	**150285**	**63489**	**66692**	**79766**	**1275342**	**1271760**	**1566866**
Johannesburg	1628846	1574631	760791	399690	384437	239233	121644	126496	131795	61620	64343	72662	1045892	999356	306122
Soweto			904165			115			1569			54			896540
Randburg	287552	341430	362481	146209	154291	138674	4656	4551	6180	1180	1833	5202	135507	180755	209028
Roodepoort	209301	219149	279340	108842	120589	109393	5827	6395	10741	689	516	1848	93943	91649	155176
Greater East Rand	**1576089**	**1836892**	**2173937**	**545641**	**573074**	**469122**	**45548**	**49860**	**56715**	**22384**	**28051**	**29145**	**962516**	**1186906**	**1605027**
Alberton	305271	367929	410257	62878	64018	54676	9842	11212	13133	262	178	3137	232289	292521	337252
Benoni	255082	288629	366343	67162	72472	54306	2202	1985	2513	15650	16759	14071	170068	197413	293412
Boksburg	186658	195905	263179	73664	75604	65494	19481	21282	22743	200	240	1902	93313	98778	170376
Brakpan	103437	130463	171363	37096	40305	35386	4782	5865	6461	48	86	1358	61511	84207	126850
Germiston	170888	171541	164252	128193	136610	110402	1914	1790	2650	2677	653	2127	38104	33487	47536
Heidelberg	51238	77055	83013	12921	12395	12789	409	608	522	987	4531	671	36921	59521	68646
Kempton Park	296456	354787	446106	91035	97455	71189	1161	1020	1728	173	119	681	204087	256193	369734
Nigel	29251	92881	106120	18020	19016	18346	5239	5632	6350	796	1251	1295	5196	66983	79636
Springs	177808	157702	163304	54672	55199	46534	518	466	615	1591	4234	3903	121027	97803	111585
West Rand	***552798***	***650917***	***668647***	***138338***	***142579***	***121482***	***14107***	***24078***	***23339***	***7687***	***24296***	***22081***	***392666***	***459964***	***496302***
Krugersdorp	188134	196213	208751	60817	62520	60228	1860	1643	1521	4239	4255	5183	121218	127794	140491
Oberholzer	145700	177768	166101	31581	32364	23977	434	400	492	176	185	228	113509	144819	140291
Randfontein	107324	116405	133032	28657	29766	24928	10208	10875	12208	840	1962	104	67619	73803	94526
Westonaria	111640	160531	160763	17283	17929	12349	1605	11160	9118	2432	17894	16566	90320	113548	120994
Greater Pretoria	**1016300**	**1150798**	**1372997**	**478600**	**551192**	**498366**	**23199**	**26668**	**30354**	**19901**	**20622**	**25201**	**494600**	**552317**	**809725**
Bronkhorstspruit	44519	38605	35523	9967	10628	7690	441	322	266	143	80	166	33968	27575	27196
Cullinan	33581	32006	82601	10933	10831	9336	759	618	881	57	26	38	21832	20531	71785
Pretoria	603661	667700	692348	394072	447261	396841	20892	24656	27508	19488	20284	24463	169209	175499	235450
Soshanguve	85611	146334	242727	87	122	38	115	155	373	30	91	186	85379	145967	241124
Wonderboom	248928	266153	319798	63541	82350	82461	992	917	1326	183	141	348	184212	182745	234170
Vaal	**547944**	**684515**	**826064**	**143900**	**154037**	**127959**	**15471**	**24468**	**18002**	**4999**	**7950**	**5095**	**383574**	**498060**	**669524**
Vanderbijlpark	355786	434004	483360	66873	70168	60972	1366	1230	1791	112	29	186	287435	362577	417272
Vereeniging	192158	250511	342704	77027	83869	66987	14105	23238	16211	4887	7921	4909	96139	135483	252252

TABLE 3.5:

GAUTENG PROVINCE CENSUS DATA BY MAGISTERIAL DISTRICT AND RACE GROUP 1980-1996: GROWTH RATES

District	*85-91 total total*	*91-96 total total*	*85-91 white total*	*91-96 white total*	*85-91 coloured total*	*91-96 coloured total*	*85-91 asian total*	*91-96 asian total*	*85-91 black total*	*91-96 black total*
total Gauteng	1.75	2.62	0.99	-3.93	2.19	1.20	3.73	1.79	2.08	5.34
Greater Johannesburg	**0.07**	**1.56**	**0.12**	**-5.86**	**0.66**	**1.80**	**0.82**	**3.65**	**-0.05**	**4.26**
Johannesburg	-0.56	1.12	-0.65	-9.04	0.65	1.06	0.72	2.48	-0.76	3.77
Randburg	2.90	1.20	0.90	-2.11	-0.38	6.31	7.62	23.20	4.92	2.95
Roodepoort	0.77	4.97	1.72	-1.93	1.56	10.93	-4.70	29.07	-0.41	11.11
Greater East Rand	**2.58**	**3.43**	**0.82**	**-3.92**	**1.52**	**2.61**	**3.83**	**0.77**	**3.55**	**6.22**
Alberton	3.16	2.20	0.30	-3.11	2.20	3.21	-6.24	77.51	3.92	2.89
Benoni	2.08	4.88	1.28	-5.61	-1.71	4.83	1.15	-3.44	2.52	8.25
Boksburg	0.81	6.08	0.43	-2.83	1.48	1.34	3.09	51.29	0.95	11.52
Brakpan	3.94	5.61	1.39	-2.57	3.46	1.95	10.21	73.65	5.37	8.54
Germiston	0.06	-0.86	1.07	-4.17	-1.11	8.16	-20.95	26.64	-2.13	7.26
Heidelberg	7.04	1.50	-0.69	0.63	6.83	-3.00	28.92	-31.75	8.28	2.89
Kempton Park	3.04	4.69	1.14	-6.09	-2.13	11.12	-6.05	41.75	3.86	7.61
Nigel	21.24	2.70	0.90	-0.71	1.21	2.43	7.83	0.69	53.13	3.52
Springs	-1.98	0.70	0.16	-3.36	-1.75	5.71	17.72	-1.61	-3.49	2.67
West Rand	**2.76**	**0.54**	**0.50**	**-3.15**	**9.32**	**-0.62**	**21.14**	**-1.89**	**2.67**	**1.53**
Krugersdorp	0.70	1.25	0.46	-0.74	-2.05	-1.53	0.06	4.02	0.88	1.91
Oberholzer	3.37	-1.35	0.41	-5.82	-1.35	4.23	0.83	4.27	4.14	-0.63
Randfontein	1.36	2.71	0.63	-3.49	1.06	2.34	15.19	-44.43	1.47	5.07
Westonaria	6.24	0.03	0.61	-7.19	38.15	-3.96	39.46	-1.53	3.89	1.28
Greater Pretoria	**2.09**	**3.59**	**2.38**	**-2.07**	**2.35**	**2.62**	**0.59**	**4.09**	**1.86**	**7.95**
Bronkhorstspruit	-2.35	-1.65	1.08	-6.27	-5.11	-3.75	-9.23	15.72	-3.42	-0.28
Cullinan	-0.80	20.88	-0.16	-2.93	-3.37	7.35	-12.26	7.89	-1.02	28.45
Pretoria	1.69	0.73	2.13	-2.36	2.80	2.21	0.67	3.82	0.61	6.05
Soshanguve	9.35	10.65	5.80	-20.81	5.10	19.20	20.32	15.37	9.35	10.56
Wonderboom	1.12	3.74	4.42	0.03	-1.30	7.66	-4.25	19.80	-0.13	5.08
Vaal	**3.78**	**3.83**	**1.14**	**-3.64**	**7.94**	**-5.95**	**8.04**	**-8.51**	**4.45**	**6.10**
Vanderbijlpark	3.37	2.18	0.80	-2.77	-1.73	7.80	-20.16	45.02	3.95	2.85
Vereeniging	4.52	6.47	1.43	-4.40	8.68	-6.95	8.38	-9.13	5.88	13.24

TABLE 3.6:
GAUTENG PROVINCE DEMOGRAPHIC PROJECTION MODEL 1980-2010: GROWTH RATES, INCLUDING NATURAL INCREASE AND MIGRATION (Urban Foundation)

Growth INCL migration

	80-85	85-90	90-95	95-00	00-05	05-10
total	2.2	4.0	3.2	3.2	2.4	3.2
white	1.9	1.2	1.1	0.9	0.8	0.8
asian	3.8	2.0	1.8	1.5	1.2	1.1
coloured	4.2	2.4	2.2	1.9	1.7	1.6
black	2.2	5.6	4.2	4.2	2.9	3.9

Growth EXCL migration

	80-85	85-90	90-95	95-00	00-05	05-10
total	2.4	1.5	1.5	1.5		
white	1.4	0.8	0.8	0.7		
asian	1.9	1.7	1.5	1.3		
coloured	2.0	1.8	1.7	1.4		
black	3.0	1.9	1.8	1.8		

Growth INCL-EXCL migration ie migration 'growth'

	80-85	85-90	90-95	95-00	00-05	05-10	
tot calc	-0.26	2.62	1.78	1.87			a bit higher than the total
total	-0.2	2.5	1.7	1.7			
white	0.5	0.4	0.3	0.2			
asian	1.9	0.3	0.3	0.2			
coloured	2.2	0.6	0.5	0.5			
black	-0.8	3.7	2.4	2.4			

Migration % of total increase

	80-85	85-90	90-95	95-00	00-05	05-10
total	-10	65	55	55		
white	25	30	30	30		
asian	50	20	15	15		
coloured	55	25	25	30		
black	-40	70	60	60		

TABLE 3.7:
GAUTENG PROVINCE GEOGRAPHICAL AND RACIAL DISTRIBUTION OF POPULATION 1980-2010 (Urban Foundation)

total

total — *% of tot*

Region	*Description*	*1980*	*1985*	*1990*	*1995*	*2000*	*2005*	*2010*
HOM1	Johannesburg	34	34	31	31	30	30	29
HOM2	East Rand	26	26	28	29	29	29	30
HOM3	West Rand	11	11	11	11	11	11	11
HOM4	Pretoria	17	17	16	16	16	16	15
HOM5	Vereeniging	11	11	12	12	13	13	13
HOM8	North East (Bronkhorstspruit, Cullinan)	1	1	1	1	1	1	1
total	**Gauteng estimate**							

white

white — *% of tot*

Region	*Description*	*1980*	*1985*	*1990*	*1995*	*2000*	*2005*	*2010*
HOM1	Johannesburg	31	28	27	25	22	21	19
HOM2	East Rand	35	34	28	25	22	20	18
HOM3	West Rand	34	35	31	27	24	22	20
HOM4	Pretoria	49	49	44	40	36	34	30
HOM5	Vereeniging	27	28	22	20	17	16	14
HOM8	North East (Bronkhorstspruit, Cullinan)	23	27	23	21	18	16	14
total	**Gauteng estimate**	**35**	**34**	**30**	**27**	**24**	**22**	**20**

coloured

coloured — *% of tot*

Region	*Description*	*1980*	*1985*	*1990*	*1995*	*2000*	*2005*	*2010*
HOM1	Johannesburg	6	7	7	6	6	6	6
HOM2	East Rand	2	3	2	2	2	2	2
HOM3	West Rand	3	3	3	3	3	2	2
HOM4	Pretoria	2	2	2	2	2	2	2
HOM5	Vereeniging	2	2	2	2	2	2	2
HOM8	North East (Bronkhorstspruit, Cullinan)	1	2	1	1	1	1	1
total	**Gauteng estimate**	**4**	**4**	**4**	**3**	**3**	**3**	**3**

asian

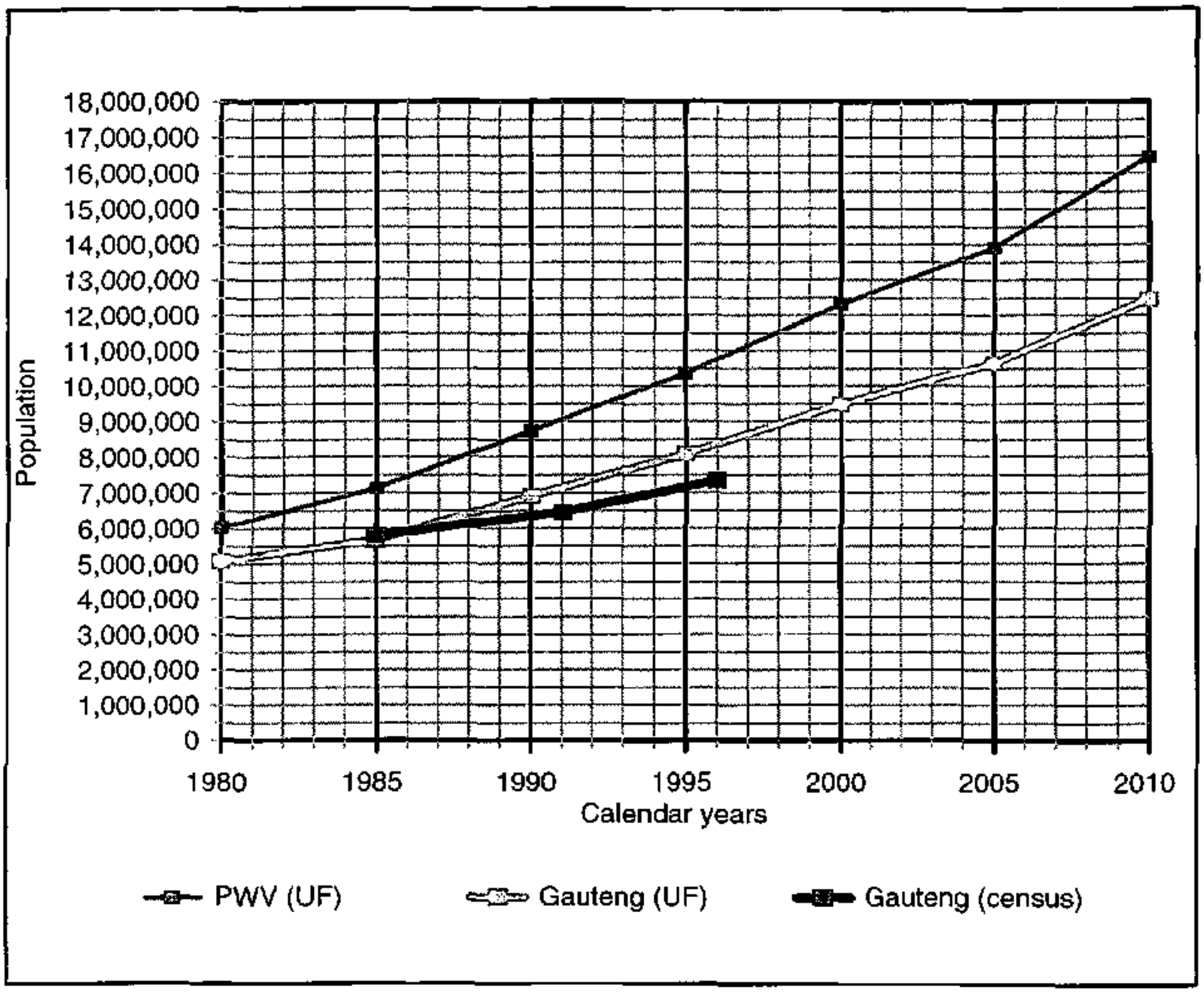
asian — *% of tot*

Region	*Description*	*1980*	*1985*	*1990*	*1995*	*2000*	*2005*	*2010*
HOM1	Johannesburg	3	3	3	3	3	3	3
HOM2	East Rand	1	1	1	1	1	1	1
HOM3	West Rand	1	1	1	1	1	1	1
HOM4	Pretoria	2	2	2	2	2	2	1
HOM5	Vereeniging	1	1	1	1	1	1	0
HOM8	North East (Bronkhorstspruit, Cullinan)	0	0	0	0	0	0	0
total	**Gauteng estimate**	**2**	**2**	**2**	**2**	**2**	**2**	**1**

black

black — *% of tot*

Region	*Description*	*1980*	*1985*	*1990*	*1995*	*2000*	*2005*	*2010*
HOM1	Johannesburg	60	62	64	66	69	71	73
HOM2	East Rand	61	62	68	72	75	77	80
HOM3	West Rand	62	61	65	69	72	74	77
HOM4	Pretoria	47	47	52	56	60	63	66
HOM5	Vereeniging	70	69	75	78	80	82	84
HOM8	North East (Bronkhorstspruit, Cullinan)	76	71	75	78	81	82	85
total	**Gauteng estimate**	**60**	**60**	**65**	**68**	**71**	**73**	**76**



<u>FIGURE 3.3</u>:
PWV AND GAUTENG POPULATION 1980-2010

3.4 Settlement patterns

A number of *scenarios for settlement patterns*, also indicating where on-site sanitation may be used on a significant scale, were investigated. The scenarios were constructed from the best available data as follows:

- Land Availability Study (Witwatersrand Metropolitan Chamber, 1992);
- Gauteng Spatial Development Framework (GSDF) (Planafrica Inc. et al., 1996).

The present and future settlement patterns of the more recent GSDF are shown in Figures 3.4.

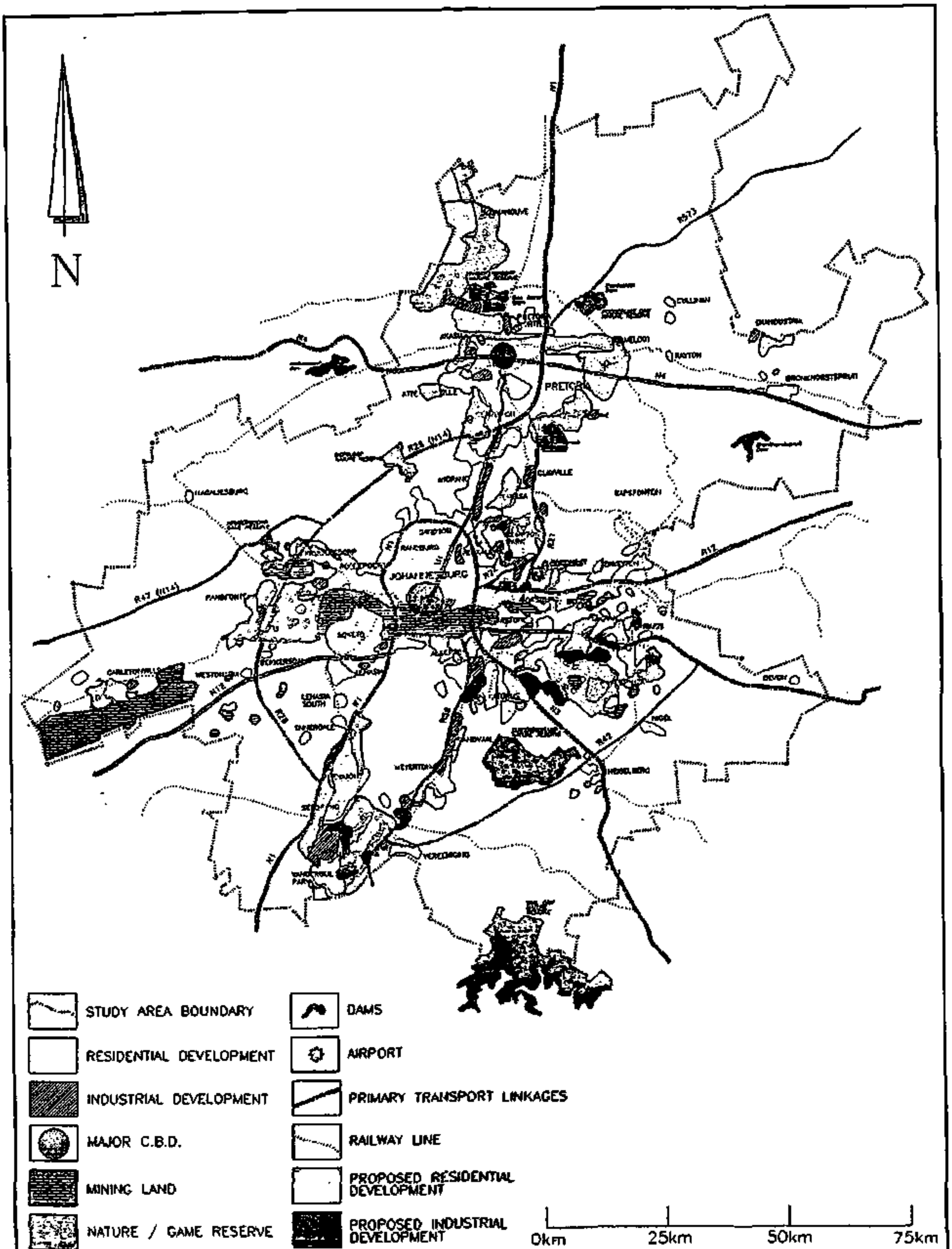


FIGURE 3.4:
GAUTENG SPATIAL DEVELOPMENT FRAMEWORK (GSDF): PRESENT AND FUTURE SETTLEMENT PATTERNS
(Planafrica Inc. et al., 1996: Plan 3: Existing Development Plans)

3.5 Current coverage of sanitation in Gauteng

Levels of service
In this study the intention has been to consider the three main levels of service (basic, intermediate and full), as envisaged in planning documents such as the Municipal Infrastructure Investment Framework (Ministry in the Office of the President and the Department of National Housing, 1995). In practice, however, the choice of level of service category has had to be guided by:

- categories used in data such as coverage statistics;
- the need to differentiate between levels of service of significantly different contaminant loading (e.g. 'essential' versus 'convenience' use of the full level of service).

Level of service combinations considered in the study include the following:

- stand-pipe and VIP (basic);
- stand-pipe (basic water supply) and aquaprivy or LOFLOS (intermediate sanitation);
- house connection and full water-borne sanitation (full) - which can be further split into 'essential' and 'convenience' usage.

While the study considers both water supply and sanitation, the focus remains on the *sanitation* level of service. Other sanitation levels of service include:

- septic tank (essentially a full level of service, although it is an on-site service)
- chemical toilet (basic, but intended for short-term, emergency use only)
- bucket toilet (used in South Africa, but generally an unsatisfactory solution)

Sanitation coverage in Gauteng

The major source of sanitation coverage data has been the coverage figures by Palmer Development Group et al. (1993b). Also used have been the earlier (and rougher) figures of Van Ryneveld (1991) from the Water and Sanitation 2000 study. Although further updated figures have not been obtained, these could be obtained (where available) from DWAF and local authorities such as Greater Johannesburg Metropolitan Council. (Gauteng Province does not itself currently have updated figures). Sanitation coverage figures are given in Table 3.8.

In order to understand the sanitation situation in Gauteng, it is also important to understand how this compares with areas *adjacent* to Gauteng, particularly in what were previously homeland areas of Bophutatswana and Kwandebele. While there are some minor changes in some of the peripheral areas such as Delmas and Sasolburg in translating coverage figures in PWV/Region H to figures for Gauteng, these do not really affect the overall picture of the province as a whole. On the other hand, it is in the areas of Bophutatswana and Kwandebele, which were *included* in PWV/Region H but *excluded* from Gauteng Province, where the major lack of access to sanitation is located in 1990. About 1.5m people out of a total of about 1.7m (88 say 90%) in these homeland areas have inadequate sanitation, compared with only about 300 000 people (0.3m) with inadequate services in the Gauteng areas out of a population of 7m (4.2 say 5%). The difference between inclusion and exclusion of these homeland areas is so significant that it alters the overall picture of sanitation provision in Gauteng: With the adjacent homeland areas *excluded* from Gauteng, it could be deduced that with a small amount of additional sanitation provision, full services could be provided throughout Gauteng, irrespective of affordability. With the adjacent homeland areas *included*, a different strategy that considers lower levels of service appears more realistic.

Furthermore, if one considers the character of areas such as Soshanguve in northern Gauteng, the sanitation solutions there are more similar to those of the neighbouring Winterveldt (in North West Province) than those of central Pretoria.

TABLE 3.8:

SANITATION COVERAGE IN GAUTENG 1990 (Palmer Development Group et al., 1993b: Table H-T3b: Region H-Wits/Vaal Triangle Metro - Sanitation Access by Race, Combined Survey Information)

		Magisterial	total	White								Coloured								Asian								Black							
Municipality	type	district	pop	pop	WB	SEP	BUC	VIP	PIT	OTH	NON	pop	WB	SEP	BUC	VIP	PIT	OTH	NON	pop	WB	SEP	BUC	VIP	PIT	OTH	NON	pop	WB	SEP	BUC	VIP	PIT	OTH	NON
Acasia Municipality	WMUN	Wonderboom																																	
Alberton Municipality	WMUN	Alberton	94270	74000	100							20000	100							270	100														
Tokoza Town Council	BLA	Alberton	140000																									140000	65						35
Phola Park		Alberton	25000																									25000							
Bedfordview Municipality	WMUN	Germiston	28020	20000	98	2														20							100	8000							100
Benoni Municipality	WMUN	Benoni/Boksburg	272789	77189	50	50														19390	100							176210	100						
Daveyton Town Council	BLA	Benoni	220000																									220000	95						5
Wattville Town Council	BLA	Brakpan	33000																									33000	100						
Boksburg Municipality	WMUN	Boksburg	109690	83730	80	10				10		25860	100							100	100														
Vosloorus Town Council	BLA	Boksburg	130000																									130000	100						
Zonkesizwe	*TPA*	*Boksburg?*	*38000*																									*38000*						*100*	
Brakpan Municipality	WMUN	Brakpan	51050	41000	100							10000	100							50	100														
Tsakane Town Committee	BLA	Brakpan	120000																									120000	75						25
Brits Municipality	WMUN	Brits	13800	12000	100							200	100							1600	100														
Oukasie	BLA	Brits	0																																
Bronkhorstspruit Municipality	WMUN	Bronkhorstspruit	14585	8500	96	4						135	50				50			450	100							5500	55				45		
Zithobeni Town Committee	BLA	Bronkhorstspruit	0																																
Carletonville Municipality	WMUN	Oberholzer	40250	40000	98	2														250	100														
Khutsong Town Council	BLA	Oberholzer	80000																									60000	4		30				66
Cullinan		Cullinan	0																																
Refilwe		Cullinan	6000																									6000	100						
Delmas Municipality	WMUN	Delmas	5020	5000	99	1														20	100														
Botleng Town Committee	BLA	Delmas	55000																									.55000	15		85				
Devon		?	0																																
Imphumulelo		?	7500																									7500						100	
Edenvale Municipality	WMUN	Germiston	51150	41000	100							150	100							10000	100														
Germiston City	WMUN	*Germiston*	126640	101316	100							1862			100					6314	100							17148	100						
Katlehong Town Council	BLA	Alberton	400000																									400000	100						
Hartbeespoort Municipality	WMUN	Brits	9400	8500	95	5						100						100										800						100	
Heidelberg Municipality (Tvl)	WMUN	Heidelberg	13100	12000	100															1100	100														
Ratanda Town Committee	BLA	Heidelberg	42350																									42350	100						
Johannesburg City	WMUN	Johannesburg	724000	500000	100							160000	100							64000	100														
Diepmeadow Town Council	BLA	Johannesburg	261000																									261000	80					20	
Soweto Town Council	BLA	Johannesburg	1100000																									1100000	100						
Kempton Park Municipality	WMUN	Kempton Park	119600	102000	95	5						400	100							200	100							17000	100						
Tembisa Town Council	BLA	Kempton Park	500000																									500000	100						
Krugersdorp Municipality	WMUN	Krugersdorp	63000	57000	100															6000	100														
Kagiso Town Council	BLA	Krugersdorp	150000																									150000	100						
Munsieville		Krugersdorp	12000																									12000	75						25
Meyerton Municipality	WMUN	Vereeniging	13000	13000	90					10																									
Midrand Municipality	WMUN	Randburg	33849	20279	41	42					18	3525	100							200	100							9845							
Modderfontein Municipality	WMUN	Kempton Park	6430	6430	100																														
Nigel Municipality	WMUN	Nigel	32000	22400	100							7500	99		1					2100	100														
Duduza Town Committee	*BLA*	*Nigel*	*130000*																									*130000*	*50*					*50*	
Orange Farm	*TPA*	*Vereeniging*	*135000*																									*135000*					*50*	*50*	
Pretoria City	WMUN	Pretoria/Wonderb	532000	441000	100							69000	100							22000	100														
Atteridgeville Town Council	BLA	Pretoria	165000																									165000	100						
Mamelodi Town Council	BLA	Wonderboom	440000																									440000	92	2	3				3
Randburg Municipality	WMUN	Randburg	120000	120000	90	10																													
Randfontein Municipality	WMUN	Randfontein	40030	28000	100							12000	100							30	100														
Mohlakeng Town Council	BLA	Randfontein	36000																									36000	100						

TABLE 3.8 (continued):

SANITATION COVERAGE IN GAUTENG 1990 (Palmer Development Group et al., 1993b: Table H-T3b: Region H-Wits/Vaal Triangle Metro - Sanitation Access by Race, Combined Survey Information)

Municipality	type	Magisterial district	total pop	White								Coloured							
				pop	WB	SEP	BUC	VIP	PIT	OTH	NON	pop	WB	SEP	BUC	VIP	PIT	OTH	NON
Roodepoort Municipality	WMUN	Roodepoort	0																
Dobsonville Town Council	BLA	Roodepoort	120000																
Sasolburg		Sasolburg	28000	28000	100														
Zamdela		Sasolburg?	76000																
Sandton Municipality	WMUN	Randburg	103264	100292	95	5													
Alexandra Town Council	BLA	Randburg?/Alexar	126000																
Ivory Park		*Kempton Park?*	*84000*																
Soshanguve	*DDA*	*Soshanguve*	*180000*																
Springs Municipality	WMUN	Springs	72000	66000	99	1													
Kwa Thema Town Council	BLA	Springs	170000																
Vanderbijlpark Municipality	WMUN	Vanderbijlpark	85000	65000	100														
Lekoa Town Council	BLA	Vanderbijlpark?	0																
Boipatong		Vanderbijlpark?	25000																
Bophelong		Vanderbijlpark?	24000																
Evaton		Vanderbijlpark	200000																
Sebokeng		Vanderbijlpark	300000																
Sharpville		Vanderbijlpark	98000																
Vereeniging Municipality	WMUN	Vereeniging	77000	67000	100							4000	100						
Verwoerdburg Municipality	WMUN	Pretoria	71000	70000	95	5													
Westonaria Municipality	WMUN	Westonaria	24000	24000	99	1													
Bekkersdal Town Committee	BLA	Westonaria	107000																
totals			8709787	2254636								314732							

Municipality	Asian								Black							
	pop	WB	SEP	BUC	VIP	PIT	OTH	NON	pop	WB	SEP	BUC	VIP	PIT	OTH	NON
Roodepoort Municipality																
Dobsonville Town Council									120000	65					35	
Sasolburg																
Zamdela									76000	60		40				
Sandton Municipality	2972	100														
Alexandra Town Council									126000	70		15				15
Ivory Park									*84000*						*100*	
Soshanguve									*180000*	*70*				*30*		
Springs Municipality	6000	100														
Kwa Thema Town Council									170000	100						
Vanderbijlpark Municipality									20000	100						
Lekoa Town Council																
Boipatong									25000	100						
Bophelong									24000	80						20
Evaton									200000	100						
Sebokeng									300000	100						
Sharpville									98000	100						
Vereeniging Municipality	6000	100														
Verwoerdburg Municipality									1000	95	5					
Westonaria Municipality																
Bekkersdal Town Committee									107000	20		80				
totals	149066								5991353							

Within Gauteng, the areas where on-site sanitation is being used are found in 3 main regions:

- Soshanguve (pit latrines - 30% of 180 000=24 000, together with water-borne sanitation) in the north;
- Ivory Park (LOFLOS systems - 100% of 84 000, in the process of being converted to water-borne sanitation) in Kempton Park (in the centre);
- Orange Farm (pits and LOFLOS systems - each 50% of 135 000=67 500 each) in Vereeniging (in the south);
- also Duduza (LOFLOS systems - 50% of 130 000=65 000 - together with water-borne sanitation) in Nigel in the south-east;
- total = 240 000 say 250 000.

There are also buckets in Khutsong, a few in Atteridgeville and some in Alexandra Township.

In the white local authorities, there are septic tanks as follows:

- small numbers of septic tanks (5% and less) in 9 local authorities;
- small, but slightly more significant numbers in 2 local authorities: Boksburg (10% of 83 730=8 400) and Randburg (10% of 120 000=12 000);
- significant numbers in 2 local authorities: Benoni (50% of 77 189=38 500) and Midrand (42% of 33 849=14 200);
- total say 100 000.

It is possible to characterise the areas with on-site (or non-water-borne sanitation types). With respect to the low-cost on-site sanitation types, all can be said to be 'fringe' areas in some sense, although they may not be on the fringe of Gauteng.

- Duduza is the only township that is really on the fringes of the broader metropolitan area (meaning Region H - as against Gauteng);
- While Soshanguve is on the fringes of Gauteng, it is still quite centrally located within Region H, being on the Pretoria side of the previously homeland areas of Bophutatswana (which now fall outside Gauteng);
- Ivory Park is in the 'gap' between Johannesburg and Pretoria;
- Orange Farm is located within the 'gap' between Vanderbijlpark/Vereeniging and Johannesburg.

The high-cost on-site sanitation types (septic tanks) are generally in the more affluent suburbs with larger plot size. Buckets are being used mainly in emergencies in densely populated townships.

3.6 Allocation of population and sanitation type to catchment areas

In order to allocate population figures within magisterial districts to catchment areas, it is necessary to make certain assumptions. As a first estimate, the following assumptions were made:

- that the population within magisterial districts is confined to areas demarcated as 'built-up areas' within those districts;
- that population is evenly spread within those built-up areas;

TABLE 3.9:
ALLOCATION OF GAUTENG POPULATION TO IMPOUNDMENT CATCHMENTS (calculated here on 1996 census data)[1]

					Greater Johannesburg							Greater East Rand							West Rand				Greater Pretoria				Vaal	
	Impoundment		tributary		Jhbg	Soweto	Randbg	Rood	Alb	Ben	Bok	Brak	Germ	Heid	KempP	Nigel	Springs	Krug	Ober	Randftn	West	Bronk	Cull	Pret	Sosh	Wond	Vereen	Vdbpk
1	Rietvlei		Rietvlei	G											0.25							0.05		0.1				
2	Hartbeespoort	1	Rietvlei																									
			plus ...																									
		2.1	Magalies (west)	part G														0.1		0.15								
		2.2	Crocodile+Jukskei	G	0.5		1	0.1					0.5		0.25			0.9						0.03				
		2.3	Hennops (east)	G											0.25									0.2				
		2.4	*dam environs*	part G																				0.1		0.05		
			sub-total																									
3	Bon Accord			G																				0.3		0.5		
4	Roodeplaat			G																		0.05	0.1	0.27		0.3		
5	Klipvoor	3	Bon Accord																									
		4	Roodeplaat																									
			plus ...	part G																			0.3		1	0.15		
6	Rust der Winter			part G																			0.5					
7	Bronkhorstspruit			G																		0.25						
8	Loskop	7	Bronkhorstspruit																									
			plus ...	part G																		0.65						
9	Arabie	6	Rust der Winter																									
		8	Loskop																									
			plus ...	part G																			0.1					
10	Vaal Barrage	10.1	Rietspruit	G																	0.5							0.9
		10.2	Klip	G	0.5	1		0.9	1	0.1	1	0.6	0.5	0.2	0.25					0.15	0.25						0.7	0.1
		10.3	Suikerbosrand	part G						0.9		0.4		0.8		1	1										0.3	
			sub-total																									
11	Boskop			part G															1	0.7	0.25							
	total				1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

	Greater Johannesburg							Greater East Rand							West Rand				Greater Pretoria				Vaal	
	Jhbg	Soweto	Randbg	Rood	Alb	Ben	Bok	Brak	Germ	Heid	KempP	Nigel	Springs	Krug	Ober	Randftn	West	Bronk	Cull	Pret	Sosh	Wond	Vereen	Vdbpk
(source for population figures: Census 1996)	760791	904165	362481	279340	410257	366343	263179	171363	164252	83013	446106	106120	163304	208751	166101	133032	160763	35523	82601	692348	242727	319798	342704	483360

					% of Gauteng	total	Greater Johannesburg							Greater East Rand							West Rand				Greater Pretoria				Vaal	
	impoundment		tributary		pop	pop	Jhbg	Soweto	Randbg	Rood	Alb	Ben	Bok	Brak	Germ	Heid	KempP	Nigel	Springs	Krug	Ober	Randftn	West	Bronk	Cull	Pret	Sosh	Wond	Vereen	Vdbpk
1	Rietvlei		Rietvlei	G	2.5	182538											111527							1776		69235				
2	Hartbeespoort	1	Rietvlei																											
			plus ...																											
		2.1	Magalies (west)	part G	0.6	40830														20875		19955								
		2.2	Crocodile+Jukskei	G	16.0	1173110	380396		362481	27934					82126		111527			187876						20770				
		2.3	Hennops (east)	G	3.4	249997											111527									138470				
		2.4	dam environs	part G	1.2	85225																				69235		15990		
			sub-total		21.1	1549162																								
3	Bon Accord			G	5.0	367603																				207704		159899		
4	Roodeplaat			G	4.0	292909																		1776	8260	186934		95939		
5	Klipvoor	3	Bon Accord																											
		4	Roodeplaat																											
			plus ...	part G	4.3	315477																			24780		242727	47970		
6	Rust der Winter			part G	0.6	41301																			41301					
7	Bronkhorstspruit			G	0.1	8881																		8881						
8	Loskop	7	Bronkhorstspruit																											
			plus ...	part G	0.3	23090																		23090						
9	Arabie	6	Rust der Winter																											
		8	Loskop																											
			plus ...	part G	0.1	8260																			8260					
10	Vaal Barrage	10.1	Rietspruit	G	7.0	515406																	80382							435024
		10.2	Klip	G	39.6	2907486	380396	904165		251406	410257	36634	263179	102818	82126	16603	111527					19955	40191						239893	48336
		10.3	Suikerbosrand	part G	11.4	836899						329709		68545		66410		106120	163304										102811	
			sub-total		58.0	4259791																								
11	Boskop			part G	4.1	299414															166101	93122	40191							
	total				100.0	7348426	760792	904165	362481	279340	410257	366343	263179	171363	164252	83013	446108	106120	163304	208751	166101	133032	160764	35523	82601	692348	242727	319798	342704	483360

- that basic and intermediate levels of service of sanitation are located in what were formerly black local authority areas, or alternatively in areas specifically set aside for new low cost housing developments; that full levels of service are assumed evenly spread throughout the built-up areas of the province.

Based on the above assumptions, the distribution of populations of the catchment areas of the major impoundments was constructed, and is given in Table 3.15.

3.7 Possible future scenarios for population and sanitation type

While the planning gives a good indication of likely population, geographical location and level of service, the scenarios for modelling the future were chosen to demonstrate if not worst case scenarios, nevertheless fairly extreme scenarios, in order to give an indication of the range of possibilities with respect to population, level of service and geographical location; and to demonstrate the sensitivity of cost of pollution to these variations.

Future scenarios are therefore addressed in more detail in Chapter 6: 'Application of the model to Hartbeespoort Dam catchment'.

3.8 Allocation of settlement patterns to groundwater catchments

It is also necessary to allocate settlements and sanitation type to *groundwater* catchments. Vegter (1995) has produced a set of national groundwater maps, together with accompanying explanation. The maps are intended to provide a groundwater 'equivalent' of the WR90 *Surface Water Resources of South Africa* series (Midgley et al., 1994a, 1994b, 1994c). For the purposes of this study, however, surface water catchments have been used for groundwater as well.

3.9 Discussion

A number of observations may be made at this stage:

1. There is a significant difference in access to adequate sanitation between Gauteng Province and Region H, with access in Gauteng Province significantly better than that of Region H.
2. Coverage figures may also be affected by large influxes of poorer people into areas, particularly south of Johannesburg.
3. Despite spatial development frameworks, trends in settlement patterns appear to be following existing patterns.
4. In terms of population alone (i.e. regardless of sanitation type), basaed on the 1996 census data:
    - 60% of the population of Gauteng is located in the Vaal Barrage catchment area;
    - 25% in the Hartbeespoort Dam catchment area (Rietvlei Dam being included within that);
    - 12% in the catchment areas of Bon Accord, Roodeplaat and Boskop Dams;

- only 3% of the population in the remaining catchments of Rust de Winter, Bronkhorstspruit and Loskop Dams.

The implication of this is that by far the greatest impact of sanitation (regardless of type) is likely to be found in the Vaal Barrage, followed some way behind by Hartbeespoort Dam, and some way again behind that by Rietvlei, Bon Accord, Roodeplaat and Boskop Dams.

4 WATER QUALITY SECTOR

As indicated in the Methodology chapter, the following topics are addressed in the Water Quality sector:

- different possible *pathways* for contaminants on the surface or in the subsurface to surface or groundwater resources;
- *rates of movement of contaminants* in the sub-surface in different unit areas;
- *contaminant loads discharged to and from different levels of service of sanitation*;
- *lake response* to contaminant concentrations in terms of algal growth;
- some comment on the approach of *Water Resources 90* in the determination of catchment hydrology.

4.1 Contaminant pathways

Contaminants to be considered

As indicated in Fourie and Van Ryneveld (1995), two broad categories of contamination are:

- Microbiological contaminants: Viruses, bacteria, protozoa and helminths.
- Chemical contaminants: of primary significance, nitrogen and phosphorus, in the form of nitrate and phosphate respectively.

Natural organic load is added to this list, not because it remains a long term problem, but because it can cause gross short term pollution. Microbiological contaminants are similar in this respect. They were, however, excluded from the study on the grounds that their persistence in the environment is generally low by comparison with other contaminants. Other contaminants (e.g. inorganic salts, surfactants) are persistent in the environment and may cause problems, but were excluded from this study. The methodologies developed in this study can be extended to these contaminants in a further study, if considered necessary. It is primarily the nutrients (nitrogen and phosphorus) that are considered here.

Illustration of contaminant pathways

Contaminant pathways from different sanitation systems are illustrated in Figures 4.1 and 4.2.

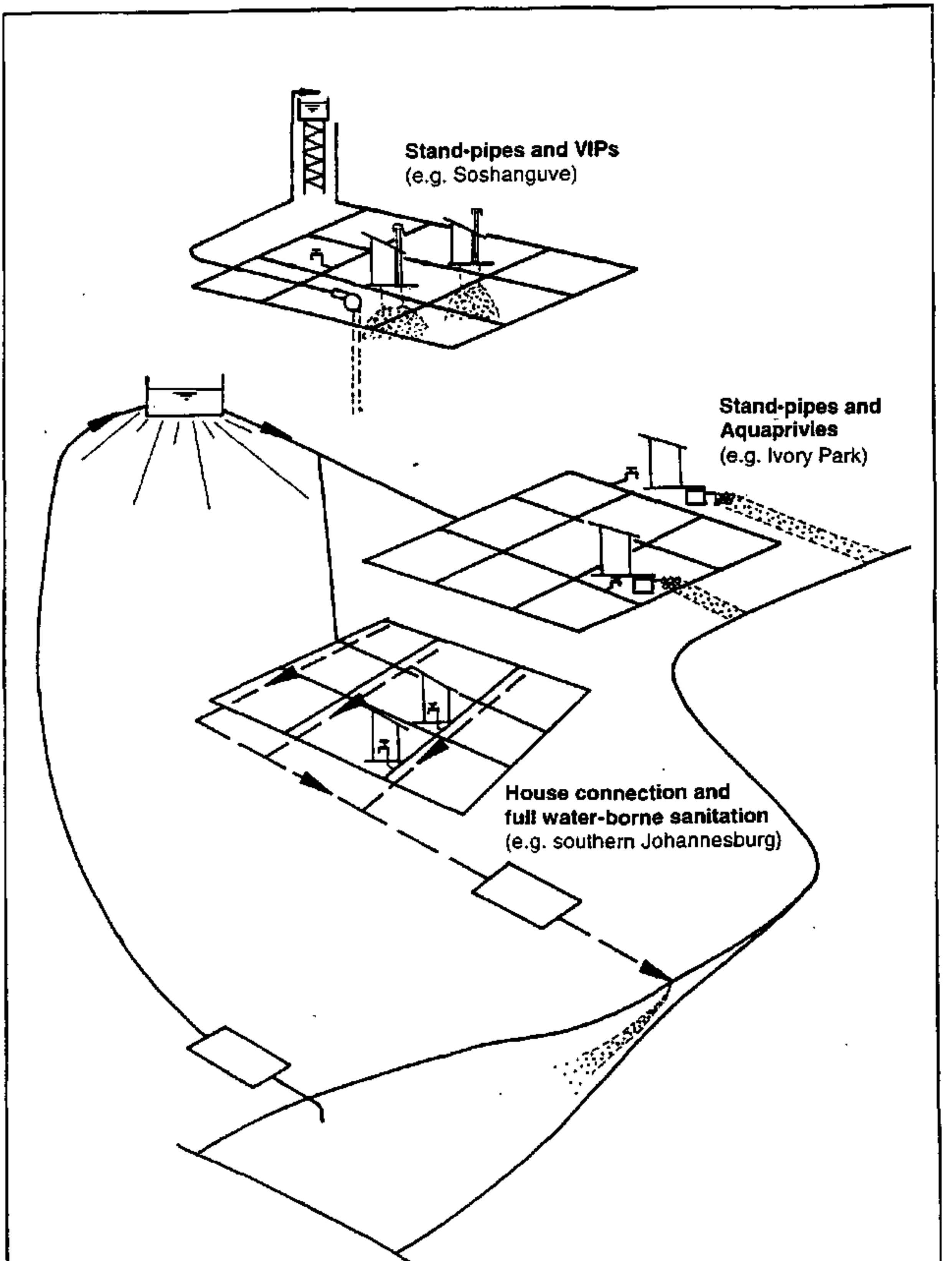
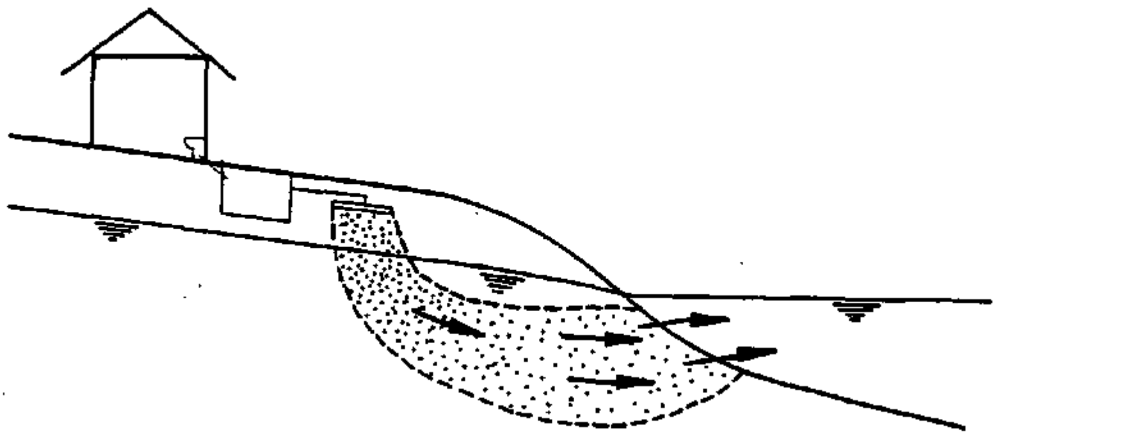
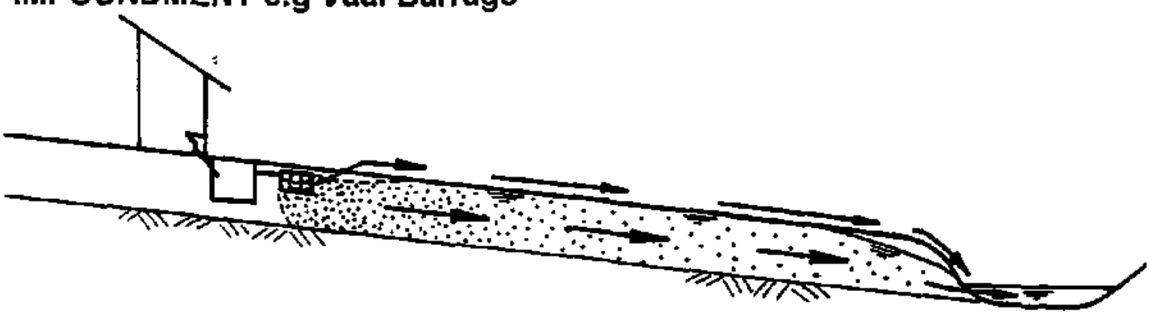


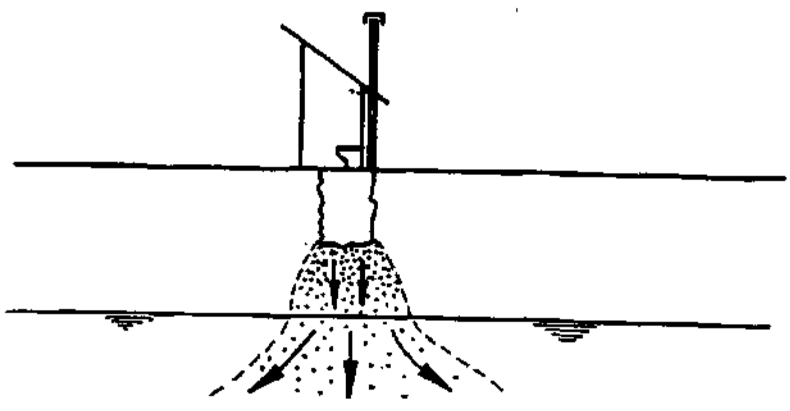
FIGURE 4.1:
GENERAL LAYOUT OF DIFFERENT LEVELS OF SERVICES OF WATER SUPPLY AND SANITATION



CASE 1: SEPTIC TASK CONTAMINANT PLUME DISCHARGING TO IMPOUNDMENT e.g Vaal Barrage



CASE 2: AQUAPRIVY/LOFLOS CONTAMINANT PLUME DISCHARGING TO WATERCOURSE e.g. Ivory Park



CASE 3: VIP CONTAMINANT PLUME DISCHARGING TO GROUNDWATER e.g. Soshanguve

FIGURE 4.2:
SUB-SURFACE CONTAMINANT PATHWAYS FOR VARIOUS TYPES OF ON-SITE SANITATION SYSTEM

4.2 Rate of movement of contaminants in the subsurface

Different *pathways* (via the surface or the subsurface or a combination of the two) have very different time frames, and pathways of different *contaminants* are also different. For movement within the subsurface, the rate of movement of moisture through the subsurface provides an upper bound for the rate of movement of dissolved or suspended contaminants.

Need for characterisation of the subsurface
In order to be able to predict the rate at which contaminants from on-site sanitation systems may travel through the sub-surface, it is necessary to have information on the hydraulic conductivity characteristics of the soils at the location in question. The relative values of hydraulic conductivity are as important as the absolute values of a particular horizon.

Hydraulic conductivity is a notoriously difficult parameter to measure accurately and there are a variety of both field and laboratory techniques currently in use for making these measurements. These are all generally time-consuming and expensive and for the present work it was judged inappropriate to adopt a technique of this type. It was rather decided to use empirical estimates of hydraulic conductivity, based on correlations with conventionally measured soil parameters, such as particle size distribution.

Procedure used for characterisation of hydraulic conductivity
Data for two particular sites were obtained from the Council for Geosciences in Pretoria, that summarised information gathered from geotechnical site investigations carried out in the areas of interest. These data generally consisted of reports by consulting engineers who had been employed to characterise a particular site with a view to future residential developments. The information on soil profiles and characteristics did not include direct measurements of hydraulic conductivity, but did include sufficient information to enable empirically based estimates of conductivity to be made.

Mr Leon Croukamp of the Council for Geosciences kindly made the relevant reports available for scrutiny in the Council's offices. Based on these reports it was possible to propose a 'typical' soil profile for both the Orange Farm and the Ivory Park sites. Upper bound hydraulic conductivities were then assigned to each of these horizons. In both cases it transpired that the upper layer (as detailed in the following section) appeared to be significantly more permeable than the underlying layer and that this latter layer could be assumed impermeable for the purposes of this project. It was thus only necessary to estimate conductivities for the upper, more permeable layers.

Characterisation of sites
Orange farm: The upper 1.5m typically comprised loose to medium dense, clayey to silty sand, which was transported material. Based on the particle size distributions and this general description, an upper bound value of the saturated hydraulic conductivity was estimated as 10^{-6}m/sec. The layer below this was generally a medium dense ferricrete or a stiff, sandy clay of residual andesite. Although it would be prudent to carry out field permeability tests to confirm the supposition of relative impermeability of this layer, it was not within the scope of the present work. Based on the visual descriptions and limited laboratory test results, it was considered justifiable to make this assumption.

Ivory Park: The upper layer generally consisted of about 1m of loose, intact, silty sand, which was transported material. This was usually underlain by a ferruginised layer of about 0.3m thickness, below which was a sandy clay of residual granite. Previous field permeability tests gave an upper bound saturated hydraulic conductivity of 10^{-5}m/sec. This value was consistent with the empirical correlations with particle size data obtained from the reports provided by the Council for Geosciences.

It should be noted that not only are the above estimates of hydraulic conductivity upper bound values, but that they are values for saturated hydraulic conductivity. As the water content of a soil decreases (and the soil thus becomes partially saturated), the conductivity decreases. This decrease may be substantial (e.g. two orders of magnitude), particularly for sands soils. The predictions of rate of groundwater movement given below are thus very much worse-case estimates.

Prediction of rate of groundwater movement

In order to predict the possible rate of groundwater movement for the two cases above, it was assumed that fully saturated flow would occur parallel to the ground surface. This implicitly assumes that there is sufficient water emerging from on-site sanitation systems up-gradient of the point in question to maintain this flow regime. This is clearly an over-simplification of likely conditions and is over-conservative. Nevertheless, it is consistent with the intention of providing a worst-case scenario.

The rate of groundwater movement, v, was estimated from:

$$v = k.i \qquad \qquad (4.1)$$

where k = saturated hydraulic conductivity and
i = hydraulic gradient (which is the rate of head loss per unit distance of travel; the hydraulic gradient is approximated by the natural ground slope).

Average natural ground slopes for built-up areas typically range between 1% and 5%. (A relatively steep section in Ivory Park where experimental work was carried out had a natural ground slope of about 5%). Using the above methodology, a hydraulic gradient (approximated by natural ground slope) of 1% and saturated hydraulic conductivities as found in Orange Farm and Ivory Park yield flow velocities as follows:

- Orange Farm ($k=10^{-6}$m/sec): v = 0.3m/a
- Ivory Park ($k=10^{-5}$m/sec): v = 3m/a

For a slope of 5%, the velocities are simply 5 times the above values i.e. 1.5m/a and 15m/a respectively.

In order to calculate possible contaminant loads to a particular water body, it is necessary to convert this parameter into one that has units of flow rate, ie m^3/year. This is achieved by multiplying the estimated flow rate obtained as indicated above by the cross-sectional area of flow (i.e. depth of flow path x length of reach). Inserting the relevant depth of flow path, the cross-sectional flow areas are as follows:

- Orange Farm (depth of relatively permeable material or flow path = 1.5m):
  flow rate = v x (1.5m x ωm) m^3/a

- Ivory Park (depth of relatively permeable material or flow path = 1.0m):
  flow rate =v x (1.0m x ωm) m^3/a
  (where, for each case, ω is the reach of the water body of interest)

These flow rates are for purely advective movement of the groundwater. No account has been taken of retardation of contaminants due to processes such as adsorption, filtration, bioaccumulation, etc.

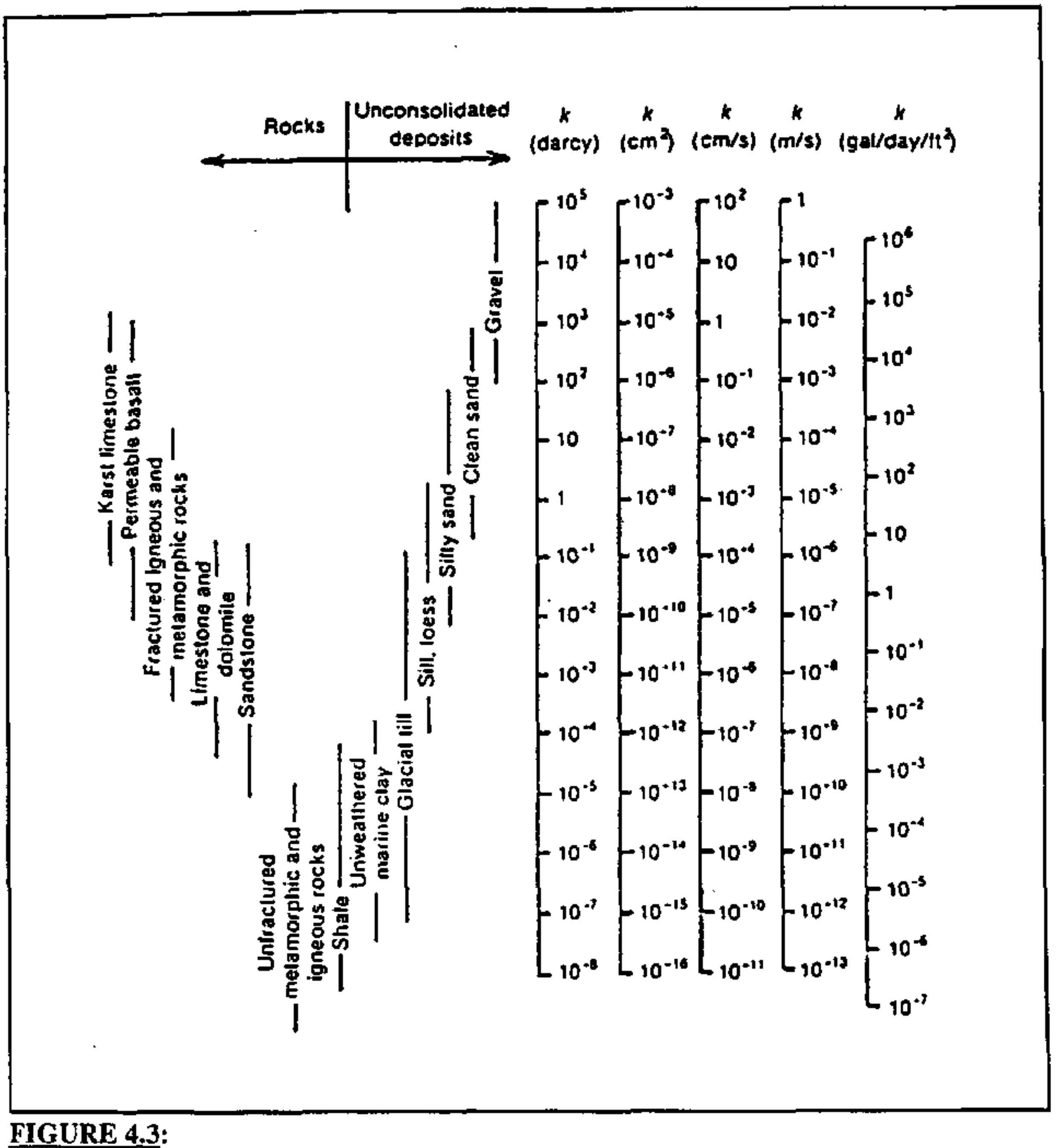


FIGURE 4.3:
RANGE OF VALUES OF HYDRAULIC CONDUCTIVITY AND PERMEABILITY
(after Freeze and Cherry, 1979; quoted by Palmer, C M (1992: p.10)

Summary

As indicated above, different pathways have very different rates of movement, and pathways of different contaminants are also different. Essentially, phosphorus does not move in the subsurface. Nitrogen does, but very slowly. Nitrogen has some effect on eutrophication. It may even be important at certain times of the year, but it is small. The main effect is from phosphorus discharged directly to the watercourse and not removed in-stream by sedimentation or reedbeds. Taking into account the pathways, rate of movement, and effect on the lake of various contaminants, the key contaminant and its pathways are:

- phosphorus discharged directly to the watercourse by waterborne sanitation;
- phosphorus originating from grey water discharged to the ground surface, that is washed off into watercourses by stormwater.

Taking account of the range of permeabilities indicated in Figure 4.3 above, as well as the fact that the rate of movement in an *unsaturated* zone of the subsurface is significantly lower than that for a *saturated* zone, the rate of movement of contaminants in the subsurface in Gauteng can be taken to be of the order of 1-10m/a. Rate of movement of contaminants by wash-off from the ground surface, transport within the surface watercourse to an impoundment in Gauteng can be of the order of 50km in 2-3 days, or a month at the most. There is about 5 orders of magnitude difference between the two rates. Subsurface movement of contaminants, with the geological conditions encountered in Gauteng (taking Ivory Park and Orange Farm as typical), is therefore unlikely to impact on water resources in any significant way within a 10 year frame. Surface wash-off and transport of contaminants, on the other hand, is likely to impact well within a 1 year time frame.

4.3 Contaminant loads discharged to and from different levels of service of sanitation

Form of expression of contaminant loading

Mass loads are considered in this study. They are a functions of two variables: contaminant concentration and effluent volume (for each contaminant).

There are three different 'groupings' for which contaminant loadings can be expressed:

- per household
- per dwelling unit
- per site (or erf)

Each grouping has a different number of people. As there is substantial variation and uncertainty in the number of people in such groupings, this study uses per capita values as the primary figure, which can then be translated into other groupings as necessary.

Sources of data

This study did not collect primary data, but relied on data from a number of other studies. Two types of data have been used in this overview:

- The first type - given in detailed field studies - provide actual measured values from specific sites i.e. primary data.
- The second type - given in guideline documents and text books - provides a set (or range) of values, based on values from various other sources i.e. secondary data.

While the secondary data have been constructed to provide wider applicability, they can be less accurate in particular circumstances than the primary data. A certain amount of adjustment and patching has therefore been necessary to construct a consistent set of values which is applicable to this specific study area (i.e. Gauteng Province) and to meet the objectives of this particular study. In particular, it has in some instances been necessary to disaggregate data given in the literature in order to allocate pollutant mass flows to different pathways.

The study took as its starting point the *Simple model illustrating the environmental impact of sanitation* by Palmer Development Group et al. (1992b). The model traced the pathways of three chemical contaminants (COD, nitrogen and phosphorus) from their source in human waste to their final destination in ground or surface water.

The data for the three levels of service are summarised as follows, presented in a comparative table, generally in units of mass loading per capita per day. Contaminant concentrations are also given at selected points in the sanitation system (because these were used by Palmer Development Group to cross-check the mass loadings given):

<u>TABLE 4.1</u>:
FLOWS AND CONTAMINANT LOADS FOR DIFFERENT LEVELS OF SERVICE OF SANITATION (after Palmer Development Group in association with University of Cape Town Water Research Group, 1992b)

Parameter	*Units*	*VIP*	*Septic tank (LOFLOS)*	*WB*	*Stormwater*	1
Water usage						2
range: total water usage	l/cap.d	20-30				3
total water usage	l/cap.d	30	114	114		4
Breakdown of water usage:						5
range of flush size	l/cap.d					6
to sanitation system (flushing)	l/cap.d	0				7
to sanitation system (cleaning)	l/cap.d					8
to sanitation system (urine)	l/cap.d					9
to sanitation system (total, including flushing, cleaning and urine)	l/cap.d	2				10
to sanitation system (total, including flushing, cleaning, urine and grey water)	l/cap.d		90.9	90.9		11
to environment (grey water)	l/cap.d	28				12
to environment (garden watering, cleaning yard or cars)	l/cap.d	0				13
Contaminant mass loadings to sanitation system (Stage 1):						14
COD (total: excreta + grey water)	gO_2/cap.d		100	100		15
COD (excreta only)	gO_2/cap.d	100				16
COD (grey water only)	gO_2/cap.d	5.6				17

Parameter	*Units*	*VIP*	*Septic tank (LOFLOS)*	*WB*	*Stormwater*	1
Total N (TN) (total: excreta + grey water)	gN/cap.d		10 (as TKN)	10 (as TKN)		18
Total N (TN) (excreta only)	gN/cap.d	10				19
Total N (TN) (grey water only)	gN/cap.d	0.56				20
Total Phosphorus (TP)	gP/cap.d		2.5	2.5		21
Total Phosphorus (TP) (excreta only - mainly urine)	gP/cap.d	2.5				22
Total Phosphorus (TP) (grey water only - detergents)	gP/cap.d	0.88				23
Contaminant concentrations to sanitation system (Stage 1):						24
COD range (total: excreta + grey water)	mg/l			1000-1200		25
COD (total: excreta + grey water)	mg/l		1100	1100		26
COD (excreta only)	mg/l					27
COD (grey water only)	mg/l	200				28
Total N (TN) (total: excreta + grey water)	mg/l		110	110		29
Total N (TN) (excreta only)	mg/l					30
Total N (TN) (grey water only)	mg/l	20				31
Total Phosphorus (TP) (total: excreta + grey water)	mg/l		27.5	27.5		32
Total Phosphorus (TP) (excreta only)	mg/l					33
Total Phosphorus (TP) (grey water only)	mg/l	31				34
Sanitation system stages:						35
Stage 1		discharged to pit	discharged to septic tank	discharged to sewer reticulation system (to treatment works)		36
Stage 2a			discharged from septic tank to soakaway			37
Stage 2/2b:		discharged from pit to subsurface	discharged from soakaway to subsurface	discharged from treatment works to surface watercourse		38
Stage 3		reach groundwater	reach groundwater			39
Contaminant removal efficiency: Stage 1-2/2a		*(Stage 1-2)*	*(Stage 1-2a)*	*(Stage 1-2)*		40
COD	%	50	60	92.7 say 93		41
TN	%	10	15	27.7 - 86.8 say 28-87		42

Parameter	*Units*	*VIP*	*Septic tank (LOFLOS)*	*WB*	*Stormwater*	1
TP	%	10	15	9		43
Contaminant removal efficiency: Stage 2a-2b			*(Stage 2a-2b)*			44
COD	%		60-90			45
TN	%		10-90			46
TP	%		50-100			47
Contaminant removal efficiency: Stage 2-3		*(Stage 2-3)*				48
COD	%	60-90				49
TN	%	10-90				50
TP	%	50-100				51
Contaminant removal efficiency: total sanitation system		*(Stage 1-3)*	*(Stage 1-3)*	*(Stage 1-2)*		52
COD	%	80-95 ave: 88	84-96 ave: 90	92.7 say 93		53
TN	%	19-91 ave: 55	24-91 ave: 58	27.7 - 86.8 say 28-87		54
TP	%	55-100 ave: 78	57-100 ave: 79	9		55
Contaminant concentrations from treatment tank/plant (Stage 2a/2) or from stormwater:			*(Stage 2a)*	*(Stage 2)*		56
COD	mg/l		440	80	0-800	57
TN	mgN/l		93.5 say 93	4.5 (TKN) 10-75 (NO_3) 14.5-79.5 (TN)	0.6-24(TKN) 0.3-16 (NO_3) 0.9-40 (TN)	58
TP	mgP/l		23.4 say 23	25 (1-standard)	0.12-8.83	59
Contaminant mass loadings discharged from total sanitation system (or by stormwater) to water resource (Stage 2/3):		*(Stage 3)*	*(Stage 3)*	*(Stage 2)*		60
COD (to groundwater)	gO_2/cap.d	20 -5 ave: 12	16 -4 ave: 10			61
COD (to surface water)	gO_2/cap.d			7	30.68 say 7.7-61.4	62
TN (to groundwater)	gN/cap.d	8.1 - 0.9	7.65 - 0.85			63
TN (to surface water)	gN/cap.d			7.2 - 1.3	2.15 say 0.5-4.3	64
TP (to groundwater)	gP/cap.d	1.125 - 0	1.06 - 0			65
TP (to surface water)	gP/cap.d			2.275 (0.091-1mg/l)	0.31 say 0.08-0.62	66

Parameter	*Units*	*VIP*	*Septic tank (LOFLOS)*	*WB*	*Stormwater*	1
Contaminant mass loadings discharged by stormwater to water resource:						67
COD (to surface water)	$kgO_2/ha.a$				800	68
TN (to surface water)	kgN/ha.a				56 (total) 23 (soluble)	69
TP (to surface water)	kgP/ha.a				8	70

Note:
Assumed domestic waste loads were as follows:

- COD = 100 g/cap.d
  Mara (1976) gives a range of 25 - 60 g/cap.d BOD_5 for domestic sewage which is equivalent to 45 - 108 g/cap.d COD assuming 1.8x BOD_5 for domestic sewage. The UCT Water Research Group recommends 100 g/cap.d COD for treatment works design for low-income communities in South Africa (Wentzel, personal communication with Palmer Development Group et al., 1992b). The figure is possibly conservative (i.e. high)
- Total Nitrogen (TN) (as TKN-N) = 10 g/cap.d
  Assumed to be CODx10% (Wentzel, personal communication with Palmer Development Group et al., 1992b). A relatively constant ratio of 10:1 between COD and TKN has been empirically found in domestic wastewater. (This is a mixture of excreta and grey water, and may also include some commercial and industrial waste)

Points highlighted by Palmer's simple model include:

- the difficulty of defining where a sanitation system 'ends', and of finding equivalent stages or end-points for different levels of service or types of sanitation system;
- similarly, the difficulty of defining a point of compliance (i.e. where does one *want* to *check* the contaminant levels from a sanitation system, be it at the point of discharge from the treatment tank/plant or some point in the environment such as entry to a surface impoundment or water table in the case of groundwater);
- while characteristics of the effluent are reasonably well known upon discharge from the treatment tank (in the case of the septic tank) or from a treatment works (in the case of water-borne sanitation), the effluent characteristics are not nearly as well known as they travel through the subsurface or in surface watercourses.

Further specific conclusions are as follows:

- The mass loadings discharged *to* all 3 sanitation systems are considered to be very similar (COD and TN are likely to be very similar; TP may be slightly higher in water-borne systems as more detergents are likely to be used).
- In all 3 systems, most (about 90%) of the COD is removed.
- Nitrogen removal in all 3 systems varies quite widely between about 25% and 90%. For the on-site systems, the removal efficiency is dependant on sub-surface soil conditions; whereas for water-borne systems, it is dependant on the particular wastewater treatment process.
- Phosphorus removal is good in the on-site systems (between about 55% and 100%), but

not nearly as good in the water-borne systems (about 10%)[7], with reasons for this being similar to those for nitrogen removal.

- A further critical difference is *where* the effluent from the different systems is discharged *to*. For the on-site systems, nitrogen is discharged primarily to the subsurface via the sanitation system and soakaway, while phosphorus is discharged *onto* the ground surface as grey water. For water-borne sanitation, both nitrogen and phosphorus are discharged directly to the surface watercourses from the treatment works.
- It should be noted that no attempt was made to incorporate stormwater figures in the mass balance. It was pointed out that a relationship did exist between the mass loading from sanitation and the stormwater loading; however it is complex and no attempt was made to address the issue in their study.

Data for the different levels of service from a range of different sources are discussed below, and then summarised in tabular form. While in the literature, there is a significant amount of data on *water demand* (including for different levels of service) - as indicated by the data given above - there appears to be considerably less available on *contaminant loads discharged to different sanitation systems* (particularly to different levels of service), even less on *removal rates for different sanitation systems*, and less still on *transport and removal rates within the environment*. It can also be commented that while there are generally better data available on higher levels of service (full water-borne sanitation discharging to a wastewater treatment works - and to a lesser extent, on-site systems discharging to a septic tank), there appears to be less available on lower levels of service (LOFLOS and VIP).

Palmer Development Group (1994a), using Heigers (1992) as a major source, has provided a comprehensive review of various characteristics of urban water supply, including *total water usage figures for different levels of service*. Heigers quotes:

- South African *national* guideline documents - Department of Community Development (1983), Department of Development Aid (1988) and Department of Planning, Provincial Affairs and Housing, 1991);
- South African *regional* guideline documents - CPA 'Brown Book'[8] - based on WHO guidelines, and RSA/Kwazulu guidelines[8] ;
- other country national studies or guideline documents - Botswana and Philippines;
- various international guidelines - Institution of Water Engineers and Scientists (1983).

Of the South African national guideline documents, The Department of Community Development 'Guidelines for the Provision of Engineering Services in Residential Townships' (1983), commonly called the 'Blue Book', suggests a range of water demand values, varying according to stand size, and which is presented in the form of a graph (Figure F2: Annual Average Daily Water Demand for dwelling houses, pF12). For stand sizes of 600m^2 and less, a constant range of water demand values between 600 and 1 200 l/site.d is given. Above 600m^2, the values rise with increasing stand size to a range of values between 2 100 and 3 500 l/site.d for a stand size of 2 000m^2. Assuming 6 people per stand, this translates into a constant range of

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7 Comment by this study: The crucial exception is nutrient removal activated sludge, for which phosphorus removal is excellent (97%).

8 No reference given by Palmer Development Group (1994a: p.7.4- 7.8)

water demand values between 100 and 200 l/cap.d for stand sizes of 600m^2 and less, rising with increasing stand size to a range of values between 350 and 583 (say 600) l/cap.d for a stand size of 2 000m^2. There are two important points to note about the 'Blue Book' guidelines:

- The document was intended for use in economic as against sub-economic townships in South Africa (and is therefore applicable to middle/high income households - as against low income households - in South Africa).
- A full level of service for water supply and sanitation is assumed.

The two subsequent national guideline documents - the 'Green Book' (Department of Development Aid, 1988), which was intended for developing communities, and the 'Red Book' (Department of Planning, Provincial Affairs and Housing, 1991), which is essentially a combination of the 'Blue' and 'Green' Books - recommend using the International Reference Centre values given in the Table 4.2 below for water usage for different levels of service.

TABLE 4.2:
TYPICAL DOMESTIC WATER USAGE FOR DIFFERENT LEVELS OF SERVICE (International Reference Centre, 1981)

Type of water supply	*Typical consumption [l/cap.d]*	*Range [l/cap.d]*
Well or standpipe >1000m	7	5-10
250-1000m	12	10-15
Well <250m	20	15-25
Standpipe <250m	30	20-50
Yard connection	40	20-80
House connection Single tap	50	30-60
Multiple taps	150	70-250

Of the South African regional guideline documents, the RSA/Kwazulu Guidelines, which were intended for use in the Durban and Pietermaritzburg metropolitan areas, draw primarily on the 'Blue Book' with some modifications; the 'Brown Book' prepared by the Cape Provincial Administration, on the other hand, has proposed the level of service and water consumption standards of the World Health Organisation, provided in tabular form (in Table 4.3) as follows:

TABLE 4.3:
WATER CONSUMPTION FOR DIFFERENT LEVELS OF SERVICE AND DENSITY OF WATER SUPPLY (Cape Provincial Administration, after WHO[9])

Available water source/ level of service	*Standpipe/well density [per no of dwellings]*	*Consumption [l/cap.d]*
If no water is readily available but has to be carted to the community		15 (minimum provision)
If a specific source is available	30-50 dwellings	20
If a pipeline can be afforded		50
If ample water is available		90
If ample water is available at sufficient pressure	6-10 dwellings	90
With the highest standpipe density and no metering		120
The next step is to provide individual domestic connections		170

The WHO also recommends that the rate of flow for standpipes should be limited to 15-20 l/min and the distance to standpipes should not be more than 150 m.

The international guideline document quoted by Palmer Development Group (1994a) is one of the volumes of the *Manual of British Water Engineering Practice* series (Institution of Water Engineers and Scientists, 1983). Of other international work (not specifically quoted by Palmer Development Group, 1994a), Mara (1982: p16), in work carried out by the World Bank as a contribution to the UN International Drinking Water Supply and Sanitation Decade, produced similar but less detailed figures, together with possible sanitation options:

9 No reference given by Palmer Development Group (1994a: p.7.7)

TABLE 4.4:
WATER CONSUMPTION AND OPTIONS FOR EXCRETA AND SULLAGE DISPOSAL FOR DIFFERENT LEVELS OF SERVICE OF WATER SUPPLY
(Mara, 1982: p16)

Water supply service level	*Typical water consumption [l/cap.d]*	*Options for excreta disposal* [1]	*Options for sullage disposal* [1]
Standpipes	20-40 [2]	Pit latrines Pour-flush toilets[3] Vault toilets[3]	Soakage pits
Yard taps	50-100	Pit latrines Pour-flush toilets Vault toilets Sewered pour-flush toilets Septic tanks	Soakage pits Stormwater drains Sewered pour-flush toilets Septic tanks
Multiple tap in-house connections	>100	Sewered pour-flush toilets Septic tanks Conventional sewerage	Sewered pour-flush toilets Septic tanks Conventional sewerage

1 The options are not listed in any order of preference
2 Consumption depends on standpipe density
3 Feasible only if sufficient water carried home for flushing

Work by Okun and Ernst (1987: p45) - also a World Bank study - recommended water consumption figures as follows (tabulated slightly differently from the original work), which give an indication of the effect of climate on water consumption:

TABLE 4.5:
WATER CONSUMPTION FOR DIFFERENT LEVELS OF SERVICE AND DIFFERENT CLIMATIC CONDITIONS (Okun and Ernst, 1987: p45)

Level of service	*Climate*	*Water consumption [l/cap.d]*	*Comment*
Public standpipe	humid average dry	10-20 20-30 30-40	
House connection	humid average dry	20-40 40-60 60-80	House connection without flush toilets and not including allowances for private irrigation, animal watering or other enterprise

Of the other primary studies quoted by Palmer Development Group (1994a), the following is of particular interest: Rivett-Carnac (1989) provided water consumption figures for communities in the Durban Functional Region using a rudimentary water supply based on standpipes:

TABLE 4.6:
WATER CONSUMPTION FOR COMMUNITIES USING A RUDIMENTARY WATER SUPPLY IN THE DURBAN FUNCTIONAL REGION (Rivett-Carnac, 1989)

Area	*Type of supply*	*Average water use [l/cap.d]*
Inanda (Released area 33)	Water kiosk	18
Sankotshe/Geargedale	Uncontrolled standpipe	12
Molweni, Embo, Nqcolosi, Qadi	Controlled standpipe	15

In these Durban examples, the standpipe density was generally less than one per 50 households.

Similar low consumption figures were obtained in Bester's Camp, an upgraded settlement about 20 km north of Durban city centre, with the following levels of service:

- VIP latrine for each dwelling
- 1 standpipe or water kiosk for every 150 households

Water consumption here was 47 l/household.d (based on 210 kl/water point.month serving an average of 150 households per water point) which translates to approximately 10 l/cap.d. It was noted that the high water cost (R2.80/kl) may have been an important influence on consumption (Palmer Development Group et al., 1992e: p30).

From these, together with a number of other studies, the following summary of consumption figures for different levels of service in urban areas can be summarised from Palmer Development Group (1994a: p7.9-7.12):

TABLE 4.7:
WATER CONSUMPTION FOR DIFFERENT LEVELS OF SERVICE OF WATER SUPPLY AND SANITATION IN DEVELOPING URBAN AREAS OF SOUTH AFRICA (Palmer Development Group, 1994a: p7.9-7.12)

Level of service	*Sanitation system*	*Water consumption [l/cap.d]*	*Comment*
Rudimentary	(assumed dry)	15-20	(1) Sanitation system assumed to be dry e.g.VIP
Planned urban standpipe supply	dry LOFLOS	20-35 35-50	(1) Distance to standpipe ≯ 250m and> one standpipe per 50 households. (2) With water carried, about 20-15 l/household.d needs to be added, assuming a flush volume of 1 to 1.5 litres
Yard connections	dry LOFLOS full flush	30-60 45-75 60-100	(1) Full flush toilets may use 30-50 l/cap.d under South African conditions
House connections with multiple taps	full flush full flush	75-100 (essential use) 100-250 (convenience use)	(1) Consumption can vary widely, depending on income level and many other factors

They did, however, make it clear that considerable variability should be expected. It should also be noted that the focus of their study was on *developing* urban communities in South Africa.

In the same report, Palmer Development Group (1994a: p5.7-5.10) more specifically gives average per capita domestic consumption for the major metropolitan areas of South Africa, which are somewhat higher than the figures given in the table above. For the PWV, low-income per capita consumption is given as 120 l/cap.d and high income as 350 l/cap.d; for South African metropolitan areas in general, the figures are given as 108 and 315 l/cap.d respectively. The report also gives two explanatory footnotes as follows (comments in square brackets have been added):

(1) Race groups were used as a very crude approximation of income groups as follows: whites, coloured and indians were taken to represent the middle and high income groups, and blacks the low income group (with the exception of Cape Town where whites only were taken to be high income, and Port Elizabeth where the high/low split was assumed similar to East London and Cape Town). This categorisation was used for the sake of convenience only. Water consumption information had already been collected by local authority (which at present are still largely racially defined) and hence it made the most sense to match this data with a broad racial classification of income groups along racial lines which is (unfortunately) a fair approximation.

(2) Average per capita consumption figures are based on information from the survey and reported on in the regional profiles. These were adjusted to match the total domestic consumption figures per metropolitan area which can be calculated from Table 5.4 [in the original report]. The figures probably provide optimistic [i.e. high] estimates for low-income per capita consumption as, where there was doubt, these figures were adjusted up in favour of the high income per capita consumption, which consequently are likely to be conservative. This conclusion is also supported by the fact that unaccounted for water (distribution losses) were not taken into account [i.e. were not subtracted from the consumption figures] when calculating average per capita consumption figures for black local authorities in the regional profiles.

It should be noted that, in terms of level of service, the high income consumption figure quoted would refer almost exclusively to house connections with multiple taps, while the low income consumption figure may refer to a mixture of levels of service.

Turner et al. (1997) have provided primary data on measurements of *water demand patterns* in Gauteng that they carried out on a range of areas with different income levels and different levels of service (although most are a full level of service):

TABLE 4.8:
WATER DEMAND CHARACTERISTICS FOR DIFFERENT AREAS IN GAUTENG (Turner et al., 1997)

	Unit	*SHL*	*POM*	*CRY*	*GRB*	*WIT*	*AZD*	*RVL*	*NDG*	*ALX*	*RAB*
Income		high	mid/ high	mid	mid	mid	mid	low/ mid	low	low	very low
Annual income		77.3	41.6	41.8	30.3	33.1	27.3	22.5	14.6	13.3	ND
Non-earning	%	31	38	33	43	41	57	58	65	61	
Density		low	low	low		med	med	med	med	very high	high
Average stand size	m^2	1460	1150	1000	1000	850	600	400	250	380	200
Population density	pph	23	24	22	33	33	37	58	72	500	123
Level of service		HC+ WB	HC+ WB	HC+ WB	HC+ WB	HC+ WB	HC+ WB	HC+ WB	HC+ WB	HC/ YT+ WB	SP+ AP
Consumption per unit area	m^3/ha.d	9.3	7.0	7.0	9.4	8.8	14.3	13.1	11.3	45.3	3.6
Consumption per stand	l/stand.d	2583	1283	1465	1139	1132	1586	1077	951	1725	159
Consumption per dwelling unit	l/du/d	1271	1283	1004	1139	1137	1378	1001	953	971	80
Consumption per capita	**l/cap.d**	**396**	**289**	**318**	**285**	**265**	**386**	**227**	**156**	**91**	**29**
People per stand	cap/ stand	6.52	4.44	4.61	4.00	4.27	4.11	4.74	6.10	18.96	5.48
People per dwelling unit	cap/du	3.21	4.44	3.16	4.00	4.29	3.57	4.41	6.11	10.67	2.76

Note:

1 ***Suburb name abbreviations:***

SHL=Sunninghill
POM= Pomona
CRY= Croydon
GRB=Grobler Park
WIT=Witpoortjie
AZD=Azaadville
RVL=Riverlea
NDG=Noordgesig
ALX=Alexandra
RAB=Rabie Ridge

2 ***Income categories:***

Income categories were defined as follows (figures in 1991 Rands). The income given is the average income of only the individual earners in the census area, according to the 1991 Census. There may be more than one earner in each household, making the combined household income greater than the average for each individual. Survey questionnaires provided estimates of the income per dwelling unit in the target areas.

Very low	<R10 000/dwelling unit.a
Low	R10 000 - R25 000/dwelling unit.a
Middle	R25 000 - R50 000/dwelling unit.a
High	>R50 000/dwelling unit.a

With the exception of Azaadville - for which per capita consumption is high - the consumption figures quoted above for full level of service fall within the bounds recommended by the 'Blue Book' guidelines; however, they are generally higher than figures quoted by other workers above (150-400 l/cap.d, as compared with about 100-250 l/cap.d for 'convenience use' suggested by Palmer Development Group (1994)). In the two cases of lower level of service - Alexandra and Rabie Ridge - per capita water consumption figures appear to fall within the ranges suggested by other workers. The higher values were confirmed in a cross-check performed on flow and population in Hartbeespoort Dam cacthment in the course of this study, where an *average* sewage discharge value for *all* water-borne sanitation services was of the order of 200 l/cap.d.

Stephenson and Hine (1986) produced flow patterns for sewage flows from different areas in Johannesburg equivalent to those by Turner et al. (1997) given above for water demand. They also provided an estimate of infiltration *into* sewers of 0.05 l/min per metre [length] of sewer per metre diameter. It was suggested that this figure would be greater for older sewers in poor soils. Urban Management (1998) provided an indication of leakage *from* sewers, quoting a report submitted to the Department of Water Affairs and Forestry by the Greater Johannesburg Metropolitan Council which estimated that 60 Ml/d of raw sewage (out of a total of 750 Ml/d i.e. 8%) was entering the environment as a result of blockages and leaks. Kittay (1991) indicated that Johannesburg Municipality was using a figure of 830 l/site.d + 12% for infiltration = 929.6 say 930l/site.d and a peak factor of 2.4 for design of full water-borne sanitation in the local authority.

With respect to *contaminant loads* - including grey water - the results of a survey of 5 households in the United States by Laak (1974), adapted and quoted by Feachem et al. (1983: Table 1-12, p19), is given in Table 4.9:

<u>TABLE 4.9</u>:
POLLUTION LOADS OF WASTEWATER FROM VARIOUS PLUMBING FIXTURES IN THE USA (mg/capita daily; values given in brackets are the percentage contribution of the source) Feachem et al. (1983: Table 1-12, p19) after Laak (1974)

Wastewater source	*BOD*	*COD*	*NO_3-N*	*NH_3-N*	*PO_4*
Bathroom sink	1 860 (4)	3 250 (2)	2 (3)	9 (0.3)	386 (3)
Bathtub	6 180 (13)	9 080 (8)	12 (16)	43 (1)	30 (0.3)
Kitchen sink	9 200 (19)	18 800 (16)	8 (10)	74 (2)	173 (2)
Laundry machine	7 900 (16)	20 300 (17)	35 (49)	316 (10)	4 790 (40)
Toilet	23 540 (48)	67 780 (57)	16 (22)	2 782 (87)	6 473 (55)
Total	48 690 (100)	119 410 (100)	73 (100)	3 224 (100)	11 862 (100)

In a number of related studies, Palmer Development Group (1992c and 1992d) as well as Fourie and Van Ryneveld (1993) have provided data on breakdown of water usage, contaminant loadings and removal efficiencies for LOFLOS sanitation systems.

Water use data for three LOFLOS sanitation systems investigated by Palmer Development Group (1992c: p1-4; 1992d: p4- 5) were described as follows (based on a survey of between 67 and 100 users per toilet type):

TABLE 4.10:
WATER USE FOR THREE LOFLOS SANITATION SYSTEMS
(Palmer Development Group, 1992c: p1-4; 1992d: p4- 5)

LOFLOS sanitation type	*tank size [litres]*	*flush volume [litres]*	*sanitation water usage [l/site.d]*	*no of users per sanitation unit [no]*	*sanitation water usage [l/cap.d]*	*flushes per person per day [flush/cap.d]*
HS Water Flush Tipping Tray Sanitation System	36	0.75 [1]	11.1	5.4	2.06	2.7 say 3
Atlas Aqua-privy	200 [2]	0.8	9.2	4.1	2.24	2.8 say 3
Calcamite Sanitary Disposal System	1 000	0 (dry)	9.5	4.7	2.02	(dry system; although water used for cleaning)
average values [3]			9.8 say 10	4.6 say 5	2.1 say 2	

[1] 0.5 litre flush quoted by Palmer Development Group (1992c: p1)
[2] liquid volume approximately 150 litres
[3] simple average of the values for each of the 3 LOFLOS sanitation types

In a later discussion, Palmer Development Group (1992c: p7) suggested values of 6 users/site, 1 l/cap.use of flush water + urine and 4 uses/cap.d, giving a figure of 4 l/cap.d flush water + urine. Slightly lower - although similar - figures (average 1.5 l/cap.d flush water usage with a 0.8 l flush volume, giving just under 2 flushes/cap.d) were reported in the specific study of 3 Atlas aquaprivies by Fourie and Van Ryneveld (1993: p18), although it was pointed out that the daily amount of water used to flush the toilet units were rough estimates made by stand occupants based on the number of buckets of water carried. (Contaminant mass loading figures, which were derived using the water volumes, would also therefore have limited accuracy).

With respect to contaminant loadings and removal efficiencies, Palmer Development Group (1992c: p8) (work carried out by Prof Gerrit Marais and Craig Peters) estimated the concentrations of organic loading from LOFLOS sanitation systems (and conventional septic tanks) to be as follows:

- in low cost housing the faecal BOD_5 contribution = 36 g/cap.d.
- assuming $COD/BOD_5 = 2$, COD = 72 g/cap.d.
- assuming that the septic tank receives no grey water - as in the case of the LOFLOS system, with effluent discharge of 4 l/cap.d (see discussion above), influent COD concentration = 18 000 mg/l COD.
- in a septic tank treating both the excreta and grey water - in a conventional septic tank system - because of the high water usage, the influent is of the order of 1 000mg/l COD

- COD reduction in a septic tank could range from 50% to 80%
- this would result in a concentration ranging between 3 600 and 9 000 mg/l COD for a LOFLOS system, and between 200 and 500 mg/l COD for a conventional system.

The most recent study on the treatment processes taking place in LOFLOS sanitation systems in South Africa was carried out by the Division of Water, Environment and Forestry Technology, CSIR (Environmentek, 1997). The study focussed on the *digester tank contents* i.e. on the processes occurring *in* the tank rather than on the *effluent* i.e. what was coming *out* of it. This did pose some difficulties for estimating effluent characteristics, in that the characteristics of the digester tank contents were generally not uniform throughout the tank, and the effluent characteristics were not always identical to those of the tank contents. However, the researchers did state in their conclusions that "the effluent discharges from all the systems monitored, although not sampled, are likely to have high COD, MLSS, VSS, ammonia and TKN concentrations in line with the concentrations measured in the vicinity of the discharge point".

Three tank sizes were considered, in the range 45 litres to 1 500 litres, as follows (Environmentek, 1997: p16-20) (Details were somewhat limited, with the researchers being careful to avoid identification of particular brand names in their study report):

- System 1: 1 000 litres; sampled top, middle and bottom
- System 2: 1 500 litres; sampled top and bottom
- System 3: 45 litres; sampled inlet and outlet

Although the particular configurations of the different systems given in the report (including entry and exit from the digester tank, as well as flushing mechanism) made it difficult to deduce what the effluent characteristics were from data given on the tank contents at various positions within the tank, the researchers *did* go on to provide figures which they considered to be representative of the characteristics of the effluent from the various LOFLOS systems, as follows:

TABLE 4.11:
COMPARISON OF EFFLUENT QUALITY FROM CONVENTIONAL SEPTIC TANKS WITH THAT OF LOFLOS SANITATION SYSTEMS (Environmentek, 1997: p.49)

Parameter	*conventional septic tanks [mg/l]*		*LOFLOS sanitation systems [mg/l]*		
	Polprasert et al. (1982) [1]	*EPA report 600/2-78-173* [1]	*Environmentek (1997)*		
			System 1 (top)	*System 2 (top)*	*System 3 (outlet)* [2]
COD	323	327	10 664	10 349	53 345
TSS	90	49	1 768	2 846	34 083
TKN	32	45	2 667	2 785	4 695
Ammonia	27		2 357	2 483	2 615

1 no references given by Environmentek (1997).

2 sampling point labelled as 'inlet' in the original report; assumed to be an error, and corrected here.

As neither the influent characteristics nor the effluent volumes were measured in the study, it was not possible to calculate actual contaminant mass loadings nor actual contaminant removal efficiencies. Nevertheless, in a discussion of the results, Environmentek (1997: p50) included a theoretical comparison of mass loadings to and from LOFLOS and to and from septic tanks receiving waste from a conventional flush, which is presented as 'comparison 1' in the table below:

TABLE 4.12:
COMPARISON OF INFLUENT AND EFFLUENT QUALITY AND REMOVAL EFFICIENCIES OF CONVENTIONAL SEPTIC TANKS WITH THAT OF LOFLOS SANITATION SYSTEMS (after Environmentek, 1997)

parameter	*units*	*comparison 1 (Environmentek, 1997: p50)*		*comparison 2*		*comparison 3*	
		LOFLOS	*normal flush*	*LOFLOS*	*normal flush*	*LOFLOS*	*normal flush*
influent mass loading:							
COD	gO_2/cap.d	130	130	100	100	100	100
N	gN/cap.d	9	9	10	10	10	10
flush + urine volume:	l/cap.d	1.75	180 [1]	3.5	100	3.5	100
influent concentration:							
COD	mg/l	74 286	722	28 571	1 000	28 571	1 000
N (as NH_4-N)	mg/l	5 143	50	2 857	100	2 857	100
removal efficiency:							
COD	%	45	45	45	45	**63**	**68**
N (as NH_4-N)	%	34	34	34	34	**16**	**70**
effluent concentration							
COD	mg/l	40 857	397	**15 714**	550	10 500	325
N (as NH_4-N)	mg/l	3 394	33	**1886**	66	2 400	30

[1] also receives dilution from bath/wash handbasin water

Note:

- ***comparison 2*** uses influent mass loadings as used in this study, together with removal efficiencies as suggested by Environmentek (quoted from Winneberger, 1984), to calculate theoretical effluent concentrations (shown in bold) for comparison with the figures obtained in the Environmentek study
- ***comparison 3*** again uses influent mass loadings as used in this study, but calculates removal efficiencies (shown in bold) to obtain effluent concentrations equal to the average of the Environmentek study figures for Systems 1 and 2.

While the comparisons between the theoretically calculated values for COD and ammonia for the normal (or full) flush system were similar to the values reported in the literature, there is an apparent discrepancy between theoretically calculated and measured values of COD for LOFLOS Systems 1 and 2. In discussion, Environmentek (1997: p50) suggested that this discrepancy might indicate the following:

(i) that a higher flush volume was used (approximately 5l) - considered unlikely
(ii) that only a portion of the daily organic contribution was deposited in the toilet, or...

(iii) that if children were present during the day, while one or both parents were absent for example at work, that the theoretical daily loads may have been less than assumed, and ...

(iv) that the rate of decomposition of organics was higher than the normally accepted 45% in those systems with extended residence times.

The additional comparisons (2 and 3) added by this study, however, suggest that a combination of different loading rates together with different removal efficiencies - as in comparison 3 - could account for the discrepancies in the effluent concentrations from LOFLOS Systems 1 and 2. How the normal flush values should be adjusted in the light of that is not entirely clear. A combination of adjusted flush volumes and removal efficiencies may be appropriate.

Environmentek (1997: p51) also went on to state in their conclusions that:

- The characteristics of the contents of these systems resemble residual septage from septic tanks with the exception that the nitrogen concentrations are considerably higher than conventional septage.
- Although the concentrations of all measured parameters were high, the nutrient load exported from the systems appears to be comparable to septic tanks receiving conventional flush volumes.

Of particular interest in the Environmentek study were the estimates of expected reductions in COD and nitrogen load in a septic tank (removal rates assumed to be similar for the LOFLOS), based on gas analyses by Winneberger (1984). Again based on Winneberger (1984), Environmentek suggested that much of the nitrogen removed from the septic tank influents can be accounted for as organic nitrogen in the sludge and that the presence of low concentrations of nitrogen in the gas collected from the septic tanks suggests that some nitrogen is lost via the nitrification denitrification pathway.

A study by Whelan and Titmanis (Table 4.12) also gives figures for the effluent from septic tanks. While there is general agreement between the effluent concentration values for conventional septic tanks quoted by Environmentek (1997) and those quoted by Whelan and Titmanis (1982), the latter values do exhibit a greater range than the former.

TABLE 4.13:
COMPARISON OF EFFLUENT CHARACTERISTICS FROM SEPTIC TANKS; DATA FROM VARIOUS STUDIES IN AUSTRALIA, USA, CANADA AND NEW ZEALAND (quoted by Whelan and Titmanis, 1982)

Case	*pH*	*expressed in [mg/l]*						
		TSS	*BOD_5*	*Total N*	*NH_4^+-N*	*NO_3^--N*	*Total P*	*Dissolved inorganic P*
a	6.6-7.4	22-47	52-316	74-237	63-201	0,01- 0,03	12-26	12-26
b				44-124	33-100	0.4-0.7	17-90	7-40
c	7.4	136		83	65	<0.02	14.8	13.0
d	6.5-7.5	176	280		97	0.03	11.6	
e	7.9	81	143		131	0.16	189.6	16.7
f				42.3	21.8	0.04	11.8	10.1

Cases:

a Perth, Western Australia; range for 5 households, 14 days (Whelan and Titmanis, 1982)

b Stevens Point, Wisconsin; range for 7 households, 1 day (Bouma et al., 1972)

c Bolton Landing, New York; mean for 1 household, 5 months (Clesceri, 1977)

d Ottawa, Canada; mean for 1 household, 2 months (Viraraghavan and Warnock, 1976a)

e Hawkestone, Ontario; mean for 1 household, 12 months (Brandes, 1976)

f Lauke Taupo, New Zealand, 1 household (Gibbs, 1977)

Note:

1 The figure of 189.6 mg/l Total P, quoted from Brandes (1976), is very high, and may be incorrect.

Of other studies which provide data on contaminant loads and removal rates, Wilhelm et al. (1994: p907) quote figures for what septic tanks receive: they receive all the liquid-transported wastes produced by a household, which average approximately 160 l/cap.d in the United States and Canada (Siegrist et al., 1976). Proteins and urea contribute over 97% of the 20 to 70 mg/l of N typically found in wastewater [presumed to be in the USA] (Laak, 1974; Tchobanoglous et al., 1985). This gives a mass loading of 3.2 to 11.2 gN/cap.d. It is not clear from what is quoted what the BOD_5 and COD figures for wastewater are, although they do give a useful breakdown of the relative oxygen demand of organic, N, S components of the wastewater.

Metcalf and Eddy (2nd ed. revised by Tchobanoglous, G) (1979:p64) give figures for typical composition of untreated domestic wastewater, including COD and N (as mg/l). Feachem et al., (1983:p6) give a useful explanation of the relationship between BOD_5 and COD:

> The BOD is the mass of oxygen required by microorganisms to oxidize the organic content of the waste. It is an indirect measurement of the concentration of biodegradable material present. BOD_5 denotes the oxygen demand exerted during the standard test, which is conducted at 20°C over 5 days. The chemical oxygen demand is the mass of oxygen consumed when the organic matter present is oxidized by strong oxidizing agents in acid solution. It includes some substances (such as cellulose) that are not available to microorganisms but excludes some (such as acetic acid) that are.

Wilhelm et al. (1994:p908) quote Lawrence (1973), Troyan et al. (1985) and Viraraghavan (1976) as giving the values of BOD_5 reduction in septic tanks broadly from 7% to 46%. They also quote figures by Laak and Crates (1978) and Winneberger (1984) as giving reductions in the total N content of the wastewater of roughly 10% to 30%, mostly due to inorganic N storage in the sludge. (The effect of garbage grinders is something that demands attention, especially where one is using figures from the United States for the characteristics of wastewater).

With respect to pollutant loads discharged by full water-borne sanitation systems, Palmer (1992a: p3) estimated sewage flow in Mdantsane to be 575 l/site.d, based on 6.43 people/site. This was an estimate by Ninham Shand, who had used 880 l/site.d (which included a 10% allowance for stormwater infiltration; hence 800 l/site.d excluding stormwater infiltration). 575/1.1/6.43 gives 81.3 l/cap.d of sewage say 80 l/cap.d. An estimate of average daily biological load per household was carried out by Ninham Shand in 1988 and found to be 255 g COD/day and OA per household of 20 g/day. This was considered to be too low.

Johannesburg Northern Works gives a good indication of effluent contaminant loads. Using monthly averages of the flows and PO_4-P mass loads, the average PO_4-P final effluent concentration over the 5 year period from October 1993 to September 1998 (i.e. hydrological years 1993/94 to 1997/98) was just over 0.6 mgPO_4-P/l. Problems with effluent quality were evidently encountered at the works in the 1998/99 hydrological year, with effluent concentrations averaging over 3mgPO_4-P/l for the month of January 1999 and over 1 mgPO_4-P/l for 6 of the 7 months between October 1998 and April 1999. Adding the data for the 1998/99 hydrological year to the previous 5 years data pushes the average up to just under 0.75 mgPO_4-P/l, still well under the 1 mgPO_4-P/l level (Rimmer, 1999).

Nitrate levels in the Buffalo River ranged between 0.5 and 4 mgN/l (from available fairly sparse data). This may be compared to a median figure of 2 mgN/l on the Vaal River below the Barrage. The nitrate levels in the tributaries are much higher, often exceeding 4 mgN/l and sometimes exceeding 12 mgN/l (Palmer 1992a: p21).

Fourie and Van Ryneveld (1993: p21) give some explanations of the *make-up of various parameters* for the nutrients, nitrogen and phosphorus, as well as *favourable conditions for removal* as follows:

> Total nitrogen is made up of nitrogen measured as Total Kjeldahl Nitrogen (TKN), nitrate and nitrite. TKN is a measure of organic nitrogen (nitrogen bound to organic molecules) and nitrogen in the form of ammonia (NH_3) and the ammonium ion (NH_4^+).
>
> In measuring ammonium (NH_4^+), nitrogen in the ammonia form (NH_3) is generally included, but at neutral to lower pH the concentration of nitrogen in the ammonia form is likely to be small in relation to the concentration in the ammonium form.
>
> Nitrogen in the nitrate form is likely to be the end product of nitrogen breakdown in the unsaturated zone where conditions are aerobic. It is typically in this form that nitrogen will be carried longer distances in with the groundwater flow.
>
> In water under normal aerobic conditions the concentration of nitrite would be expected to be low, generally negligible, as nitrite is rapidly oxidized to nitrate. The occurrence of high nitrite levels would indicate some oxygen presence, but insufficient to promote the transformation to nitrate.
>
> In the case of phosphorus, the total phosphorus (TP) measurement includes phosphorus in the phosphate form (PO_4)and phosphorus which is bound up in organic molecules (Organic P). With bio-degradation P can be expected to be converted from organic P to the phosphate form. Phosphates are generally adsorbed onto soil particles, particularly in clayey conditions.

The following data give an indication of the effectiveness of soil in removing nitrogen from septic tank effluent (Lewis et al., 1980: Table 4.1, p52; quoted in abbreviated form in Appendix 2 by Palmer, 1992b):

TABLE 4.14:
SUMMARY OF NITROGEN REMOVAL BY LAND DISPOSAL OF SEPTIC TANK EFFLUENT (Lewis et al., 1980: Table 4.1, p52)

Location	*Soil type*	*Depth sampled [m]*	*Loading rate [mm/d]*	*Influent [1] N content [mg/l]*	*Calculated N removal [%]*	*Remarks*	*Investigator*
Virginia USA	Sand, silt and clay (50%, 20% and 30%	1.0	20	12-36	76-77	Changes in chemical content of septic tank effluent during travel in perched water table	Reneau (1979) [2]
Connecticut USA	Coarse sand	0.9	-	102	75	Drainfield alternately dosed and rested for six months	Starr and Sawhney (1980)
North Carolina USA	Loamy sand (83%, 13% and 4%) over saturated organic clay	1.8	3.3	30-55	22-93	Column studies simulating a sound disposal system	Stewart et al. (1979)
Wisconsin USA	Loamy sand	0.6	10-600	78-85	20-80	5 disposal systems studied, greatest removal observed in system submerged in groundwater	Walker et al. (1973a)
Wisconsin USA	Glacial lake deposits	3-6	80	75-85	<20	estimated input to groundwater 2kgN/cap.a [i.e.5.5gN/cap.d]	Walker et al. (1973b)
Ontario Canada	Clayey sand	0-0.8	50	77-11	15-90	Fluctuating water table; tile submerged for part of study period	Viraraghavan and Warnock (1976b) [3]
Wisconsin USA	Sand over anaerobic silt loam	0.9	80	42	32	Laboratory column studies simulating a mound disposal system	Magdof et al. (1974)
Wisconsin USA	Sand over clayey topsoil	0.6	50	40-58	55	Mound disposal system - low permeability soils and seasonally high water table	Bouma et al. (1975)

assumed to be influent to the drainfield (i.e. effluent from the septic tank)
Reference for Reneau (1979) omitted by Lewis et al. (1980); however, reference for Reneau and Pettry (1975) (for work also carried out in Virginia, USA) was included and has been included in the reference list of this study.
Reference indicated as Viraraghavan and Warnock (1979) by Lewis et al. (1980) in the original table, but (1976) in the reference list - as indicated here.

The variation in removal efficiency (15-93%) really is quite wide. It should, however, be noted that these variations are not random, but are influenced by a number of factors (Wilhelm et al., 1994). These factors include:

- whether the subsurface is aerobic or anaerobic, which in turn depends on the depth of the water table, amount of moisture in the subsurface (affected by effluent loading rate), and the ease with which oxygen can penetrate the subsurface;
- amount of organic carbon available.

Based on the above literature, the following values for water usage, contaminant loading and removal efficiencies for different levels of service of sanitation were selected:

TABLE 4.15:
WATER USAGE, CONTAMINANT LOADING AND REMOVAL EFFICIENCIES FOR DIFFERENT LEVELS OF SERVICE OF SANITATION

Parameter	*Units*	*SP+VIP*	*SP+AP (LOFLOS)*	*HC+WBe (essential use)*	*HC+WBc (convenienc e use)*	1
Water usage						2
range: total water usage	l/cap.d	20-30		75-150	150-400	3
total water usage	l/cap.d	30	30	125	250	4
Breakdown of water usage:						5
range of flush size	l/cap.d					6
to sanitation system (flushing)	l/cap.d	0	2			7
to sanitation system (cleaning)	l/cap.d	0.5				8
to sanitation system (urine)	l/cap.d	1.5	1.5			9
to sanitation system (total, including flushing, cleaning and urine)	l/cap.d	2	3.5			10
to sanitation system (total, including flushing, cleaning, urine and grey water)	l/cap.d			100	200	11
to environment (grey water)	l/cap.d	28	26.5			12
to environment (garden watering, cleaning yard or cars)	l/cap.d	0	0	25	50	13
Contaminant mass loadings to sanitation system (Stage 1):						14
COD (total: excreta + grey water)	gO_2/cap.d	105.6	100	100	100	15
COD (excreta only)	gO_2/cap.d	100	70			16
COD (grey water only)	gO_2/cap.d	5.6	30			17
Total N (TN) (total: excreta + grey water)	gN/cap.d	10.56	10 (as TKN)	10 (as TKN)	10 (as TKN)	18
Total N (TN) (excreta only)	gN/cap.d	10	7			19
Total N (TN) (grey water only)	gN/cap.d	0.56	3			20
Total Phosphorus (TP)	gP/cap.d			2.5	2.5	21

Parameter	*Units*	*SP+VIP*	*SP+AP (LOFLOS)*	*HC+WBe (essential use)*	*HC+WBc (convenience use)*	1
Total Phosphorus (TP) (excreta only - mainly urine)	gP/cap.d	2.5	2.5			22
Total Phosphorus (TP) (grey water only - detergents)	gP/cap.d	0.88	0.88			23
Contaminant concentrations to sanitation system (Stage 1):						24
COD range (total: excreta + grey water)	mg/l			1000-1200		25
COD (total: excreta + grey water)	mg/l			1000	500	26
COD (excreta only)	mg/l		20 000			27
COD (grey water only)	mg/l	200	1 153 say 1 100			28
Total N (TN) (total: excreta + grey water)	mg/l			100	50	29
Total N (TN) (excreta only)	mg/l		2 000			30
Total N (TN) (grey water only)	mg/l	20				31
Total Phosphorus (TP) (total: excreta + grey water)	mg/l			25	12.5	32
Total Phosphorus (TP) (excreta only)	mg/l					33
Total Phosphorus (TP) (grey water only)	mg/l	31				34
Sanitation system stages:						35
Stage 1		discharged to pit	discharged to septic tank	discharged to sewer reticulation system (to treatment works)	discharged to sewer reticulation system (to treatment works)	36
Stage 2a			discharged from septic tank to soakaway			37
Stage 2/2b:		discharged from pit to subsurface	discharged from soakaway to subsurface	discharged from treatment works to surface watercourse	discharged from treatment works to surface watercourse	38
Stage 3		reach groundwater	reach groundwater			39
Contaminant removal efficiency: Stage 1-2/2a		*(Stage 1-2)*	*(Stage 1-2a)*	*(Stage 1-2)*		40
COD	%	50	60	93-97		41
TN	%	10	15	28-87		42
TP	%	10	15	9-97		43

Parameter	*Units*	*SP+VIP*	*SP+AP (LOFLOS)*	*HC+WBe (essential use)*	*HC+WBc (convenience use)*	1
Contaminant removal efficiency: Stage 2a-2b			*(Stage 2a-2b)*			44
COD	%		60-90			45
TN	%		10-90			46
TP	%		50-100			47
Contaminant removal efficiency: Stage 2-3		*(Stage 2-3)*				48
COD	%	60-90				49
TN	%	10-90				50
TP	%	50-100				51
Contaminant removal efficiency: total sanitation system		*(Stage 1-3)*	*(Stage 1-3)*	*(Stage 1-2)*		52
COD	%	80-95 ave: 88	84-96 ave: 90	93-97		53
TN	%	19-91 ave: 55	24-91 ave: 58	28-87		54
TP	%	55-100 ave: 78	57-100 ave: 79	9-97		55
Contaminant concentrations from treatment tank/plant (Stage 2a/2) or from stormwater:			*(Stage 2a)*	*(Stage 2)*		56
COD	mg/l		800-3 200 ave: 2 000	30-70 say 40	30-70 say 40	57
TN	mgN/l		180-1 520 ave: 840	4.5 (TKN) 8-75 (NO_3) 12.5-79.5(TN) say 12.5(TN)	say 12.5(TN)	58
TP	mgP/l		23.4 say 23	0.8-23 say 0.8	0.8-10 say 0.8	59
Contaminant mass loadings discharged from total sanitation system (or by stormwater) to water resource (Stage 2/3):		*(Stage 3)*	*(Stage 3)*	*(Stage 2)*	*(Stage 2)*	60
COD (to groundwater)	gO_2/cap.d	5-20 ave: 12	2.8-11.2 ave: 7			61
COD (to surface water)	gO_2/cap.d	5.6 say 6	30	3-7 say 4	say 8	62
TN (to groundwater)	gN/cap.d	0.9-8.1 ave: 4.5	0.6-5.3 ave: 3			63
TN (to surface water)	gN/cap.d	0.56 say 0.6	3	1.25-8 say 1.25	say 2.5	64
TP (to groundwater)	gP/cap.d	0-1.1 ave: 0.55	0-1.1 ave: 0.53			65
TP (to surface water)	gP/cap.d	0.88 say 0.9	0.88 say 0.9	0.08-0.23 say 0.08	say 0.16	66

Note:
(shaded figures given in the notes (e.g 61) refer to cross-referenced page numbers)

4 HC+WBe
(1) Mara (1982: p.16) 61 gives a water consumption figure of >100 for house connection with full water-borne sanitation.
(2) Palmer (1992c:p2) assumes a value of 114 l/cap.d, based on a COD of 100 gO_2/cap.d and a COD concentration of 1100 mg/l COD in domestic wastewater from low-income communities in South Africa, and assuming that 80% of the water usage is returned as sewage to the treatment works (Palmer Development Group et al., 1992b: p.3) 54, 55.
HC+WBe+c:
(3) water usage of 125 and sewage flow of 100 (see line 11) assumes 80% of the water usage is returned as sewage to the treatment works; similarly for water usage of 250 and sewage flow of 200.
AP (LOFLOS):
(4) The AP is not quite the same as a septic tank; note that Palmer Development Group et al. (1992b) has used a septic tank in his simple model, which is closer to full water-borne sanitation than to the AP (They give 114 for water usage for both HC and AP/LOFLOS)

7 AP (LOFLOS):
(1) Palmer Development Group et al. (1992d:p4,5): Atlas: 2.24l/cap.d, 0.8l flush giving 2.8 say 3 flushes/cap.d; Calcamite: 2.02l/cap.d, no flush, but water is apparently being used for cleaning; HS: 2.06 l/cap.d; average (based on a survey of between 67 and 100 users per toilet) 2.1 l/cap.d. 66

8 VIP: 1 l/household.d=approx 0.2 l/cap.d

9 VIP/AP (LOFLOS): same as amount consumed; Gotaas (1956) gives 1.0-1.3 kg/cap.d i.e. 1.0-1.3l/cap.d

10 AP (LOFLOS): Palmer Development Group et al. (1992c:p7): 1 l/cap.use of flush water and urine; 4 uses/cap.d = 4 total 66

11 WBe+c:
(1) Palmer Development Group et al. (1992a:p3): estimated sewage flow for Mdantsane 81.3 say 80 l/cap.d (based on 575 l/site.d and 6.43 people/site). The value excludes stormwater infiltration estimated at 10%. 70
(2) Johannesburg Design Branch (Kittay, 1991) uses 155 l/cap.d (830 l/site.d +12%infiltration = 930 l/site.d + peak factor of 2.4). 65
(3) Drews (1986: p11) suggests sewage flows generally of the order 60-90 for the lower income group, and 130-180 for people in the middle to higher income group.
(4) Franceys et al. (1992: p61) suggest that in most developing countries, the maximum sewage flow may be assumed to be between 100 and 200 (written within the context of septic tank design). They also suggest that if the water supply per capita is known, the sewage flow may be taken as 90% of the water supply.

12 VIP, AP (LOFLOS): grey water assumed disposed of to environment rather than down the aquaprivy; clean water assumed used for flushing rather than grey water.

13 WBe: total water use (125) minus total to sanitation (100); similar for WBc.
WBc: Franceys et al. (1992: p61) suggest that if the water supply exceeds about 250 l/cap.d, the excess is likely to be used for watering gardens (this figure appears very high).

15 AP (LOFLOS), WBe: (1) Palmer Development Group et al. (1992b) gives 100; based on Mara (1976) who gives 25-60 g/cap.d BOD_5 equivalent to 45-108 g/cap.d COD assuming COD=1.8x BOD_5; UCT Water Research Group recommends 100 for treatment works design for low-income communities in South Africa. 54, 57
(2) Environmentek (1997:p50) gives 130 (in a theoretical analysis). 68

16 AP (LOFLOS): (1) Palmer Development Group et al. (1992c: p8) (work carried out by Marais and Peters): BOD_5 in low cost housing areas is about 0.08lb=36 g/cap.d. Assuming COD=2x BOD_5, COD=72 say 70
(2) Feachem et al (1983:p4-16) gives characteristics of excreta.

17 AP (LOFLOS): total (100) minus excreta (70)=grey water (30)
VIP: (1) Palmer Development Group et al. (1992b: p5) suggests 200mg/l in a flow of 140 l/site.d, giving COD of 28 say 30 g/site.d and 6 g/cap.d using a household size of 5 (5 times lower than the estimate used here for LOFLOS=30). 55
(2) Feachem et al (1983: p16-20) gives characteristics of sullage.

18 AP (LOFLOS)+WBe: (1) Palmer Development Group et al. (1992b) (based on personal communication with Wentzel) recommends 10 (10% of COD) as TKN-N, based on a relatively constant ratio of 10:1

between COD and TKN empirically found in domestic wastewater (this is a mixture of excreta and grey water and may also include some commercial and industrial waste). 54, 55, 57

LOFLOS: (2) Environmentek (1997:p50) gives 9 (in a theoretical analysis). 68

19 VIP:

(1) Lagerstedt et al. (1994: p62) use a figure of 4 kgN/cap.a in excreta to VIPs in Eastern Botswana (based on protein intake), which is equivalent to 11 gN/cap.d.

(2) Lewis, Foster and Drasar (1980) quote Committee on Nitrate Accumulation (1972) as estimating the amount of nitrogen in human wastes to be about 5 kgN/cap.a, which is equivalent to 13.7 gN/cap.d

20 Palmer Development Group et al. (1992c:p5) suggests 20 mgN/l in a flow of 140 l/site.d, giving 2.8 say 3 gN/site.d and 0.6 gN/cap.d using a household size of 5 (as with the COD, 5 times lower than the estimate used here). 55

21 Palmer Development Group et al. (1992b) (based on personal communication with Wentzel) recommends 2.5 (2.5% of COD), based on a relatively constant ratio of 1000:25 between COD and TP empirically found in domestic wastewater. 55

22 Pillay (1994: p3.5) quotes Machlin (1973) giving 0.6 gP/cap.d, assumed to be the major source of P in human excreta

23 Pillay (1994:p4.2) gives a figures obtained from a study by Lever Bros. in Kwazulu-Natal (Palmer, S, 1993) of 0.106 kgP/cap.a for rural areas, equivalent to 0.29 say 0.3 gP/cap.d; and a figure of 0.229 kgP/cap.a for urban areas, equivalent to 0.64 say 0.6 gP/cap.d. In the same study, Pillay (1994: p4.22) quotes Heynicke and Wiechers (1986) who calculated the per capita detergent consumption for the whole country in 1983 to be 5.2kg (as compared with figures of 1.63 and 3.53kg for rural and urban respectively, obtained from the Lever Bros study referred to above. Using the same ratio of P to detergent use, this gives a figure of about 0.9 gP/cap.d.

41 AP (LOFLOS):

(1) Marais and Peters in the Palmer Development Group study (1992c: p.8) quoted above suggested 50-80% removal. 66, 67

(2) Wilhelm et al. (1994: p908), quoting Lawrence (1973), Troyan et al. (1985) and Winneberger (1984), suggested 7-46% BOD_5 reduction (Winneberger (1984) suggested 45% reduction). 70

VIP: figures estimated as slightly lower than LOFLOS

42 AP (LOFLOS):

(1) Laak and Crates (1978) and Winneberger (1984) suggested reductions in the total N content of the wastewater of roughly 10% to 30%, mostly due to inorganic N storage in the sludge. 70 (Winneberger (1984) suggested 34% removal. 68)

VIP: figures estimated as slightly lower than LOFLOS

46 Removal rates based on figures of 15-93% removal quoted by Lewis et al (1980) from various studies. 72

50 Removal rates again based on figures of 15-93% removal quoted by Lewis et al (1980) from various studies. 72

Based of the above data, the following summary table was used for the flows and contaminant loads discharged by the different levels of service of sanitation in Gauteng. In compiling a list for Gauteng province, it was possible to be more specific than Palmer, particularly with the water-borne sanitation.

TABLE 4.16:
SUMMARY OF FLOWS AND CONTAMINANT LOADS FOR DIFFERENT LEVELS OF SERVICE OF SANITATION IN GAUTENG

Parameter	*units*	*WBc*	*WBe*	*SEP*	*LOFLOS*	*VIP*	*BU*	*CHEM*	*NON*
to surface water:									
Flow	l/cap.d	200	100				2	2	
TP	gP/cap.d	0.16	0.08				0.0016	0.0016	
TN	gN/cap.d	2.5	1.25				0.025	0.025	
COD	gO2/cap.d	8	4				0.08	0.08	
to ground surface:									
Flow	l/cap.d				26.5	28			20
TP	gP/cap.d				0.9	0.9			2.5
TN	gN/cap.d				3	0.6			10
COD	gO2/cap.d				30	6			100
to groundwater:									
Flow	l/cap.d				3.5	2			
TP	gP/cap.d				0.53 say 0.6	0.55 say 0.6			
TN	gN/cap.d				3	4.5			
COD	gO2/cap.d				7	12			

4.4 Lake response to nutrient loading

The impacts of eutrophication were set out earlier in the report (see section 2.1). This section continues from there by describing in more detail the nature of the relationship between nutrient loading and lake response. Response of a lake to nutrient loading can be divided into three components (or sub-models):

- *nutrient export* or loading from a catchment (which in turn is split into point and non-point sources)
- nutrient concentration in the lake in response to inflow or loading (*nutrient budget*)
- *nutrient-algae* relationship (usually measured as nutrient-chlorophyll a relationship)

Before proceeding with the three sub-models, however, it is necessary to establish a number of principles with respect to eutrophication.

Eutrophication and trophic state

Eutrophication is a change in the trophic state of a lake or reservoir and follows a progression from an oligotrophic state through mesotrophic to a eutrophic state. Trophic state is the ability of the reservoir to support life, or 'level of enrichment' ('Trophic' = concerned with nutrition or the food chain). While trophic state has been considered as an objective in itself by some workers, this study does not consider it as such. This study asks the question "So what? *Why* is it a problem?" and then goes on to *quantify* the extent of the problem in terms that can be costed. Some aspects can be costed directly (e.g. the additional cost of water treatment); others have to be costed indirectly (e.g. the loss of recreational facility etc) by willing to pay (or willingness to accept) studies.

By identifying the relationship between nutrient loading and in-lake algal concentration, followed by the relationship between in-lake algal concentration and water treatment cost, this study has been able to translate nutrient loading into cost.

Limiting nutrient concepts

In identifying the relationship between nutrient loading and in-lake algal concentration, it is necessary to determine the key variables (particularly the key contaminants) governing this relationship. Pillay (1994: pp. 2.10-2.11) quotes Edmondson (1991) as reporting that about twenty elements have been found to be essential for algal growth. The major inorganic ions such as calcium, magnesium, sodium, potassium, chloride, sulphate are present in much higher concentrations (mg/l) than needed for growth, while elements such as nitrogen and phosphorus are present in much smaller concentrations (μg/l), and therefore may not always be available for algal uptake. The constituent that *limits* production to the greatest extent as a result of its scarcity is referred to as the *limiting constituent*.

Pillay (1994: p. 2.11) also quotes Thomas (1973) as pointing out that phosphate more often than nitrogen is present in low concentrations in water, and that this may be attributed to a number of factors including:

- natural inflows containing little phosphate, but large amounts of nitrate
- fewer phosphates than nitrogenous compounds being washed off agricultural lands .
- rainwater containing large quantities of nitrogenous compounds that can be utilised by plants

Consequently phosphorus is more often the limiting constituent than nitrogen.

While the theory of nutrient limitation does appear to hold, the actual situation may, however, well be more complex than this. Pieterse et al. (1996) points out that for N:P ratio of <1:10 N is limiting, N:P ratio >20 P is limiting, but in between the limitation swings seasonally, dependent on a number of other factors. What needs to be understood, however, is that different algal species are dominant at different N:P ratios; and therefore as the N:P ratio changes, so do the dominant algal species shift. This point is made more generally by Giller (1984) in his discussion of Niche Theory and its various supporting principles. Notwithstanding these comments, phosphorus has tended to be the limiting nutrient in the impoundments of Gauteng (and its immediate proximity). Certainly for Hartbeespoort Dam, this appears to be the case from the data presented later in the report (see chapter 6).

Consistency of forms of nitrogen and phosphorus

In tracing the movement and fate of nutrients (from excreta through the sanitation system into the subsurface, into surface watercourses, into impoundments and then its fate in the lake - either uptake in algae or settling to the sediments), it is important to ensure consistency in measurement throughout. One needs to be measuring the same thing at all stages.

One tends to find that in particular stages (e.g. in a sanitation system or in the subsurface), one particular form may predominate, and therefore one measures that form. At a different stage, a different form may predominate; and it is important to maintain consistency (e.g. bioavailable phosphorus is what algae can utilise, but may comprise only a small fraction of TP). A distinction also needs to be made between what can practically be measured as against what is theoretically present.

OECD (1982, p.39) gives an indication of the relationship between orthophosphate and Total Phosphorus, and between mineral nitrogen and Total Nitrogen. With increasing trophy, the mineral component tends to become the dominant fraction. On average the orthophosphate-P fraction increases from less than 20% for TP concentrations of 10 mg/m^3 and less to over 45% for TP concentrations of 200 mg/m^3 and over. For nitrogen, the trend, although less dramatic is similar with mineral nitrogen as a fraction of TN increasing from 60% for TN concentrations of 500 mg/m^3 and less to 70% for TN concentrations of 5 000 mg/m^3 and over. OECD also pointed out that in both cases, individual lakes may be at variance with the rule.

Analytically orthophosphate in a water sample may be measured by filtering the sample through a 0.45μm filter. However, other phosphorus compounds such as polyphosphates, dissolved organic phosphates and fine particulate phosphorus may also be included in the orthophosphate measurement. Although the fractions of these other compounds are small in comparison with the orthophosphate, the phosphorus fraction that passes through the 0.45μm filter is referred to as soluble reactive phosphorus (SRP) (Sonzogni et al., 1982). Total Phosphorus (TP), on the other hand, is measured after acid digestion of an unfiltered sample, providing a measure of dissolved and particulate organic and inorganic fractions, including adsorbed fractions (APHA et al., 1985).

Bath and Marais (1991) investigated the relative proportions of soluble and particulate phosphorus in runoff from an agricultural catchment in the Berg River (Western Cape), and showed that more than 80% of the phosphorus was present in particulate form. Discharges from wastewater treatment works, on the other hand, consist primarily of bioavailable phosphorus.

In transferring between different forms, Pillay (1994: p2.8) pointed out that "[w]hile a proportion of the phosphorus of dead algae may be rapidly recycled for further uptake, only additional incoming phosphates would be able to maintain prolonged algal blooms since about one-third of phosphorus from the decay of organic matter will always be lost from the system".

Dudley and Tomicic (of Water Research Centre plc and DHI respectively), describing their integrated computer modelling of catchments (in a project titled 'Integrated planning and management of urban drainage, wastewater treatment and receiving water systems' carried out under the European Union (EU) Innovation Programme), pointed out the assumptions that they made in ensuring compatibility between measurement of different water quality parameters in different parts of the catchment: For nitrogen, the sewage works models use, as a minimum:

- total ammoniacal nitrogen
- oxidised nitrogen
- soluble organic nitrogen and
- particulate organic nitrogen

whereas the sewerage models use only ammoniacal nitrogen and river models use only ammonia (but divide ammonia into ionised and non-ionised forms).

Sewerage and river models commonly ignore phosphorus, while sewerage models generally look only at soluble inorganic phosphorus. In order to deal with these differences, the three models have defined a set of transformations to map different determinands between the programs. The sewage was characterised using the following assumptions:

- filtered COD ≡ soluble COD
- non-filterable COD ≡ particulate COD
- biodegradable COD a constant fraction, typically 90%
- volatile suspended solids 75% of the total suspended solids
- soluble and particulate organic nitrogen in a 50:50 ratio.

The development of this unified urban catchment modelling system will '... lead to modelling scenarios that consider the catchment and permit engineering focus to be on the entire system, rather than on the three sub-areas [of sewerage, sewage treatment and receiving water].'

With on-site systems, TN and TP were used as the primary nutrient measures. For water-borne systems, PO_4-P was generally measured in the effluent from wastewater treatment works. Lake response modelling (e.g. OECD modelling) used TN and TP in their lake response relationships. Wherever possible, comparable measures are used. Where different measures are used that may have a significant effect on the accuracy of the modelling method used in the study, this is pointed out.

Sources of nutrients and processes in lakes affecting the movement and fate of phosphorus

In assessing the effect of nutrients - particularly phosphorus - from sanitation systems on lakes, it is useful to have some understanding of the full range of sources of phosphorus. Thornton (1986) has reviewed literature on nutrients in African lakes from the point of view of nutrient sources, in-lake nutrient kinetics and nutrient sinks, with particular reference to nitrogen and phosphorus, and their cycling rates into and out of various biotic and abiotic compartments. Of particular interest is a section on sources of nutrient, which has been summarised below, together with supporting evidence derived from Gauteng lakes.

For the purpose of the paper, the term 'nutrients' refers predominantly to phosphorus, nitrogen (especially nitrate) and silicate although the macronutrients (sodium, potassium, calcium, magnesium, chloride, sulphate and carbonate/bicarbonate) are included as appropriate.

A distinction is made between *allochthonous* nutrient sources (i.e. geological, biological and atmospheric sources originating outside the lake basin) and *autochthonous* (i.e. geological, biological and atmospheric sources originating within the lake basin itself). At issue is whether the nutrients have been imported from outside the lake basin, or whether they are simply being recycled within the basin.

Allochthonous (i.e. sources originating outside the lake basin). Sources are classed as geological, biological and atmospheric, and listed (with examples or indication of magnitude) as follows:

- *catchment geology*;
- *degree of development* (Thornton and Walmsley, 1982 examined the catchments of 31 southern African lakes; P export coefficients ranged from 1 $mgP/m^2.a$ for for 'rural' catchments to 162 $mgP/m^2.a$ for 'urban' catchments, exceeding 50 $mgP/m^2.a$ from catchments receiving municipal wastewater discharges;
- *rainfall and dry precipitation* (fallout) (i.e. atmospheric rather than geological in origin) (contribute 10-25% of N and P loading to Lake Midmar (Breen, 1984);

- *transformation of gaseous nitrogen by lightning* (Balon and Coche, 1974 suggest $1 gN/m^2.a$ in addition to wet and dry precipitation);
- there is little indication of *acid rain*, but Bosman and Kempster (1985) have reported pH values as low as 3.9 in the vicinity of Roodeplaat Dam;
- excreta of *fauna*, such as birds, hippopotomi, elephants and domestic cattle. Human sources are significant loading sources;
- *plant material* can also provide - or modify the provision of nutrients. (Toerien and Walmsley (1979) have noted a reduction of about 30% in N and P loads carried into Rietvlei Dam as a result of the Hennops River passing through extensive reed beds dominated by *Phragmites*, before entering the dam. They also found that the removal of nitrate, as in the case of all other nitrogenous compounds, was higher during the dry winter weather than during wet summer weather conditions, in contrast to Harrison et al. (1960) quoted by Toerien and Walmsley (1979), who in their study of Olifantsvlei south of Johannesburg found that nitrate was not effectively removed during the winter when the reeds died down.)

Autochthonous sources (i.e. geological, biological and atmospheric sources originating within the lake basin itself) are as follows (sometimes it is difficult to distinguish between whether nutrient sources have originated from within or outside the lake basin e.g. avian excretory inputs):

- *Lake sediments* are the major geological or abiotic source (Twinch (1984) has suggested a more dynamic role for bottom sediments in regulating phosphorus levels in Hartbeespoort Dam. Working in the upper reaches of the lake, he described a dynamic interaction between uptake of phosphorus from the sediments and its release into the water column, dependant on the P concentration and residence time of the overlying water. He showed that there was a net uptake of P by the sediments, which reduced the concentration in the water by up to 50%. Sediment-water interactions involving N are less clear, although there is some evidence from other African lakes. Thornton suggests that if N-limitation is as widespread as suggested by several authors, then the sediment-water interactions involving N need to be further examined.
- *Atmospheric sources (N fixation)* has been reported in Rietvlei Dam by Ashton (1981), where nitrogen fixation by *Anabaena cincinalis* was found to account for up to nearly 50% of the N input.

Regeneration of nutrients

Nutrients may be regenerated biologically during the processes of excretion and decomposition. From the data available, it appears that excretion of nutrients by planktonic algae and macrophytes is likely to be a relatively minor pathway of nutrient input, as is the faunal contribution to nutrient level by recycling. Jarvis (personal communication with Thornton, 1986[10]) has estimated zooplanktonic regeneration of P in Hartbeespoort Dam to be only 0.08 $mg/m^2.d$ or 0.2% of the daily inflow load. The National Institute for Water Research (NIWR) (1985) has estimated the excretion of phosphorus by fish, *Oreochromis mossambicus*, in Hartbeespoort Dam to be 118 kgP annually (extrapolated to the lake as a whole), compared with 188 kgP released by the phytoplankton, and a mean total load of 200 to 300 tP entering the lake

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10 See also Jarvis (1987)

annually.

A number of studies have indicated that the decomposition of plant material may play a greater role in the nutrient cycle than excretory or live-release processes. Examination of the decomposition of phytoplankton in Hartbeespoort Dam by NIWR (1985) indicated a net release of 95% of the cellular P at a rate of 0.6-12 mg/m^3.h or roughly 4 times the rate of release by living phytoplankton.

In summary, with few exceptions (such as lakes with closed lake basins, as indicated by Beadle, 1981) autochthonous sources provide a relatively small proportion of the nutrients in African lakes, as compared with allochthonous sources - particularly in systems influenced by man.

Snoeyink and Jenkins (1980) have listed the physical, chemical and biological processes governing the movement and fate of phosphorus in lakes and impoundments: turnover and stratification, soluble complex formation, precipitation and dissolution, adsorption and desorption, redox processes, biological uptake and mineralization. This is illustrated by Dallas and Day (1993).

Historical development of models from Vollenweider to present, with application of these to Gauteng

With application to South Africa, there have been essentially three major thrusts in eutrophication modelling approaches:

- The first, typified by Toerien et al. (1975), provided a *trophic status classification* of South African impoundments. This provided an initial indication of possible eutrophication problems rather than a quantitative predictive model of lake productivity.
- The second, the *Vollenweider/OECD-type models* (Vollenweider, 1976; OECD, 1982), consisting of 3 components or sub-models: for modelling nutrient export, nutrient budget and nutrient-algae relationships. These were essentially *static* models, or in certain instances dynamic models with an annual time step. Considerable work was carried out on the application of the Vollenweider/OECD models to South African impoundments.
- The third, *South African REM-type dynamic models* (Grobler, 1985a), provided similar sub-models to the OECD-type models, but with a much smaller time step (weeks or months, depending on data availability) to address the particular problem of hydrological variability in South African impoundments. The most recent variation on the REM model was provided by Meyer and Rossouw (1992), which formed the basis for models developed and applied in this particular study.

A review of some of this literature has been included in this study, to provide some point of reference for understanding and assessing the models used in this study. A key requirement of this study was to be able to construct appropriate transfer functions linking contaminant loads from different sanitation systems to the lake response to the costs of treatment. The models need to be simple enough so as not to require excessive data (especially in the case of a planning model such as this one), but at the same time detailed enough to model the effects of different sanitation systems.

Trophic status classifications

Toerien et al. (1975) provided a preliminary trophic status classification of 98 major South African impoundments. This constituted some of the early work on eutrophication in South Africa. The purpose of their classification was to select those impoundments which should achieve attention. The method that they used for classification was by comparison of algal bioassay responses of water samples from the impoundments. The authors pointed out that South African impoundments are mostly monomictic i.e. overturn of the water occurs once a year in the autumn (Allanson and Gieskes, 1961). Thereafter the water is well mixed throughout the winter until spring (late September or early October) when temperature stratification may again develop. They pointed out that the highest concentrations of plant nutrients are likely to occur in the surface water layers some time after turnover and before stratification occurs - which is also the time of year which they covered by their water samples.

For each impoundment, algal growth potential (AGP) was determined, measured as mg of dry weight/l of algal cells. The test alga used, *Selenastrum capricornutum*, is not a nitrogen fixer. Therefore, if a sample was growth limited by nitrogen, the response of the *S. capricornutum* would not be representative of those of nitrogen fixers (which would be limited only by the secondary limiting nutrient). A modified AGP value was therefore determined to include the potential for growth of nitrogen fixers for those impoundments which are primarily limited by nitrogen. Results are given in Table 4.17.

TABLE 4.17:
UNADJUSTED AND MODIFIED ALGAL GROWTH POTENTIAL (AGP) VALUES FOR IMPOUNDMENTS AND THEIR FEEDER STREAMS (after Toerien et al., 1975)

Impoundment	*AGP[1] (lake)*	*Primary Limiting Nutrient*	*mod. AGP[2] (lake)*	*Rank[3]*	*Ratio Mod.AGP/ AGP (lake)*	*Feeder stream*	*AGP (stream)*
Loskop	29.5	P	(29.5)	46	(1)	Olifants	23.3
Rust der Winter	32.5	P	(32.5)	43	(1)	Elands	74.0
Bronkhorstspruit	23.7	N	34.5	40	1.5	Bronkhorstspruit	19.5
Vaal Barrage	19.1	N	300.0	5	15.7	Vaal	-
Roodeplaat	105.7	N	491.4	3	4.7	Edendale	30.6
						Pienaarsrivier	90.9
Hartbeespoort	272.0	N	549.1	2	2.0	Krokodil	521.6
						Magalies	65.0
Rietvlei	30.0	N	660.4	1	22.0	Swartspruit	25.1

Note:

1 AGP (Algal Growth Potential) for *S.capricornutum*

2 Modified AGP = 1.25 times AGP of -P assay (to include the potential for growth of nitrogen fixers for those impoundment which are primarily limited by nitrogen)

3 Ranked according to modified AGP from highest to lowest value for the 98 impoundments; only those impoundment whose catchments drain Gauteng are shown here (original paper indicated rank the other way round i.e. lowest to highest)

The AGP value for the 98 impoundments investigated in the study ranged between 1.2 mg/l for Clanwilliam Dam to 272.0 mg/l for Hartbeespoort Dam. In 65 of the impoundments phosphorus was the primary limiting nutrient and in 33 nitrogen was the primary limiting nutrient. The modified AGP values were higher than the unadjusted AGP values by amounts which ranged between 1.4 mg/l for Bloemhof Dam to 630.4 mg/l. Impoundments with modified AGPs values above 100 mg/l can be considered to be seriously eutrophied. This is especially true for Vaal Barrage, Roodeplaat, Hartbeespoort and Rietvlei Dams where AGP values in excess of 250 mg/l were recorded. An AGP of 250 mg/l is equivalent to approximately 0.3 mg available P/l (or 300 mg/m^3) and indicates that the phosphorus loadings on these impoundments must be very high.

Although not included here, Toerien et al. did also include for comparative purposes a set of results on hypolimnetic oxygen depletion taken from Schutte and Bosman (1973). (Oxygen depletion in the hypolimnetic water during the summer stratification is indicative of an imbalance between the photosynthetic and respiration activities in an impoundment (Stumm, 1974) and is considered to be a measure of the trophic status). Some correspondence between the modified AGP results and the hypolimnetic oxygen profiles is evident.

Except in the indirect manner indicated above of relating AGP to available P concentration, the preliminary trophic status classification of Toerien et al. (1975) (as indicated earlier) provided *an initial indication of possible eutrophication problems rather than a quantitative predictive model of lake productivity.* Such models - certainly in respect of lake response to nutrient load - were first introduced by Vollenweider (1976).

Vollenweider did provide a trophic status classification, as indicated in the OECD table below, but also correllated lake productivity - specifically Chl *a* - with a number of commonly used water quality parameters - including Secci disc, Total P - to produce standardised relationships (within certain bounds of probability) (OECD, 1982: Table 7.1, p75).

TABLE 4.18:
RELATIONSHIP BETWEEN TROPHIC STATUS AND CERTAIN WATER QUALITY PARAMETERS (OECD, 1982: Table 7.1, p75)

Trophic state	*Total P [mg/m³]*	*Chl 'a' [mg/m³]*	*Chl 'a' max [mg/m³]*	*Secci Disk [m]*	*Secci Disk min [m]*
ultra oligotrophic	≤4.0	≤1.0	≤2.5	≥12	≥6.0
oligotrophic	≤10.0	≤2.5	≤8	≥6	≥3.0
mesotrophic	10 - 35	2.5 - 8	8 - 25	6 - 3	3 - 1.5
eutrophic	35 - 100	8 - 25	25 - 75	3 - 1.5	1.5 - 0.7
hyper eutrophic	≥100	≥25	≥75	≤1.5	≤0.7

Vollenweider/OECD-type models

The components of eutrophication modelling are most clearly described by Grobler (1985d): The three components or sub-models (as set out at the beginning of this section) are:

- *nutrient export* or loading from a catchment (which in turn is split into point and non-point sources)
- nutrient concentration in the lake in response to inflow or loading (*nutrient budget*)
- *nutrient-algae* relationship (usually measured as nutrient-chlorophyll a relationship)

Modelling of each of these components is therefore discussed in turn.

Nutrient export

For practical purposes, the following break-down scheme was recommended for estimating the total nutrient load on a lake (OECD, 1982: p12):

a) external:

- the phosphorus and nitrogen load via the tributaries (including "point" sources along the tributaries, and "diffuse" or "non-point" sources on the drainage basin);
- the point and diffuse sources load which directly enter the lake through the shores;
- the phosphorus and nitrogen load which falls on to the surface of the lake as wet or dry precipitation;

b) internal:

- phosphorus and nitrogen which re-enter from sediments. The net result of the interchange of nutrients between water and bottom sediments can be estimated by making nutrient balances covering relevant periods of time.

A review of loading from various sources has been given by Thornton (1986) above. For the purposes of this study, nutrient export from catchments is generally split into two main components:

- *point source* (mainly discharge from sewage treatment works)
- *non-point source* (which for the purposes of this study can be split into natural run-off from the catchment, and run-off associated with sanitation systems). Run-off associated with sanitation systems can consist either of leaks and bursts from the reticulation system of off-site (i.e. water-borne) sanitation systems, or effluent from on-site sanitation systems.

Point source loads can be obtained from sewage treatment works. Non-point source loads are more difficult to determine.

Non-point source load estimates generally use models of the form given in the table below. Grobler and Rossouw (1988a - not referenced; quoted by Rossouw, 1990) provide figures for the non-point source TP export from catchments as follows:

TABLE 4.19:
NON-POINT SOURCE PHOSPHORUS EXPORT FROM CATCHMENTS DRAINING GAUTENG Grobler and Rossouw (1988a - not referenced; quoted by Rossouw, 1990)

Dam	*Drainage basin*	*Gauging station*	*Non-point source TP export model*[1]
Hartbeespoort	Crocodile	A2M13	$P = 0.160\ R^{1.280}$
Rietvlei			
Roodeplaat			
Bronkhorstspruit	Olifants	B1M05	$P = 0.129\ R^{0.992}$
Loskop			
Vaal Barrage	Upper Vaal	C1M06, C1M07	$P = 0.275\ R^{1.347}$

Note:

[1] P = mass load of P [mass/area.time]
R = run-off [area/time]

There are two main approaches to the determination of nutrient export:

- *actual measurement* of water quality and flow on tributaries discharging into the impoundment, where such monitoring data are available (e.g. at a weir site)
- *combination* of *actual measurement* (of the discharges from point sources) and modelling (of non-point source discharges from the catchment).

There are only really 2 points at which one can measure the loads (for calibration):

- Point source discharges from sewage treatment works: at point of discharge.
- Diffuse loads: at a weir, often close to the point of discharge/exit from the catchment

Because a weir at the point of discharge/exit from the catchment measures the total load at that point (i.e. point source and diffuse source loads combined), it is not easy to differentiate between the effect of

- point source nutrient losses in the catchment or watercourse (through sedimentation, uptake or entrapment e.g. in wetlands); as distinct from ...
- magnitude of the diffuse source loads.

It is also difficult to separate out the effect of the increased run-off as a result of urbanisation

Smith and Stewart (1977) (quoted by Toerien and Walmsley, 1979) have pointed out the inaccuracies that may arise in the estimation of mineral loads carried by rivers. Certain inaccuracies may be attributed to the occurrence of flash floods, and the fact that no sampling dates coincided with the peak flow. In their study of Rietvlei Dam, Toerien and Walmsley (1979) calculated contaminant loadings by three different methods:

- *Method A* = Mean concentration for year x total flow per year (which gave the highest value)
- *Method B* = Mean concentration for dry weather period x total flow for dry weather period + Mean concentration for wet weather period x total flow for wet weather period (Walmsley and Butty, 1980, refer to the dry weather period as May to September, and the wet weather period as October to April).
- *Method C* = $F_1C_1 + F_2C_2 + ... + F_nC_n$
  where F = Total flow between sampling periods
  C = Concentration values
  1,2..., n = two-weekly sampling periods

Since the differences between the different estimates were not more than about 15% (reflected by the regression coefficients that they provided), they chose to use the mean of the three methods. For the loading from the Kempton Park sewage treatment works - which was relatively constant - they simply used Method A.

Actual regression analyses yielded the following relationships between the different methods:

- *Method B* = 11.49 + 0.85(*Method A*), r = 0.989, n = 15
- *Method C* = 7.84 + 0.91(*Method A*), r = 0.998, n = 15
- *Method C* = 1.05(*Method B*) - 1.49, r = 0.996, n = 15

Results from the experience gained in the OECD Study Programme indicated that the likelihood of errors in load estimates can be as high as ±50% (OECD, 1982: p12).

Discrepancies between estimated and measured nutrient export loads for the Hartbeespoort catchment reported by Twinch et al. (1986b) were of similar magnitude to the maximum values indicated by the OECD above. (It should be noted that the point load portion of the 'estimated' loads is in fact measured, but is measured at source rather than close to the point of discharge into the impoundment. A more detailed study by Pitman (1985), who used the product of daily flow and mean phosphate concentration in effluents from sewage treatment works in the catchment to calculate loads, produced estimates that were 4%, 6% and 19% lower than those of Grobler and Silberbauer (1984).

Steynberg et al. (1985) evaluated the impact of eutrophication and different management strategies in the Vaal River Barrage upstream of the Board's number one intake at Vereeniging (sampling point V7). The study is a very useful one in that it attempts to model the effect of increased nutrient loading on the Vaal Barrage. The following table is included here to give an indication of the variability in nutrient loadings on the Barrage:

TABLE 4.20:

PHOSPHORUS EXPORT FROM CATCHMENTS DISCHARGING TO THE VAAL BARRAGE, PHOSPHORUS BUDGET AND CHLOROPHYLL a CONCENTRATIONS: 1973 to 1984 (Steynberg et al., 1985) (Part 1: 1973-1978)

Parameters			*1973*	*1974*	*1975*	*1976*	*1977*	*1978*
Phosphorus input into catchments [t/a]	Suikerbosrand River catchment	Point source	114.0	152.2	102.9	81.1	99.8	116.2
		Diffuse source	77.8	96.7	151.4	134.7	108.0	157.0
		total: all sources (1)	191.8	248.9	254.3	215.8	207.8	273.2
	Klip River catchment	Point source	616.0	700.8	767.8	750.45	643.0	775.1
		Diffuse source	59.1	80.1	105.0	100.32	97.2	100.1
		total: all sources (2)	675.1	781.0	872.8	850.77	740.2	875.2
Phosphorus input into Vaal Barrage [t/a]	Suikerbosrand River catchment at S2 (3)		43.0	18.1	22.7	38.94	32.5	23.9
	Klip River catchment at K19 (4)		251.8	264.9	158.6	178.34	146.7	186.8
	Vaal Dam catchment at V2		150.0	206.7	1 435.3	994.93	258.3	262.3
	total (5)		444.8	489.8	1 616.6	1 212.21	437.5	434.0
Water volumes into Vaal barrage [Ml]	Suikerbosrand River catchment at S2		43 038	69 069	79 712	155 460	109 329	209 148
	Klip River catchment at K19		48 382	139 681	183 871	207 281	224 415	265 154
	Vaal Dam catchment at V2		476 964	858 406	2 247 929	2 713 059	685 133	937 049
	total		568 384	1 067 157	2 511 512	3 075 799	1 018 877	1 411 350
Phosphorus input relationships		(1) : (3)	1 : 0.224	1 : 0.073	1 : 0.089	1 : 0.180	1 : 0.156	1 : 0.088
		(2) : (4)	1 : 0.373	1 : 0.339	1 : 0.182	1 : 0.210	1 : 0.198	1 : 0.213
		(1)+(2) : (5)	1 : 0.513	1 : 0.476	1 : 0.697	1 : 0.136	1 : 0.461	1 : 0.412
Data recorded at the Board's No. 1 Intake (V7)	*Netto volume* [Ml]		411 817	891 117	2 264 038	2 799 683	703 283	1 078 956
	Estimated P concentration [µg/l]		1 080	550	710	430	620	440
	Actual P concentration [µg/l]		-	480	470	375	304	286
	Difference: estimated and actual P concentrations [µg/l]		-	70	240	50	320	154
	Retention time [d]		5.62	2.59	1.02	0.83	3.29	2.14
	Estimated P loading [t/a]		-	427.7	1 064.1	1 049.9	213.8	308.6
	Relationship: P entering Barrage and estimated P at V7		-	1 : 0.962	1 : 0.658	1 : 0.866	1 : 0.489	1 : 0.650

TABLE 4.21:
PHOSPHORUS EXPORT FROM CATCHMENTS DISCHARGING TO THE VAAL BARRAGE, PHOSPHORUS BUDGET AND CHLOROPHYLL a CONCENTRATIONS: 1973 to 1984 (Steynberg et al., 1985) (Part 2: 1979 to 1984)

Parameters			*1979*	*1980*	*1981*	*1982*	*1983*	*1984*
Phosphorus input into catchments [t/a]	Suikerbosrand River catchment	Point source	117.0	164.1	218.9	207.4	221.4	259.3
		Diffuse source	68.0	142.3	114.5	90.9	75.6	106.5
		total: all sources (1)	185.0	306.3	333.4	298.3	297.0	365.8
	Klip River catchment	Point source	900.8	821.0	605.2	621.3	690.7	752.3
		Diffuse source	55.1	110.3	84.2	74.2	63.7	68.9
		total: all sources (2)	955.9	931.3	689.3	695.5	754.4	821.2
Phosphorus input into Vaal Barrage [t/a]	Suikerbosrand River catchment at S2 (3)		4.5	20.0	8.0	5.6	0.8	12.5
	Klip River catchment at K19 (4)		222.7	346.8	324.0	283.8	331.7	371.2
	Vaal Dam catchment at V2		66.8	30.3	30.3	38.3	62.2	55.7
	total (5)		294.0	397.0	362.6???	327.8	394.6	439.4
Water volumes into Vaal barrage [Ml]	Suikerbosrand River catchment at S2		34 089	86 672	79 684	43 424	7 743	41 611
	Klip River catchment at K19		259 477	276 748	258 346	243 321	238 819	227 712
	Vaal Dam catchment at V2		339 883	254 624	307 088	368 301	615 425861	387 740
	total		633 449	618 044	645 119	655 046	988	657 063
Phosphorus input relationships	(1) : (3)		1 : 0.024	1 : 0.065	1 : 0.024	1 : 0.019	1 : 0.003	1 : 0.034
	(2) : (4)		1 : 0.233	1 : 0.372	1 : 0.470	1 : 0.408	1 : 0.440	1 : 0.452
	(1)+(2) : (5)		1 : 0.258	1 : 0.321	1 : 0.355	1 : 0.330	1 : 0.375	1 : 0.370
Data recorded at the Board's No. 1 Intake (V7)	Netto volume [Ml]		210 155	197 433	170 221	137 195	268 564	346 087
	Estimated P concentration [µg/l]		1 400	201	2 130	2 390	1 470	1 260
	Actual P concentration [µg/l]		402	622	643	620	717	778
	Difference: estimated and actual P concentrations [µg/l]		998	1388	1 487	1 770	753	482
	Retention time [d]		11.01	11.72	11.59	16.86	8.61	9.57
	Estimated P loading [t/a]		84.48	122.8	109.5	85.06	192.6	269.3
	Relationship: P entering Barrage and estimated P at V7		1 : 0.287	1 : 0.309	1 : 0.302	1 : 0.259	1 : 0.487	1 : 0.613

Three studies give an indication of the different export loads from catchments with different sanitation types:

- Upper Rietspruit catchment
- Hennops River Valley
- Rietvlei Dam catchment

Palmer Development Group (1992f) in their study of the Upper Rietspruit quoted water quality data from a study that was being carried out at the time by Rand Water and Watertek titled 'Techniques for microbial water quality investigation of South African rivers'. The catchment under consideration (measured as the section down to the confluence with the Klein-Rietspruit; also called the Leeuspruit) has an approximate area of $420km^2$, about 40% of the area of the Rietspruit as a whole. The average flow from the whole catchment for the period October 1990 to September 1991 was 1.4 m^3/s; and apportioning flow to the upper portion of the catchment on the basis of area, the flow from the Upper Rietspruit was estimated at 0.56 m^3/s. The total population was estimated at that stage to be 636 000, of which 401 000 were in the catchment area of the eastern tributary. The catchment has about half on-site sanitation and half water-borne sanitation.

TABLE 4.22:
NITROGEN LOADING FROM THE UPPER RIETSPRUIT CATCHMENT Palmer Development Group (1992f) (quoting a study by Rand Water and Watertek)

Station	*NH3 [mgN/l]*	*NO3 [mgN/l]*	*TKN [mgN/l]*	*TN [mgN/l]*	*estimated flow [m3/s]*	*mass load [tN/a]*	*area [km2]*	*load per unit area [kg/ha.a]*
KR	9.8	2.7	11.6	14.3	0.28	125	210	5.95 say 6
RKRA	<0.5	0.4	3.2	3.6	0.28	31	210	1.48 say 1.5
RSA	6.2	2.8	6.7	9.5	0.56	165	say 420	3.9 say 4
SN/SO	2.0	13.5	2.4	15.9		59[1]		
RSB1	3.2	10.1	2.8	12.9	0.56	224	420	5.33 say 5

[1] Mass load from sewage treatment works calculated as 224 - 165 = 59.
TN loadings of between 1.3 and 7.2 gN/cap.d for 188 000 people using on-site sanitation would result in loads of between 88 say 90 and 487 say 490 tN/a (a bit higher than the estimate of 59)

Note:

1. Figures are for period June 1991 to January 1992
2. Mass flows are calculated assuming that the flow from the Upper Rietspruit as a whole can be measured at point RSB1 = 0.56 m^3/s (for period October 1990 to September 1991)
3. Assume that the eastern catchment, measured at point KR, has a run-off proportional to its size, roughly half of flow for the Upper Rietspruit as a whole = 0.28 m^3/s

The above figures do not, on their own, permit any distinction to be made between contaminant loads from different levels of service, but they do permit some estimate to be made of the nutrient loading from natural run-off from a catchment (as against that associated with a developed catchment with sanitation). As a very rough estimate, it might be deduced that the nutrient load from sanitation-related sources is 4.5 kgN/ha.a, while that from natural sources in the catchment is 1.5 kgN/ha.a.

A second set of values for nutrient export is provided by Hoffmann (1994) in his study of the Hennops River Valley. Two sets of unit export data are provided: detailed export data from each of the sub-catchments in the Hennops River Valley study, and a comparison of these values with those from studies of other urban catchments:

TABLE 4.23:
UNIT EXPORT LOADS FROM THE SUB-CATCHMENTS OF THE HENNOPS RIVER VALLEY (after Hoffmann, 1994: Table 6.15, p. 55)

catchment label and monitoring point	*description*	*area [ha]*	*unit export load [kg/ha.a]*			
			NH_3-N		*PO_4-P*	
			summer	*winter*	*summer*	*winter*
A (point 6)	NCP and Birch Acres	1075.0	1.9	0.0	5.8	0.0
B (point 7)	Norkem Park, Birchleigh North and Tembisa	3594.9	19.9	12.4	4.5	5.6
C (point 5)	Eskom College, President Park Agricultural holdings, Rabie Ridge, Ivory Park and Tembisa	3158.6	0.7	0.8	3.7	1.7
D (point 2)	Clayville Industrial Area	2391.9	4.7	0.8	3.4	0.9
E (point 3)	Glen Austin Agricultural Holdings and Olifantsfontein	4069.4	16.6	12.4	20.0	25.9
F (point 11)	Olifantsfontein and Sterkfontein Agricultural Land	2767.9	-	-	-	-
G (point 15)	Doornkloof Agricultural Land, Irene, Randjiesfontein, Verwoerdburg CBD	6504.1	-	0.6	0.6	1.0

TABLE 4.24:
UNIT EXPORT LOADS FROM THE VARIOUS URBAN CATCHMENTS (after Hoffmann, 1994: Table 6.16, p. 56)

Catchment type	*Unit export load [kg/ha.a]*					
	BOD	*COD*	*NH_3-N*	*TN*	*PO_4-P*	*TP*
North American cities[1]:						
• parks and green zones	1.1	-	-	0.2	-	0.04
• residential	34	-	-	9.0	-	1.6
• commercial	90	-	-	11.2	-	3.4
• industrial	34	-	-	7.8	-	2.2
Pinetown, Natal: commercial[2]	49	321	-	7.5	-	1.3
Durban, Natal: residential[3]	-	-	-	3.9	-	0.6
Hennops River Valley:						
• Tembisa formal settlement	53.5	125.7	16.6	16.9	2.3	4.9
• Ivory Park informal settlement	-	70.5	4.0	9.3	0.8	3.1
• Clayville industrial and commercial	20.0	190.4	3.5	4.7	0.3	2.6

Sources:
1 Novotny (1992)
2 Simpson et al. (1980)

[3] Simpson et al. (1978)

Nutrient budget

The development of *P budget* models applied to South African impoundments is described by Twinch et al. (1986b). P export loads for their study were obtained from two sources: firstly using daily data from a gauging weir close to the dam; secondly using measured and projected point source inputs and export coefficients for diffuse sources (Grobler and Silberbauer, 1984). Twinch et al. pointed out that while the former method may provide more accurate loading estimates (Grobler et al., 1982), the lack of adequate gauging facilities precludes its use at many sites.

The focus of Twinch et al.'s work was to investigate how well the P *export* models described the actual situation; however the investigation assessed the various P *budget* models, making the comment that '...the reliability of load/response models, such as the OECD suite of models, was heavily dependent on the use of accurate estimates of the phosphorus load that actually enters the receiving water body'. They went on to point out that '...at best, load calculations, such as those used in the OECD study, are characterised by errors of ±35% and this is regarded as the major source of data scatter in the OECD relationships (OECD, 1982: p.36).

Twinch et al. (1986b) carried out a study of Hartbeespoort Dam similar to what Steynberg et al. (1985) did for the Vaal Barrage, comparing the various P budget models in the lake over the period 1980/81 to 1983/84.

In describing the four different P budget models used by them, Twinch et al. (notation amended slightly for consistency) give a useful overview of the various Vollenweider/OECD-type nutrient budget models used in South Africa:

The first was the Vollenweider nutrient budget model (Vollenweider, 1976; OECD, 1982)

$$[P] = L/q_s(1+\sqrt{T_W}) \qquad \text{(4.2)}$$

where:

[P] = predicted mean annual total phosphorus concentration [g/m^3]
L = areal phosphorus loading rate [g/m^2.a]
T_w = water residence time [a]
q_s = areal hydraulic loading, = z/T_w [m/a]
z = mean depth [m]

This nutrient budget model tends to over-estimate in-lake total phosphorus concentrations (or underestimate phosphorus sedimentation losses). It is therefore essential to incorporate an appropriate correction factor, as specified by OECD (1982: p.66). The most appropriate correction factor was found to be that of the combined OECD data set (rather than that of any individual OECD projects e.g. Nordic, Alpine or USA lakes, or shallow lakes and reservoirs).

This produces a second model, the OECD combined data model, as follows:

$$[P] = 1.55 \; (\; L/q_s(1+\sqrt{T_W}) \;)^{0.82} \qquad \text{.......................... (4.3a)}$$

For completeness, the model for shallow lakes and reservoirs is as follows:

$$[P] = 1.02 \; (\; L/q_s(1+\sqrt{T_W}) \;)^{0.88} \qquad \text{.......................... (4.3b)}$$

where:

[P] = predicted mean annual total phosphorus concentration [g/m^3] (assumed incorrectly described as [mg/m^3] by Twinch et al. (1986b))
L = areal phosphorus loading rate [g/m^2.a]
T_w = water residence time [a]
q_s = areal hydraulic loading, = z/T_w [m/a]
z = mean depth [m]

Thornton and Walmsley (1982) analysed 31 Southern African impoundments and derived a correction factor, based on linear regression analysis of predicted and observed phosphorus concentrations, to account for significant overestimates of in-lake total phosphorus concentration using the Vollenweider nutrient budget model. This provided the third model as follows:

$$[P] = (\; L/q_s(1+\sqrt{T_W}) \; - \; 0.09 \;) \; / \; 1.39 \qquad \text{.................. (4.4)}$$

where:

[P] = predicted mean annual total phosphorus concentration [g/m^3]
L = areal phosphorus loading rate [g/m^2.a]
T_w = water residence time [a]
q_s = areal hydraulic loading, = z/T_w [m/a]
z = mean depth [m]

A further modification for use in South African impoundments was made by Grobler and Silberbauer (1984), who incorporated a larger sedimentation factor to produce a fourth P budget model as follows:

$$[P] = P_{inflow}/(Q+sV) \qquad \text{.............................. (4.5a)}$$

where:

[P] = predicted mean annual total phosphorus concentration [mg/m^3]
P_{inflow} = annual phosphorus load [kg]
Q = water inflow [10^6 m^3]
V = volume of lake [10^6 m^3]

s = phosphorus sedimentation coefficient (a value of 3.5 was used in the study by Twinch et al. (1986b) in place of the 2.9 shown in Grobler and Silberbauer; Grobler 1984)

By substitution of related parameters, the Grobler and Silberbauer model may be rewritten as follows, to make it more similar to the previous models:

$$[P] = L/q_s(1 + s/T_W) \qquad (4.5b)$$

where:

[P] = predicted mean annual total phosphorus concentration [g/m^3]
P_{inflow} = annual phosphorus load [kg/a]
Q = water inflow [10^6 m^3/a]
V = volume of lake [10^6 m^3]
A = Lake area [km^2]
L = areal phosphorus loading rate, = P_{inflow}.1000/A [g/m^2.a]
T_w = water residence time, = Q/V [a]
q_s = areal hydraulic loading, = z/T_w or Q/A [m/a]
z = mean depth [m]
s = phosphorus sedimentation coefficient (a value of 3.5 was used in the study by Twinch et al. (1986b) in place of the 2.9 shown in Grobler and Silberbauer; Grobler 1984)

Nutrient-algae

Pillay (1994) has provided a useful summary of phosphorus-chlorophyll models as follows:

OECD general (1982: Table 6.7, p71):

$$[Chl] = 0.37\ P^{0.79} \qquad (4.6a)$$

OECD shallow lakes and reservoirs (1982: Table 6.7, p71):

$$[Chl] = 0.54\ P^{0.72} \qquad (4.6b)$$

Walmsley and Thornton (1984)

$$[Chl] = 0.416\ P^{0.675} \qquad (4.7)$$

where:

[P_{dam}] = annual mean inlake phosphorus concentration
[P_{inflow}] = annual mean inflow phosphorus concentration
[Chl] = annual mean chlorophyll *a* concentration

Pillay (1994: p3.10) applied the OECD lake budget and P-Chl *a* models to the Inanda impoundment, and found that the models significantly underestimated the total phosphorus and chlorophyll *a* concentrations in the impoundment. (For Inanda impoundment, weekly monitoring data were available since its completion in 1989, providing 4 full years of data for investigating nutrient loading/algal production relationships). Pillay therefore decided to derive new relationships for the Inanda impoundment. The algal data used was the monthly average of weekly algal measurements on an integrated sample (0-5m) collected from the main basin of the impoundment near the wall. The monthly soluble phosphorus loadings were calculated from weekly phosphorus measurements and daily flows from the Umgeni River inflow to the impoundment located about 16km river distance away from the main basin site. Inspection of the data revealed that the peaks in phosphorus loading appeared to precede the peaks in algal production, and a forward shift of the monthly phosphorus loading by one month offered better visual correlation.

A noteworthy observation by Pillay (1994: p. 3.11) was that all published models used chlorophyll *a* as a measure of algal biomass. This is generally done because it is a simple measurement. However, for an impoundment that shows seasonal variation in algal genus, chlorophyll *a* may not always be appropriate to use, since different algal genera have different chlorophyll *a* concentrations. More particularly, the nuisance blue-green algae (e.g. *Microcystis, Anabaena*) which proliferate when the nutrient loading to the impoundment is high, have a much lower chlorophyll *a* concentration than the less problematic green algae (e.g. *Chlorella*) which dominate when nutrients are scarce (such as in winter and drought periods) (Umgeni Water, 1994). The variability of cellular chlorophyll content depending on algal species - and hence the weakness of the use of chlorophyll *a* to represent algal biomass - was also made by Nicholls and Dillon (1978) (quoted by OECD, 1982: p135), who showed from a literature survey that the chlorophyll content of algae can range from 0.1 to 9.7 per cent of fresh algal weight. Radiation intensity and nutrient availability , particularly nitrogen, appeared to be major factors affecting the chlorophyll content of algal cells.

As a consequence total algal count was used in preference to chlorophyll *a* reading. The best correlation between measured soluble phosphorus loading and algal numbers was obtained by averaging weekly algal data and monthly soluble phosphorus loadings over tow months, with the soluble phosphorus loading shifted forward by one month to compensate for the observed lag in algal count. A total of 24 data points were obtained for the period February 1990 to January 1994 (earlier figures while the impoundment was filling up for the first time being discarded). Partial water retention times were also used.

As an aside, it is interesting to note that Pillay (1994: p. 4.3) assumed that only the detergent phosphorus which derived from laundry washed directly at the watercourse or stream would reach the impoundment. (The rest would be immobilised in the subsurface).

Carrying out a regression analysis on data from the Inanda impoundment, Pillay (1994: p. 4.10) identified the following relationship:

$$Algal\ Count = 0.055\ SRP\ Loading^{1.83} \quad \ldots\ldots (4.8)$$

where *SRP Loading* = average SRP loading on the impoundment over 2 consecutive months [kg/month]
Algal Count = Predicted average count over 2 consecutive months one month after the SRP Loading [No]

The difficulty with these nutrient-algae models is that they use only phosphorus in the model. While most impoundments in Gauteng are phosphorus-limited, Rietvlei is considered to be nitrogen-limited. Furthermore, nitrogen does play some part in the trophic status of even phosphorus-limited lakes.

One of the nutrient-algae models that has included both nitrogen and phosphorus is the Smith model, as follows (Smith and Shapiro, 1981, quoted by Chapra, 1998):

$$\log(Chl\ a) = 1.55\log(p) - b \qquad (4.9)$$

where:

$$b = 1.55\log\left[\frac{6.404}{0.0204(TN{:}TP) + 0.334}\right]$$

However, the Smith model was not used with success in this particular study.

Summary comment on Vollenweider/OECD-type models

The models quoted by Twinch et al. (1986b) as applied by them on annual data sets, are essentially a series of static models. Data from one year are not carried over to the following year. Nevertheless, they do roughly approximate a dynamic model with an annual time step.
On this basis, the static Grobler and Silberbauer model (1984) was able to model to phosphorus concentrations in Hartbeespoort Dam with an average error of about 20% below the measured concentrations over the 4 year period 1980/81 to 1983/84.

However, as Grobler (1985a) points out, '...[t]he fundamental assumption of the OECD phosphorus budget model (Jones and Lee, 1982) namely that a catchment-receiving waterbody system is in a steady state, is violated when it is applied to most reservoirs in South Africa because river flows, water levels in reservoirs, outflows and total phosphorus loads on reservoirs vary considerably in the short and long term.' He goes on to point out that, if appropriate input data are available, the steady state assumption can be avoided by using a *dynamic* phosphorus budget model to simulate time series of phosphorus concentrations in reservoirs. These are described in the following sub-section.

South African REM-type dynamic models

According to Meyer and Rossouw (1992), who carried out a careful statistical analysis of the application of the Reservoir Eutrophication Model (REM) to two impoundments (Hartbeespoort Dam and Witbank Dam), the Reservoir Eutrophication Model (REM) is described by Grobler (1985d, 1985b, 1986a). The REM has three submodels:

- phosphorus export model, consisting of point source and non-point source components (modelling the export of phosphorus from the catchment)
- phosphorus budget model (modelling the mass balances of phosphorus in the reservoir)
- chlorophyll concentration model (modelling the chlorophyll concentrations resulting from the phosphorus concentrations)

In mathematical form, these three models are as follows:

- REM phosphorus export model:

$$P_t = aR_t^{\,b} \qquad \text{(4.10)}$$

Where P_t = phosphorus load for period t [mass/time]
R_t = corresponding volume of run-off for period t [m^3/time]

- REM phosphorus budget model:

$$P_t = P_{t-1} + PIN_t + POUT_t - s_t \cdot \frac{P_t + P_{t-1}}{2} \qquad \text{(4.11a)}$$

Where P_t = mass of phosphorus in the lake at the end of month t
P_{t-1} = mass of phosphorus in the lake at the end of month t-1
PIN_t = mass of phosphorus entering the reservoir in month t
$POUT_t$ = mass of phosphorus leaving the reservoir in month t
s_t = sedimentation rate for month t

If it is assumed that the reservoir is completely mixed, $POUT_t$ can be estimated as the product of the average in-lake phosphorus concentration and outflow volume:

$$POUT_t = \frac{\frac{P_t}{W_t} + \frac{P_{t-1}}{W_{t-1}}}{2} \cdot WOUT_t \qquad \text{(4.12)}$$

Where W_t = volume of water in the reservoir at the end of month t
W_{t-1} = volume of water in the reservoir at the end of month t-1
$WOUT_t$ = volume of water leaving the reservoir (i.e. outflow) in month t

Substituting for $POUT_t$ in the earlier form of the REM Phosphorus budget model, the model simplifies to the following:

$$P_t = \frac{P_{t-1}\left(1 - \frac{s_t}{2} - \frac{WOUT_t}{2W_{t-1}}\right) + PIN_t}{1 + \frac{s_t}{2} + \frac{WOUT_t}{2W_t}} \qquad \text{(4.11b)}$$

- REM chlorophyll concentration model:

$$[Chl_{mean\ summer}] = 0.45\ [P]^{0.79} \quad \text{(4.13)}$$

Where $[Chl_{mean\ summer}]$ = mean summer chlorophyll concentrations [µg/l]
$[P]$ = mean summer phosphorus concentrations [µg/l]

Using uncertainty or error analysis, what Meyer and Rossouw found was a '...high degree of uncertainty associated with the REM models for individual reservoirs, [suggesting] the application of the REM procedure may lead to incorrect conclusions regarding the impact of proposed water management strategies for phosphorus control.' Inaccuracies that they found of the 3 sub-models were as follows:

- *REM phosphorus export model:* The mean level of the errors obtained when the model was fitted to their data was not always independent of run-off.
- *REM phosphorus budget model:* Different sedimentation rates needed to be applied to inflow and in-lake phosphorus sedimentation
- *REM chlorophyll concentration model:* The relationship between phosphorus and chlorophyll concentrations was very weak (for the specific reservoirs under consideration); incorporation of concentrations of various nitrogen compounds in the model improved the correlation significantly.

The three components of the improved RSEM model was as follows:

- *RSEM phosphorus export model:*
  Not used here. It proved too complicated. There is insufficient data available.

- *RSEM nutrient budget model:*

$$P_t = (1 - s_1)\ P_{t-1} + (1 - s_2)\ PIN_t - POUT_t \quad \text{(4.14a)}$$

Where P_t = mass of phosphorus in the lake at the end of month t
P_{t-1} = mass of phosphorus in the lake at the end of month t-1
PIN_t = mass of phosphorus entering the reservoir in month t
$POUT_t$ = mass of phosphorus leaving the reservoir in month t
s_1 = general in-lake sedimentation rate
s_2 = sedimentation rate for inflow only

$$P_t = \frac{P_{t-1}\ (1 - s_1 - \dfrac{WOUT_t}{2W_{t-1}}) + PIN_t\ (1 - s_2)}{1 + \dfrac{WOUT_t}{2W_t}} \quad \text{(4.14b)}$$

- *RSEM nutrient-algae model:*
  Using log-transforms of the Jones and Lee (1982) model applied to the Hartbeespoort Dam, the following was obtained:

$$\ln[Chl] = +(1.21\ln[TP] + 0.58\ln[KN] + 0.51\ln[NO_3]) - (0.36\ln[NO_2] + 0.76\ln[PO_4] + 0.67\ln[NH_4]) \quad (4.15)$$

  Of particular significance is the fact that while [TP] is strongly correlated with [Chl], $[NO_3]$ - and not [TP] alone - is also positively correlated with [Chl].

  The problem with this model is that the various components were not all independent of one another. Meyer therefore stated that the coefficients should not therefore be interpreted as giving an indication of the relative impact of the different components on algal growth.

In practice, although multiple regression may have yielded a similar relationship, it did not further clarify the matter of nutrient limitation, and in particular the relative importance of nitrogen and phosphorus.

4.5 Hydrology using Water Resources 90

While actual streamflow and water quality data can be used for determination of *past* contaminant load, MAR (Mean Annual Riverflow) - together with contaminant concentrations - is considered to be the most appropriate figure for *future* contaminant loads. Nutrient export is related to MAR. Nutrient lake budget is also related to MAR values. MAR is also used to indicate the magnitude of the resource and, related to that, the maximum yield or utilisation of the resource.

A few preliminary comments need to be made:

MAR is used by Midgley et al. (1994a: p3.4) to refer to Mean Annual *Riverflow*, and it is pointed out that the term *Runoff*, widely adopted in the past was generally incorrect usage.

It is also pointed out that MAR '...purports to be the long term average riverflow derived from the relevant catchment under "virgin" conditions, ie in its pristine state prior ro any of man's land-use changes that have affected the hydrology'; and further that MAR '...is assumed to be a stable, stationary value, unique to the particular catchment, and derived by averaging annual riverflow values over a period long enough to ensure the damping out of the effects of extremes - particularly of flood.' (Midgley et al., 1994a: p3.4)

The calculation of MAR under present-day conditions is described by Midgley et al., (1994a: pp5.27-5.30) in section 5.6.3.
Sources of data are as follows (Midgley et al., 1994a: pp2.10-2.12):

- *Irrigation:* Reports covering the various basin studies that have been undertaken in recent years on behalf of DWAF. In areas not covered by basin studies it was necessary to resort to the various agricultural censuses, Department of Statistics (1976), coupled with data provided by DWAF. Details of major schemes are summarised in Appendix 5.2. The estimated breakdown of the total irrigation development in each quaternary is given in Appendix 8.

- *Water transfers* (including abstractions from a river or dam, direct transfers from one river system to another and indirect transfers to a river system in the form of effluent discharge from towns or major industries): In most cases the authority concerned was approached for data on water transfers. However, much of the information is assembled in the Water Quality Sub-Directorate of DWAF for purposes of checking compliance with permits for abstraction or discharge. Details on all major water transfers are given in Appendix 5.3
- *Urban areas:* Present and past urban areas can be estimated from planimetry of 1:50 000 topographical maps dating back over several decades. Information on urban and impervious areas is given in Appendix 5.4. It is not clear whether the urban areas indicated on the base maps were obtained from this source - and what date these developments are indicative of.
- *Wetlands, aquifers and other channel losses:* (while transmission losses in the more humid areas are in general relatively low - and can usually be neglected, losses in rivers traversing arid regions can be extremely severe. Substantial bed losses can also occur in rivers traversing dolomitic formations. Wetlands also increase system losses. As wetlands are usually underlain by impermeable formations, the losses are essentially due to evapotranspiration rather than to groundwater.) No sources for these data are indicated. Details of these losses are given in are given in Appendices 7 and 8.

Section 2.3 (pp2.14-2.18) lists and describes a number of statistical measures for characterising streamflow data and models thereof.

A family of curves relating MAR to MAP (mean Annual Precipitation) is given in Appendix 9. The curves were derived by plotting quaternary MAR against MAP and grouping those that exhibited similar MAR/MAP relationships. Each group was assigned a response number.

The study makes the point that bed losses in rivers traversing dolomitic formations are '...notoriously difficult to estimate' and that field measurements must usually be made (p3.7). Likewise '...parts of rivers that comprise long wetland reaches warrant special treatment.' In this regard, the streams draining the Witwatersrand towards the Vaal Barrage are singled out for special mention. Estimates of losses from known wetlands and aquifers are given in Appendix 5.5, but do not include any of the wetlands, aquifers or channels of relevance to the current study (of Gauteng).

The following data relating to Tertiary and quaternary catchments is given in Appendix 8: p8.1-8.6:

- gross area, as well as net area (less endogenous zones);
- irrigation area;
- evaporation zone, as well as MAE [mm];
- MAP;
- MAR, as well as MAP-MAR response curve.

5 COSTING SECTOR

Topics covered in this section are as follows:

- Costing of *surface water treatment* (Unit cost at different capacities for different sets of processes)
- Costing of *ground water treatment* (Unit cost at different capacities for different sets of processes)
- Costing of *other impacts and remedial measures* (recreation, land values, agriculture)
- Relationship between trophic status of an impoundment and the set of treatment processes required.

5.1 Costing of water treatment for surface water

Costs were obtained from literature and updated to present day costs. The costs of particular concern were the *additional* costs of treatment for eutrophied water above those for 'ordinary' or non-eutrophied waters. These were required for both

- capital cost (additional processes required e.g. DAF)
- operating costs (chemicals, power etc, as well as additional backwashing and replacing sand on filters)

Good figures for the overall costs of treatment were provided by Palmer Development Group (1994b costs).

While no specific reference is made to the trophic state of the impoundments - and hence the waters - used in the treatment plants costed here, it has been assumed here that the waters treated have been without serious algal problems (as yet), and that conventional processes (settling and filtration) have been used.

Capital costs:

- Table A2 for base data (3 points plotted on graph in Figure II, together with the straight line)
- Figure II: log-log graph: R7m for 10Ml/d (equivalent to R0.7m per Ml/d); different for other treatment capacities e.g. R30-40m for 100Ml/d (R0.3m to R0.4m per Ml/d) and about R45-55m for 200Ml/d (R0.225m to R0.275m per Ml/d)
- Table 3: R0.15m per Ml/d (low) R0.2m per Ml/d (med) and R0.3m per Ml/d (high) assumed to be for the capacity assumed for the next phase for the PWV (given as 200Ml/d)
- These costs may be generalised by the following approximate formula, obtained graphically from the log-log graph in Figure II:

$$\text{cost} = 1.66 \times \text{capacity}^{0.61} \qquad \text{(5.1a)}$$

$$\text{unit cost} = 1.66 \times \text{capacity}^{-0.39} \qquad \text{(5.1b)}$$

where units are as follows: cost [Rm; 1993 costs]
capacity [Ml/d]

with a variation of -25% and +50% at a capacity of 200Ml/d
-44% and +39% at capacity of 50Ml/d
-43% and +57% at capacity of 10Ml/d
-29% and +29% at capacity of 3Ml/d
on average + or -40%

O&M costs:

- Table 10 and Table A9: Cost of purification for Rand Water (1991/92 year) = 5.3c/kl (which makes up 8.2% of the total bulk water cost, including capital)
- The comment was made that the costs are highly variable, which is related to the staff element. The major costs are chemicals, electricity and staff. Chemicals and electricity are not substantially affected by scale, but staff costs are. Larger works can use a greater degree of automation and fewer people per Ml/d treated.

Grigg (1986: p.317) discusses the use of cost indices. In terms of the relative weighting between different aspects of the cost of water treatment works, Qasim et al. (1992) give figures for US works. Following a similar approach, Palmer Development Group et al. (1993a: p.25, Appendix 1) provided escalation indices for *sanitation* infrastructure for the years 1987 to 1992 as follows:

TABLE 5.1:
ESCALATION INDICES FOR SANITATION SYSTEMS
(after Palmer, 1993a:p.25, Appendix 1)

Year	*Labour*	*Material*	*Plant*	*Weighted average*	*Average annual % increase*
1985	100	100	100	100	
1987 (July)	140	122	120	128	13.1
1988	160	145	142	149	16.4
1989	184	174	173	177	18.8
1990	209	200	196	202	14.1
1991	236	224	212	224	10.9
1992 (estimate)	268	250	229	250	11.6

Note:

1 Base year 1985: Index = 100
2 Weighting: Labour: 35%
Materials: 35%
Plant: 30%
3 Total increase 1987 to 1992 = 250/128 = 1.95; equivalent to 14.3% per annum

TABLE 5.2:
SOUTH AFRICAN INFLATION RATES 1972 to 1998 (South African Institute of Race Relations, 1999; Statistics South Africa, 1999a and 1999b)

Year	*Change in consumer price index (CPI) [%]*	*Change in producer price index (PPI) [%]*
1972	7.0	7.1
1973	9.8	15.0
1974	11.9	17.4
1975	13.3	16.0
1976	10.6	16.0
1977	11.7	12.8
1978	10.5	9.8
1979	12.9	15.6
1980	13.7	16.0
1981	15.4	13.8
1982	14.5	14.1
1983	12.7	10.6
1984	11.3	8.1
1985	16.6	17.1
1986	18.4	19.5
1987	16.1	14.0
1988	12.9	13.2
1989	14.8	15.2
1990	14.2	12.0
1991	15.4	11.5
1992	13.9	8.2
1993	9.7	6.6
1994	8.9	8.2
1995	8.7	9.6
1996	7.4	6.9
1997	8.6	7.1
1998	6.9	3.5

In the period since 1985, the average annual consumer price index (CPI) inflation rate could be characterised by two relatively uniform periods:

- *1985 to 1992:* 15.3 say 15% per annum
  (*1987 to 1992:* 14.5% per annum)
- *1993 to 1998* (and assumed to continue through to 2000): 8.4 say 8% per annum

For the period 1987 to 1992, the average annual inflation figure calculated on the CPI (14.5%) agrees very closely with the composite figure of Palmer Development Group et al. (1993b) (14.3%) given in Table 5.1 above. On the basis of this comparison, inflation rates based on the CPI - and, more specifically, the values for the two periods given above - were used to escalate or de-escalate prices obtained from the literature.

Using the two inflation rates (15% and 8%) given above, these costs may be updated to 2000 as follows:

Capital costs:

- 1993 cost for 200Ml/d plant = R42m (using formula given above)
  2000 cost = R71.9m

O&M costs:

- 1991/92 cost of purification = 5.3c/kl
  2000 cost = 9.8c/kl

In order to convert capital cost to an ongoing annual cost, the following formula for annualised cost may be used:

$$Annualised\ cost = Once\text{-}off\ cost \times \frac{i(1+i)^N}{(1+i)^N - 1} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (5.2)$$

Variables as follows:

N	repayment period (20 years, say)
r	interest rate (0.20 say)
f	inflation rate (0.15 say)
i	discount rate, which is calculated according to the formula:

$$i = (\frac{1+r}{1+f} - 1) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (5.3)$$

(and which gives a value of 0.04347826 for the values of r and f given above)

For the variables given above,

$$Annualised\ cost = Once\text{-}off\ cost \times 0.07586580 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (5.4)$$

Using the above figures and assuming a utilisation of 200Ml/d for the treatment works, this translates into a cost of treatment as follows:

- Capital cost per year = R71.9m × 0.07586580 = R5.45m/a
  Assuming 200Ml/a production per Ml/d capacity for 200Ml/d capacity, this translates into a production of 40 million kl/a and a cost of 13.6c/kl.
- O&M cost = 9.8c/kl
- Total cost of treatment = 23.4c/kl (2000 costs)

These figures may be compared to the costs of water treatment works treating water from the highly eutrophied Hartbeespoort Dam impoundment, presented by Haarhof et al. (1992). This study was based on the three treatment works of:

- Schoemansville (new plant June 1991: activated carbon, pH correction, flotation, filtration, chlorination)
- Kosmos (redesigned plant commissioned January 1987), same processes as Schoemansville)

- Brits (new treatment plant to be commissioned in 1992: prechlorination settling, rapid sand filtration, activated carbon columns)

The maximum treatment capacity of the plants ranged between 10Ml/d and 90Ml/d, with an average of approximately 50Ml/d.

Costs for the phase separation processes were given as follows (Haarhof et al., 1992: Table 1: 31). These costs include both capital and operating components.

TABLE 5.3:
COSTS OF PHASE SEPARATION PROCESSES WATER TREATMENT WORKS (1991) (Haarhof et al., 1992)

Process	*Unit cost [c/kl] (1991 costs)*		
	min	*max*	*ave*
Direct filtration	4.4	7.5	6.0
Settling and filtration	6.7	12.7	9.7
Flotation and filtration	6.6	11.9	9.3
Flotation/filtration (DAFF)	5.9	10.4	8.2
Settling and flotation and filtration	8.4	16.7	12.6

Updating these costs to 2000, using the two inflation rates of as explained earlier (giving a factor of 2.13), the following figures are obtained:

TABLE 5.4:
COSTS OF PHASE SEPARATION PROCESSES WATER TREATMENT WORKS (2000) (adjusted from Haarhof et al., 1992)

Process	*Unit cost [c/kl] (2000 costs)*		
	min	*max*	*ave*
Direct filtration	9.4	16.0	12.8
Settling and filtration	14.3	27.1	20.7
Flotation and filtration	14.1	25.3	19.8
Flotation/filtration (DAFF)	12.6	22.2	17.5
Settling and flotation and filtration	17.9	35.6	26.8

From the above table, it may be deduced that the incremental cost of flotation, added to a conventional process (settling and filtration) for treatment plants of capacity of around 50Ml/d = 26.8-20.7 = 6.1 say 6c/kl.

Haarhof et al. (1992) also gave 1991 costs for the use of activated carbon for the control of taste and odour. PAC is considerably cheaper than GAC. At a projected average dosage of 5mg/l over a full year (say 10mg/l for about 3 months and 3mg/l for the rest), the unit cost of PAC dosage is between 4 and 6c/kl (2000 costs). GAC dosage is about 25c/kl (2000 costs), which is roughly the same as the total for settling, filtration and flotation.

Offringa (1996) gave the following figures for certain advanced processes:

- For a 35 Ml/d plant (Rietvlei), costs would be as follows:
  - GAC only: 20.4c/kl (2000 costs; 15c/kl in 1996)
  - Ozone and GAC: 28.6c/kl (2000 costs; 21c/kl in 1996) (taken from Van Staden and Haarhof ,1996; see also Van Staden, 1996)
- For a 1000 Ml/d plant (Rand Water), it would cost 8.2c/kl (2000 costs; 6c/kl in 1996) for GAC without ozonation.

The difficulty with these figures is that they are not calculated on a comparable basis.

Figures given by Rencken and Kerdachi (1991) are as follows: Initial cost estimates for an algae removal plant and GAC filtration station at the Wiggins water treatment works indicated that the total cost, including capital redemption would be approximately 36.8c/kl (2000 costs; 15c/kl in 1990). They also quoted Haynes, Viljoen and Steynberg (1989) who cited total cost estimates of 6c/kl and 9c/kl (1989 figures) for microstraining and GAC respectively. It should be noted that the 1989 figure for GAC is approximately the same as the 2000 figure for Rand Water quoted by Offringa. There may therefore be an error in one of figures. The authors made the point that the proposed additional processes would allow water of whatever quality to be treated at the Wiggins works. The price of bulk delivered water from Wiggins as sold to Durban Corporation for 1990 was 67c/kl. The estimated increased costs (of 15c/kl) would therefore represent a 22% increase in the bulk price of the water. The percentage price increase to the consumer would be quite a bit less than that.

Based on the figures quoted above, the following costs have been assumed for treatment works treating surface waters in Gauteng:

TABLE 5.5:
TOTAL COSTS OF WATER TREATMENT FOR DIFFERENT PROCESSES USED IN TREATMENT OF SURFACE WATER (2000)

Process	*Treatment costs [c/kl] (2000) for different plant capacities*	
	50Ml/d	*200Ml/d*
Conventional treatment (settling and filtration)	(31)	23
Flotation	7	(6)
PAC	6	(5)
GAC	20	(16)
Ozonation	8	(7)

Note:
Assumed values are given brackets; other values are taken from the literature (using some judgement where differing values were given in the literature).

The increase in water treatment cost is therefore a step-wise function as one moves to new processes in the treatment train. Based on the data presented in Table 5.5 above (figures rounded very slightly), the cost sequence for the smaller sized - i.e. 50Ml/d - plant capacity (2000 costs) for different process combinations are estimated as follows:

- conventional (settling and filtration) 30c/kl
- conventional + flotation 37c/kl
- conventional + PAC 36c/kl
- conventional + GAC 50c/kl
- conventional + flotation + GAC + ozone 65c/kl

For a large capacity works (i.e. 200Ml/d) water treatment costs are about 20-25% lower than the above figures.

Maximum additional cost of treatment to deal with poor quality raw water roughly *doubles* the costs of conventional treatment. For a relatively small works (50Ml/d) the magnitude of the increase (from 30c/kl to 65c/kl) amounts to about 35c/kl. For a larger works (200Ml/d), the proportional increase would remain about the same, but the magnitude of the increase would be somewhat less - about 30c/kl.

There is little more specific data on the variation of these individual process costs with change in raw water quality. Two studies, both based on the experience of Umgeni Water, give some indication of this. The first is a study by Dickens et al. (1996) on the Nagle Dam-Durban Heights system, which gives an indication of the effect of algal rupture on treatment cost of eutrophic waters. The second study, by Graham et al. (1998) reports on the effect of water quality on treatment costs within the Umgeni Water Operational Area. The objectives of the study were:

- to identify the main factors or contaminants affecting treatment costs at waterworks (WW) in the Umgeni Water operational area; and
- to predict treatment costs from observed levels of contaminants.

Four systems were investigated: Hazelmere plus Durban Heights, DV Harris and Wiggins (the top three WW operating within the Umgeni Water operational area during the study period, both in terms of amounts of water processed and costs involved in processing).

Multiple regression analysis was carried out to try and establish relationships between treatment cost and a range of water quality variables. These are summarised in tabular form for the four water treatment works below. The equations can be constructed as follows (giving the example of Hazelmere):

$$\text{Cost} = 62.3 + 0.026\text{Turb} + 135.0\text{Mn} + 0{,}049\text{SS} + 1.633\text{TOC} + 0.004\text{Al} + 1.653\text{SO}_4 + 8.026\text{K} + 9.296\text{pH} - 1.71\textit{Chlorella} - 0.310\ \text{Alk} + 22.7\text{NO}_3$$

TABLE 5.6:
MULTIPLE REGRESSION ANALYSIS CONSTANTS FOR TREATMENT COST OF WATER FROM VARIOUS SOURCES IN UMGENI WATER AREA (after Graham et al., 1998)

Variable	*abbreviation*	*units*	*Hazelmere*	*Durban Heights*	*DV Harris*	*Wiggins*
Cost						
constant			62.330	67.89	45.500	34.087
Trend	Trend	Month			0.024	0.032
Temperature	Temp	°C		0.383	0.165	0.465
pH	pH		-9.296	-8.681		-5.279
Turbidity	Turb	NTU	0.026	0.084	-0.010	0.091
Suspended Solids	SS	mg/l	0.049	0.084	-0.021	0.104
Secchi Disc	Secchi	m		-0.748		
Dissolved Oxygen	DO	mg/l O_2		-0.940	-0.463	
Total Organic Carbon	TOC	mg/l	1.633	0.618	0.234	1.196
Conductivity	Cond	mS/m		0.617	-0.508	
Total Dissolved Solids	*TDS*	*mg/l*				0.024
Total Aluminium	Al	μg/l	0.004			0.016
Iron	Fe	mg/l		1.613		4.253
Manganese	Mn	mg/l	135.031		-97.369	
Potassium	K	mg/l	8.026	0.823	2.150	
Nitrate	NO_3	mgN/l	22.677	3.177	5.075	3.156
Sulphate	SO_4	mg/l	1.653			0.090
Silicon	Si	mg/l		0.577	0.285	0.486
Alkalinity	Alk	mg/l	-0.310		-0.415	
Total Hardness		mg/l $CaCO_3$		0.256	-0.345	
Coliforms	Colif	colony counts/100ml		0.005	0.028	0.009
E.Coli		colony counts/100ml			0.075	
Anabaena	*Anabaena*	cells/ml		0.001		0.001
Microcystis	*Microcystis*	cells/ml		0.021		
Chlorella	*Chlorella*	cells/ml	-0.031		-0.006	

The study (Graham et al., 1998: p97) reported as follows "Classical multiple regression modelling of important algae against environmental variables was attempted to gain a statistically rigorous model of how the abundance of these algae was affected by the environment. However the predictive ability of all multiple regression models was poor ($R_a^2 < 0.5$) even with appropriate transformations of the response variables (algal abundance data). There were indications that interactions among environmental variables, spatial locations (lakes) and algae themselves were important. In other words, the effects of environmental variables on the different algal genera were not consistent over all lakes. This was not surprising given the variation in physico-chemistry between lakes....*The statistically rigorous multiple regression modelling of key algae against environmental variables was therefore not successful in this study* [italics added]. The semi-quantitative empirical models developed in the ordination analyses had to suffice as far as getting predictive models for algae/environment relationships."

5.2 Costing of water treatment for groundwater

There are a number of possible processes that can be used for the treatment of contaminated groundwater. For microbiological contamination, chlorination or other similar disinfection processes are adequate. For chemical contamination, more sophisticated processes are required. For nitrate removal, these include (Letimela, 1993: p. 13):

- chemical reduction
- physical-chemical (ion exchange)
- biological reduction

Processes that would remove other ions as well include:

- reverse osmosis (RO)
- ultrafiltration (UF)

For chemical reduction, only ferrous ion has been found to be economically attractive. The process requires a catalyst (copper) for denitrification, and the process must take place within an alkaline solution. Disadvantages are that only 70% of the nitrate is reduced, and large amounts of ferrous ion are required (Letimela, 1993: p.13). Letimela also points out that neither conventional coagulation nor lime softening are effective removal methods, due to the high solubility of nitrate in water.

Ion exchange involves passing the feed water through a bed of ion exchange resin. By means of these ion exchange resins, nitrate is exchanged for chloride or bicarbonate. It is a comparatively simple process, requiring a minimum of skilled attention; and there is no risk of bacteriological contaminantion of groundwater. Disadvantages include firstly the selectivity of the resin for sulphate rather than nitrate ($SO_4>NO_3>HCO_3$). A second disadvantage is the large volume of brine produced, with high nitrate, sulphate and chloride concentration. The method also has high running costs due to large amounts of salt required for the regeneration of the resin (50-120g/l NaCl) (Letimela, 1993: p. 16).

Biological denitrification entails facilitating the utilisation of nitrate in place of oxygen by aerobic heterotrophic bacteria, converting it to nitrite, ammonia or nitrogen gas. This anaerobic reaction requires organic carbon to be added to the water to provide the necessary energy for the bacteria. Methyl alcohol, ethanol and acetic acid are generally used as energy sources. Most denitrifying systems use methyl alcohol as the carbon source. Hiscock (1990) has explored methods for treating nitrate contaminated groundwater in UK aquifers, and particularly the possibility of developing underground denitrification. Advantages are that biological denitrification removes only (or mainly) nitrate, while the physico-chemical processes are generally unspecific, removing other inorganic constituents as well (Letimela, 1993: p. 20). The disadvantage is that the system is sensitive to bacterial toxins, and can fluctuate in its performance. There is also a danger that the bacterial population may contain pathogens, which need to be dealt with.

Letimela (1993) has provided costs for two denitrification processes as follows, assumed to be 1993 costs:

TABLE 5.7:
TOTAL COSTS OF WATER TREATMENT FOR DIFFERENT PROCESSES USED IN TREATMENT OF GROUNDWATER (1993) (Letimela, 1993)

Process	*Treatment costs [c/kl] (1993) for different plant capacities*	
	10kl/d	*20kl/d*
Ion exchange		
• capital cost	148	78
• running cost	35	33
sub-total	183	111
Biological denitrification		
• capital cost	125	70
• running cost	25	25
sub-total	150	95

Updating these costs to 1996, using an inflation rates indicated earlier, the following figures are obtained:

TABLE 5.8:
TOTAL COSTS OF WATER TREATMENT FOR DIFFERENT PROCESSES USED IN TREATMENT OF GROUNDWATER (2000) (Adjusted from Letimela, 1993)

Process	*Treatment costs [c/kl] (2000) for different plant capacities*	
	10kl/d	*20kl/d*
Ion exchange		
• capital cost	253	133
• running cost	60	56
sub-total	313	189
Biological denitrification		
• capital cost	214	120
• running cost	43	43
sub-total	257	163

Parameters used for the calculation of the costs are as follows, using methods set out by Kuiper (1971):

- Interest rate 20%
- Period of payment 10 years
- Assumed plant utilisation 85% of design capacity
- (Raw) water quality 60 mg/l NO_3-N

Exact details of the method of calculation were not given by the author.

Major capital components were as follows:

- Ion exchange column
- resin

- pumps
- treated water tower
- regenerant tank
- tank stand

5.3 Costs of other remedial measures

Figures have been given for the increased cost of water treatment from both surface water and from groundwater. There are, however, a number of *other costs* that are incurred that are relevant to this assessment and that need to be identified:

In-stream treatment measures:
- cost of *wetlands* for in-stream reduction of the nutrients

Consequences of pollution:
- cost of *removal of macrophytes*, and keeping the problem under control
- cost of *removal of algal growth from irrigation canals*; alternatively, assigning a cost to *reduced flow in irrigation canals.*
- *cost (or benefit) of high-nutrient waters for agriculture/irrigation.*

Loss of amenity:
- cost of damage to boats or health problems for swimmers as a result of toxic algae
- cost of loss of direct recreation (fishing, boating, swimming)
- cost of loss of value (walking along the river)
- cost of loss of hotels, tourism
- cost of reduction in property values

Non-use, or existence value

In-stream treatment measures
For treating contamination along the flow path of the Kaalspruit below Tembisa en route to Centurion Lake - and then Hartbeespoort Dam - wetlands were considered, as well as a water treatment plant at the entrance to Centurion Lake.

A sub-surface flow system (SFS) was designed (Brown, 1993) using an EPA design method (USEPA, 1988) to treat the average flow rate and water quality in the watercourse (as monitored) to acceptable standards (the minimum acceptable standard being recreational water standards). The contamination in this particular instance emanated primarily from sewer leaks and overflows from Tembisa.

Because the actual flow rate varies according to the hydrological characteristics of the watercourse, the standards to which the water was treated had to be expressed in statistical terms.

Detention ponds were provided to retain the most contaminated portion of a 'first flush' of stormwater (after a dry period), and feed that water into the wetlands for treatment, while allowing the rest of the storm to bypass the treatment process.

For a flow rate of $0.2m^3/s$, 16 reedbeds of 200m wide x 60m long and 1m deep, 8 on each side of the watercourse, were found to be required.

For treating water in the surface water body, a water treatment works was designed, which included:

- abstraction from the lake
- coagulation
- dissolved air flotation
- disinfection
- delivery to end users

Although potable water would need a filtration process as well, it could be omitted in this case as the water was to be treated only to recreational quality standards (as for the wetland).

The capital cost of the wetland was estimated to be R4-million (R8-million if suitable clay material could not be found in-situ for a reedbed lining, and a geomembrane had to be used). The capital cost of an equivalent water treatment works was estimated to be R2-million.

Assuming 24 000 sites in Ivory Park, these costs translate to roughly R200/site (R400/site if geomembrane used) for the wetland, and roughly R100/site for the treatment works (1993 costs).

These translate to values of R340, say R350/site for the wetland (R700/site if geomembrane used), and R170, say R175/site for the treatment costs (2000 costs). It should be stressed that these are merely order of magnitude costs. The cost of the wetland translate into an annual cost of between R5 and R10/cap.a.

Costs of consequences of pollution

Chemical control of water hyacinth on Hartbeespoort Dam = R220 000 in 1977/78. For several years previously, water hyacinth had been removed manually or had been shredded by special barges at a total cost estimated at between R600 000 and R1m. Applying the annual CPI inflation rates from 1978 to 2000 gives an escalation factor of about 12.5, indicating annual chemical control costs on Hartbeespoort Dam of the order of R2.75m at 2000 costs (Department of Water Affairs (DWA), 1986: p4.6).

5.4 Translation of costs per unit volume of water treated to a cost for the resource

Bruwer (1979) gives costs of a large number of interventions to deal with the causes or the effects of eutrophication. Areas of concern are flagged and total costs given; however, there is no real attempt in the work to link these costs to the causes of eutrophication or to nutrient levels. This makes it very difficult to assess the financial impact of particular pollution - or the the benefit of particular interventions. It is essential that costs are taken one stage further, and allocated to particular pollution problems.

In order to assign a cost to the pollution, it is necessary to apply this unit cost at some level of utilisation of the resource. Thus can be done at two levels:

- firstly, at the *current utilisation* of the resource (to give the actual current cost of the pollution);
- secondly, at the *maximum firm yield* of the resource (to give an indication of the potential or 'opportunity' cost of the pollution).

For *surface water*, WR90 (Midgley et al., 1994a, 1994b, 1994c) gives figures for the MAR of catchments in South Africa.. For calculation of the maximum firm yield of the resource, it is suggested that this be limited to the *natural* runoff from the catchment (MAR).

Assuming a maximum yield (assumed to be natural MAR) for the Gauteng portion of the catchment of the Vaal Barrage downstream of Vaal Dam - essentially consisting of the catchments of the Suikerbosrant River (C21) and the Rietspruit/Klip River (C22) - of 275Mm^3/a at an additional unit cost of treatment of 30c/m^3, the total *additional* cost of treatment will amount to R82.5, say R83million/a. For a population of 4.5 to 5million people in the catchment (in 2000), this translates only R18, say R20/cap.a. At the lower concentrations, it will increase the use of PAC (say 7c/kl), which amounts to less than R4/cap.a.

For groundwater, Haupt (2000) provides a method for assessing the magnitude of the firm yield. He suggests a number of different parameters:

- Harvest Potential (which is essentially the recharge)
- Exploitable potential (Harvest Potential reduced by a factor, dependent on borehole yield)
- Ground Water Portion of Harvest Potential (Harvest Potential less the Base Flow, which is the contribution to surface water).

In this study, to avoid double counting with surface water, Ground Water Portion of the Harvest Potential is suggested as the measure of firm yield of a groundwater resource.

Similar calculations to those for surface water can be made for the use of groundwater resources. Assuming a maximum yield (assumed to be the Groundwater portion of the Groundwater Harvest Potential) for the Gauteng portion of the catchment of the Vaal Barrage downstream of Vaal Dam - essentially consisting of the catchments of the Suikerbosrant River (C21) and the Rietspruit/Klip River (C22) - of 125Mm^3/a at an additional unit cost of treatment of R1.90/m^3, the total *additional* cost of treatment will amount to R237.5, say R238million/a. For a population of 4.5 to 5million people in the catchment (in 2000), this translates only R53, say R50/cap.a.

For the Gauteng portion of the catchment of the Vaal Barrage downstream of Vaal Dam, the sustainable yield of groundwater is about *half* that of the surface water. The additional cost of treatment of groundwater due to deteriorated raw water quality is about *five* times the equivalent additional cost of treatment for surface water. Translated to a cost per person per year, the additional cost of treatment of groundwater is therefore about *2.5* times the equivalent cost for surface water treatment. However, with current utilisation of groundwater of this catchment only about 6% (7.5Mm^3/a) of the maximum yield, this cost is still far from being realised.

5.5 Costing of different levels of service of sanitation

Costs of provision (construction, operation and maintenance) of different levels of service of water supply and sanitation in Gauteng for the year 2000 were obtained by updating figures from studies by Palmer Development Group et al. (1993a) and Palmer Development Group (1994b), together with methods set out in Van Ryneveld (1995). Particular methods and parameters used were as follows:

- *Household size* assumed was 5.5.

- *Inflation figures for escalation of costs from earlier dates to 2000:* Based on data given in Table 5.2, cumulative factors for the Consumer Price Index (CPI) 1.89 and 1.72 for the periods 1992 to 2000 and 1993 to 2000 respectively were used. CPI inflation figures for 1999 and 2000 were estimated at 8% per year.
- *For conversion of capital cost to an ongoing annual cost,* methods and parameters given earlier in the chapter (Formulae 5.1 to 5.3) were used.
- *Unit capital cost figures for bulk and connector services* are given in Table 5.9 below. These unit costs are factored in proportion to water usage to obtain capital costs for bulk and connector services of each level of service.

TABLE 5.9:
UNIT CAPITAL COST OF WATER SUPPLY IN GAUTENG 1993 and 2000 [R million per Ml/d] (used in Table 5.10) (after Palmer Development Group et al., 1993a and Palmer Development Group, 1994b)

	1993 costs [Rm per Ml/d]	*2000 costs [Rm per Ml/d]*
Bulk:		
Dam	1.7	2.9
Treatment	0.2	0.3
Transfer	1.5	2.6
Connector:		
Store	0.2	0.3
Transfer	0.34	0.58
Total:	*3.94*	*6.68*

Based on these parameters for water supply and similar parameters for sanitation, the costs of different levels of service of water supply and sanitation in Gauteng for 2000 are given in tabular and graphical form in Table 5.10 and Figure 5.1 respectively:

TABLE 5.10:

COSTS OF DIFFERENT LEVELS OF SERVICE OF WATER SUPPLY AND SANITATION IN GAUTENG 2000 (after Palmer Development Group et al., 1993a and Palmer Development Group, 1994b)

WATER SUPPLY

	water usage [l/cap.d]	water usage [l/site.d]	cap 1993 [R/site]	o&m 1993 [R/site.a]	cap 2000 [R/site]	o&m 2000 [R/site.a]	cap 2000 [R/site.m.]	o&m 2000 [R/site.m.]	tot 2000 [R/site.m.]
SP									
Internal			750		1290		8.16		8.16
Bulk & connector	40	220	867	99	1491	170	9.43	14.17	23.60
Total			1617	99	2781	170	17.58	14.17	31.76
YT									
Internal			1143		1966		12.43		12.43
Bulk & connector	90	495	1950	321	3354	552	21.20	45.96	67.16
Total			3093	321	5320	552	33.63	45.96	79.59
HC - normal									
Internal			1567		2695		17.04		17.04
Bulk & connector	150	825	3251	386	5592	663	35.35	55.28	90.63
Total			4818	386	8287	663	52.39	55.28	107.67
HC - high									
Internal			2071		3562		22.52		22.52
Bulk & connector	300	1650	6501	541	11182	930	70.69	77.52	148.21
Total			8572	541	14744	930	93.21	77.52	170.73

SANITATION

	cap 1992 [R/site]	o&m 1992 [R/site.a]	cap 2000 [R/site]	o&m 2000 [R/site.a]	cap 2000 [R/site.m.]	o&m 2000 [R/site.m.]	tot 2000 [R/site.m.]
BU							
Internal	600	15	1134	28	7.17	2.36	9.53
Emptying/treatment		253		478		39.85	39.85
Total	600	268	1134	507	7.17	42.21	49.38
VIP							
Internal	1500	27	2835	51	17.92	4.25	22.18
Emptying/treatment		30		57		4.73	4.73
Total	1500	57	2835	108	17.92	8.98	26.90
AP							
Internal	1200	63	2268	119	14.34	9.92	24.26
Emptying/treatment		30		57		4.73	4.73
Total	1200	93	2268	176	14.34	14.65	28.99
WB							
Internal	2500	45	4725	85	29.87	7.09	36.96
Bulk & connector	1200	128	2268	242	14.34	20.16	34.50
Total	3700	173	6993	327	44.21	27.25	71.46

WATER SUPPLY AND SANITATION

	cap 2000 [R/site]	o&m 2000 [R/site.a]	cap 2000 [R/site.m.]	o&m 2000 [R/site.m.]	tot 2000 [R/site.m.]
SP + VIP					
Internal service	4125	51	**26.08**	4.25	30.33
Bulk & connector	1491	227	9.43	18.90	28.33
Total	5616	278	35.51	**23.15**	**58.66**
YT + AP					
Internal	4234	119	**26.77**	9.92	36.69
Bulk & connector	3354	608	**21.20**	50.68	71.89
Total	7588	727	47.97	**60.60**	**108.58**
HC(normal) + WB					
Internal	7420	85	**46.91**	7.09	54.00
Bulk & connector	7860	905	**49.69**	75.44	125.13
Total	15280	990	96.60	**82.53**	**179.13**
HC(high) + WB					
Internal	8287	85	**52.39**	7.09	59.48
Bulk & connector	13450	1172	**85.03**	97.68	182.71
Total	21737	1257	137.42	**104.77**	**242.19**

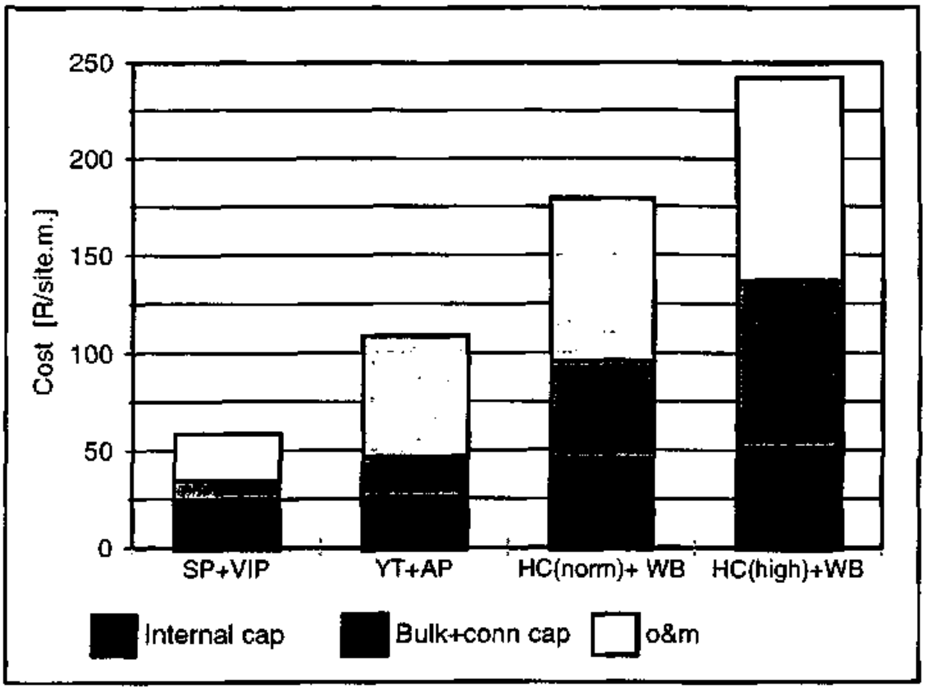

FIGURE 5.1: HOUSEHOLD COST OF WATER AND SANITATION FOR DIFFERENT LEVELS OF SERVICE IN GAUTENG [R/site.m. 2000 costs] (after Palmer Development Group et al., 1993a and Palmer Development Group, 1994b)

While it is more usual to present figures for the cost of different levels of services of water supply and sanitation in the form as presented above (costs per site per month), it is more convenient for purposes of comparison with the costs of water treatment, to present the costs in units of per capita per year. These are given in summary form, rounded to the nearest R5/cap.a in Table 5.11 below:

TABLE 5.11:
SUMMARISED COSTS OF WATER SUPPLY AND SANITATION IN GAUTENG 2000 [R/cap.a] (obtained from Table 5.10 - [R/site.m.] /5.5*12, rounded to the nearest R5/cap.a) (after Palmer Development Group et al., 1993a, and Palmer Development Group, 1994b)

	SP+VIP (Basic)	*YT+AP (Intermediate)*	*HC+WB (Full; essential use)*	*HC+WBc (Full; convenience use)*
O&M:	50	135	180	230
Capital (bulk and connector)	20	45	110	185
Capital (internal)	60	60	100	115
Total:	**130**	**240**	**390**	**530**

5.6 Preliminary conclusions on costing

1 For all water treatment - both surface water and groundwater - the cost is a *step-wise function* as one moves to new processes in the treatment train, with deteriorating raw water quality.

2 *Costs of surface water treatment:* For the smaller sized - i.e. 50Ml/d - plant capacity (2000 costs) the cost sequence for different process combinations is estimated as follows:

- conventional (settling and filtration) 30c/kl
- conventional + flotation 37c/kl
- conventional + PAC 36c/kl
- conventional + GAC 50c/kl
- conventional + flotation + GAC + ozone 65c/kl

For a large capacity works (i.e. 200Ml/d) water treatment costs are about 20-25% lower than the above figures.

3 *Maximum* additional cost of surface water treatment to deal with poor quality raw water roughly *doubles* the costs of conventional treatment. For a relatively small works (50Ml/d) the magnitude of the increase (from 30c/kl to 65c/kl) amounts to about 35c/kl. For a larger works (200Ml/d), the proportional increase would remain about the same, but the magnitude of the increase would be somewhat less - about 30c/kl.

4 *Costs of groundwater treatment:* Treatment of groundwater resources is considerably more expensive than the treatment of surface water resources - with groundwater treatment ranging between R1.60/kl and R3.15/kl depending on plant capacity and process.

5 Because groundwater is generally not treated before use (in certain cases, it may be disinfected), the *additional* cost of treatment due to poor raw water quality for groundwater is suggested to be the *full* cost of treatment. This may not be entirely reasonable, but is suggested as a *very worst case* scenario for the purposes of this study.

6 Assuming this to be the case, the *additional* cost of groundwater treatment is somewhere between 4 and 9 times the *additional* cost of surface water treatment (30-35c/kl).

7 *Costs of provision (i.e. construction, operation and maintenance) of the different levels of service of water supply and sanitation* in Gauteng (2000 costs) are:

- Stand-pipe and VIP (basic) R130/cap.a
- Yard tap and aqua-privy (intermediate) R160/cap.a
- House connection and water-borne sanitation (full; *essential* use) R260/cap.a
- House connection and water-borne sanitation (full; *convenience* use) R530/cap.a

8 Assuming a maximum yield (assumed to be natural MAR) for the Gauteng portion of the catchment of the Vaal Barrage downstream of Vaal Dam - essentially consisting of the catchments of the Suikerbosrant River (C21) and the Rietspruit/Klip River (C22) - of 275Mm^3/a at an additional unit cost of treatment of 30c/m^3, the total *additional* cost of treatment will amount to R82.5, say R83million/a. For a population of 4.5 to 5million people in the catchment (in 2000), this translates to only R18, say R20/cap.a. At the lower concentrations of contaminants, it will increase the use of PAC (say 7c/kl), which amounts to less than R4/cap.a.

9 A key requirement is that the (clean) water imported from Lesotho Highlands should not be mixed with (contaminated) water from the Vaal Barrage (requiring more sophisticated

treatment processes).

10 Similar calculations to those for surface water can be made for the use of groundwater resources. Assuming a maximum yield (assumed to be the Groundwater portion of the Groundwater Harvest Potential) for the Gauteng portion of the catchment of the Vaal Barrage downstream of Vaal Dam - essentially consisting of the catchments of the Suikerbosrant River (C21) and the Rietspruit/Klip River (C22) - of 125Mm^3/a at an additional unit cost of treatment of R1.90/m^3, the total *additional* cost of treatment will amount to R237.5, say R238million/a. For a population of 4.5 to 5million people in the catchment (in 2000), this translates to only R53, say R50/cap.a.

11 For the Gauteng portion of the catchment of the Vaal Barrage downstream of Vaal Dam, the sustainable yield of groundwater is about *half* that of the surface water. The additional cost of treatment of groundwater due to deteriorated raw water quality is about *five* times the equivalent additional cost of treatment for surface water. Translated to a cost per person per year, the additional cost of treatment of groundwater is therefore about 2.5 times the equivalent cost for surface water treatment. However, with current utilisation of groundwater of this catchment only about 6% (7.5Mm^3/a) of the maximum yield, this cost is still far from being realised.

12 By comparison with the costs of a higher level of service of water supply and sanitation, the maximum additional costs of treatment are small. For surface water, the additional cost of treatment (R20/cap.a) is only about 15% of the difference in cost between a basic and a full level of service (*essential* use) (R130/cap.a). If water usage for the full level of service increases towards *convenience* use, then the relative cost of treatment will drop even more. For groundwater, the additional cost of treatment (R50/cap.a) is about 40% of the level of service cost difference.

13 In summary, even *conservative* estimates of additional treatment costs (either surface water or groundwater), *fully* (i.e. very conservatively) assigned to pollution from sanitation systems, are still *well less than half* the cost difference between basic and full (essential use) levels of service of water supply and sanitation (based on the particular catchments used in the analysis).

14 Quantitative estimates of the costs of loss of recreation and property value as a result of deteriorated impoundment water quality may be significant, and requires further investigation.

6 APPLICATION OF THE MODEL TO HARTBEESPOORT DAM CATCHMENT

In order to model sanitation provision in Gauteng, together with the impact of water quality and the resultant cost, it is necessary to integrate and apply the various sectors of planning, water quality and costing set out in previous chapters; and this was done by applying them to the specific impoundment of Hartbeespoort Dam.

Furthermore, while the costing sector provides a *ceiling* on the additional cost of treatment from deteriorated water quality in Gauteng, it is necessary to model the actual movement of contaminants and their impact in order to *allocate* the costs of pollution to different sources.

6.1 Choice of Hartbeespoort Dam for application of the model

Firstly, why apply the model to a specific impoundment?
While a number of key conclusions could be drawn simply from the methodology together with the previous three sectors, it is only in the application of the model to an impoundment that the methodology can be validated. More specifically, the application of the model to a specific impoundment was able to permit:

- fine-tuning of a number of *general* parameters e.g.
  - unit flows and loads from water-borne sanitation;
  - relationship between growth rates of population, water demand, LOS.
- confirmation of the applicability of the model, and calibration of the various transfer functions, and their change over time:
  - nutrient export (point and non-point source loads);
  - nutrient budget;
  - nutrient algae.
- checking of the effect of the hydrological regime;
- development of a better understanding of the variability of the data.

Most importantly, application of the model to the Hartbeespoort Dam catchment was used to illustrate and provide insight into the problem of sanitation in Gauteng as a whole. More than that, however, it shaped the direction of the model, highlighting which factors were critical and which weren't.

Secondly, why apply the model to Hartbeespoort Dam?
While Vaal Barrage is the impoundment where the majority of Gauteng's population are located - and therefore where the greatest impact of sanitation is likely to be felt, Hartbeespoort Dam was chosen for more detailed study for the following reasons:

- Although not the *most* critical impoundment, it *one of the two* most critical impoundments
- There are fewer watercourses and contaminant sources in the catchment, making it somewhat *simpler* than the Vaal Barrage; which would permit clarification of principles involved
- *Eutrophication is a definite problem* in Hartbeespoort Dam
- Hartbeespoort Dam has been *extensively studied*

- Flow and water quality *data were readily available* from DWAF

As it turned out in the end, it was possible to *extrapolate* the principles established at Hartbeespoort Dam sufficiently well to the Vaal Barrage and other impoundments to permit statements to be made about the whole of Gauteng.

6.2 Time periods used in modelling

In applying the model to a specific catchment, different modelling approaches were necessary for different time periods:

- *Past:* covering years up until most recent data available; hydrological years 1980 to 1998 for water quality data; up to 1996 for demographic data; essentially data over past 20 years; although there are gaps in some of the data, and certain data has only been collected more recently.
- *Present:* assume the 2000 hydrological year; although we are in the present, data are generally not yet available for the present; furthermore the present hydrological year is still incomplete. Data for the present therefore needs to be estimated.
- *Future:* projection to year 2010 (single year in 10 years time); this must be estimated.

These different time periods had different characteristics:

- While there were uncertainties in both the past and the future, the *nature of the uncertainty* was different. In the past, uncertainty arose as a result of lack of data (or inconsistent methods of measurement etc); whereas in the future uncertainty arose as a result of it not having taken place.
- A certain amount of patching and inference was therefore required to reconstruct the past. The past was also used to *develop an understanding* of the processes at work so as to enable one to construct (or model) possible and likely scenarios for the future.
- While *sensitivity analyses* of uncertain parameters needed to be carried out for both past and future, the nature of uncertainty was different
- For the past, it is primarily a *cost allocation* problem. In the past, one generally know what happened in the lake, but need to allocate it to different sanitation systems. In the future, one needs to construct scenarios of what might *happen*. Critical to this is to be able to identify critical factors that might significantly affect the cost of pollution of different levels of service of sanitation.
- One needs to identify the key characteristics of the different elements of pollutant movement and cost. There are several transfer functions that need to be identified.

6.3 Construction - or reconstruction - of past, present and future situations/scenarios

While the *most likely* situations were constructed - or reconstructed - for the past and present, *extreme* scenarios were constructed for the future. Having chosen extreme scenarios for the future, the time horizon was set at a relatively close 10 years (i.e. the year 2010). This was considered to be sufficiently close to be realistic for present decision-making, while at the same time considered to be far enough into the future to allow significant differences from the present to develop.

For the future (2010), families of scenarios were considered under each of two subsections:

- planning; and
- water quality.

Details of these scenarios are given in Table 6.5 (section 6.7)
From past behaviour, existing models as described in the previous chapters were tested and calibrated, using data obtained for Hartbeespoort Dam. These models were then used:

- to extrapolate to the present and
- to construct a number of extreme scenarios for 2010.

Models calibrated were as follows:

- Hydrology and nutrient export (i.e. flows and contaminant loads)
- Dam balance and nutrient budget (i.e. in-lake contaminant concentrations)
- Nutrient algae (i.e. algal response)

In practice, the calibration did *not* follow the linear path indicated in the list above. In fact, the starting point was to check the nutrient algae model, to check the nutrient limitation of the lake i.e. to see whether the algal response to nutrient concentrations in the impoundment was determined by N, P or by both. The most satisfactory relationship was found to be with P alone, indicating P limitation in the lake.

6.4 Hydrology and nutrient export

Stewart, Sviridov & Oliver in association with BKS Incorporated (SSO et al.) (1992) applied the WR90 method to the Upper Crocodile River sub-system to produce a stationary hydrological record for the catchment i.e. the hydrological record with any effects of development taken out; in other words, as if the catchment was in its undeveloped state. In the process of doing this, they also determined the various components of total flow, namely naturalised flow, urbanisation flow, irrigation abstractions and point source discharges.

Details of hydrological sub-catchments are as follows:

TABLE 6.1:
DETAILS OF HYDROLOGICAL SUB-CATCHMENTS FOR HARTBEESPOORT DAM, BASED ON DWAF WEIR CATCHMENTS (SSO et al.,1992: p.5)

Sub-catchment (and gauge number)	*Main Rivers*	*Incremental Catchment Area [km²]*	*Sub-catchments immediately upstream*	*Level*
A2R001	Crocodile	390	A2H012, A2H013	1
A2H012	Crocodile, Hennops	621	A2H044, A2H045, A2R004	1.1
A2H013	Magalies	1171	-	1.2
A2H044	Jukskei	389	A2H042	1.1.1
A2H045	Crocodile	134	A2H049, A2H050	1.1.2
A2R004	Rietvleispruit	479	-	1.1.3
A2H042	Jukskei	409	-	1.1.1.1
A2H049	Bloubankspruit	371	-	1.1.2.1
A2H050	Crocodile	148	-	1.1.2.2

In the SSO study, *incremental* catchment areas and flows were used i.e. catchment areas and flows at upstream weirs were subtracted from areas and flows at downstream weirs; whereas DWAF values are the *total* values at a particular weir (e.g. A2H012). This study has followed the DWAF approach rather than the SSO approach.

Total flow
The DWAF flows at weirs A2H012 and A2H013 do not agree exactly with the calculated streamflows used in the Hartbeespoort Dam balance. The variation is approximately 5-10% maximum. These variations are of the same order of magnitude as the smaller components of the flow.

The actual flows into Hartbeespoort Dam were considered to be the most important ones. From those, the constituent parts (Natflow, Urbflow, Irrigation demand and point discharge) were constructed. The Irrigation demand and Urbflow components are relatively minor components; however the point flow (and naturalised flows) are quite big.

Naturalised flow
WR90 gives naturalised flows for quaternary catchments as well as for the major weirs entering Hartbeespoort Dam i.e. A2H012 and A2H013.

Irrigation flow:
There are two reasons for looking at the irrigation in the Upper Crocodile River Sub-system: The first is to look at the effect of irrigation in the Hartbeespoort Dam catchment on the water balance of the *catchment*. The second is to look at the utilisation of the water from the *dam itself*. The first is one of the factors affecting the *magnitude* of the contamination. The second is where the *impact* of the contamination is felt.

Hartbeespoort, Roodekopjes, Buffelspoort and Middelkraal Dams together with the associated canals, pipes and works are the only Government Water Schemes (GWS) within the sub-system. Within the area of jurisdiction of a GWS, no water may be abstracted directly from the river without a permit from the Department of Water Affairs. SSO et al. (1992: Table 2.1, p.7) give details of the various GWS. In the Hartbeespoort GWS, the Government canals service a scheduled irrigation area of 13 044ha, the Old furrows, 2 800ha and the Dam basin 374ha, giving a total of 15 218ha, all with an annual irrigation quota of 6 200m^3/ha = 94.4Mm^3/a.

Topographical maps are unsuitable for determining actual irrigation areas because areas marked as "cultivated" usually consist of all land which could potentially be cultivated, including so-called "dry-land" farmland (SSO et al, 1992: p.10).

Detailed information on and results of the satellite image analysis can be obtained from the HRI report *Mapping of irrigated land in the Crocodile River catchment (Western Transvaal) with the aid of satellite imagery captured in 1988* (SSO et al, 1992: p.12).

Assumptions about irrigation in various sub-catchments:

TABLE 6.2:
DETAILS OF IRRIGATION IN HARTBEESPOORT DAM CATCHMENT (SSO et al., 1992)

Sub-catchment (and gauge number)	*Main Rivers*	*Incremental Catchment Area [km^2]*	*Level*	*Change in irrigation*
A2R001	Crocodile	390	1	constant since 1920
A2H012	Crocodile, Hennops	621	1.1	Irrigation has increased as effluent and runoff from urbanised areas has increased from 1920 to 1987.
A2H013	Magalies	1171	1.2	constant since 1920
A2H044	Jukskei	389	1.1.1	Irrigation has increased as effluent and runoff from urbanised areas has increased from 1920 to 1987.
A2H045	Crocodile	134	1.1.2	Irrigation has increased as effluent and runoff from urbanised areas has increased from 1920 to 1987.
A2R004	Rietvleispruit	479	1.1.3	Irrigation has increased as effluent and runoff from urbanised areas has increased from 1920 to 1987.
A2H042	Jukskei	409	1.1.1.1	constant since 1920
A2H049	Bloubankspruit	371	1.1.2.1	Irrigation has increased as effluent and runoff from urbanised areas has increased from 1920 to 1987.
A2H050	Crocodile	148	1.1.2.2	Irrigation assumed constant from 1920 to 1980, then increasing along with increasing effluent returns (from Roodepoort's Driefontein sewage works, which began releasing effluent into the sub-catchment in 1978)

Borrowing from the *Klip River study* (SSI et al., 1996), the following details on irrigation were used:

The irrigation modules of WRSM90 calculate the irrigation water demand using the following equation:

DEM = AIRRE*PINDEX*(f*Eo-r*Ro)

where:

DEM = irrigation demand in a particular month (10^6m^3)
AIRRE = irrigation area in km^2 (input for various years spanning the calibration record period)
PINDEX = proportion of the annual irrigation area that is irrigated in this month of the year
f = crop factor for that month of the year, which when applied to Eo will give potential crop evapotranspiration
Eo = A-pan evaporation for that month of the year
r = effective rainfall factor for that month of the year (a value of 1.00 was used throughout)
Ro = rainfall in mm (calculated from MAP and input rainfall file).

Annual irrigation areas were obtained from Stewart, Sviridov and Oliver and Wits Hydrological Research Unit survey of 1977. In the absence of better information:

- These areas were assumed to be valid for the model calibration period, i.e. 1977 to 1993.
- PINDEX was assumed to be 1.00 throughout (i.e. the entire annual irrigation area was irrigated in each month of the year).
- Crop factors (f) were selected to produce an average net annual irrigation demand of approximately 600mm, distributed evenly throughout the year.

More detailed information on irrigation was in fact obtained from the SSO et al. study on the Crocodile River (SSO et al., 1992). This information is likely to enable a more accurate estimate to be made of the irrigation flows both in the dam basin and downstream of it.

Urbanisation flow:
As a consequence of increased paved areas, urbanisation within a catchment causes an increase in surface runoff as a result of paved areas, and a decrease in sub-surface flow. The net effect is an increase in total run-off from the catchment. (SSO et al.,1992: p43-44).

Past and present urbanised areas were determined using planimetry of 1:50 000 topographical maps dating from 1945 to 1983. From graphical representation of this data, it appears that the growth in urbanisation has tended to follow the Rand Water Board primary growth rate of 5.37% per annum. The same figure was therefore assumed for the urbanisation growth rate.

This figure for growth in water demand appears to be in agreement with estimated figures of Department of Water Affairs (DWA) for the Vaal River water supply area (DWA, 1986: p.5.23-5.24). For the purpose of the Water Affairs study, the supply area is divided into 2 regions:

- The Upper Vaal River supply region

- The PWV metropolitan region and the Vaal River region downstream of the Vaal Barrage. The city of Kimberley and the towns of Welkom, Klerksdorp, Potchefstroom and Rustenburg are included in this region.

Likely average annual growth in water demand for the whole Vaal River water supply area was estimated at between 5.2% and 4.0% per year. From the accompanying graph, higher growth rates were estimated for the PWV area.

TABLE 6.3:
URBANISED AREAS AND IMPERVIOUS PROPORTIONS OF SUB-CATCHMENTS (after SSO et al., 1992: Vol. I: Text, Table 2.17, p.44)

Sub-catchment (and gauge number)	*Main Rivers*	*Level*	*Urbanised area 1983 planimetred [km²]*	*Urbanised area 1987 projected [1] [km²]*	*Incremental Catchment Area [km²]*	*Impervious proportion (A_p) in 1987 [2] [%]*
A2R001	Crocodile	1	6	7	390	0.22
A2H012	Crocodile, Hennops	1.1	42	52	621	1.05
A2H013	Magalies	1.2	0	0	1171	0
A2H044	Jukskei	1.1.1	58	71	389	2.28
A2H045	Crocodile	1.1.2	0	0	134	0
A2R004	Rietvleispruit	1.1.3	25	31	479	0.81
A2H042	Jukskei	1.1.1.1	183	226	409	6.91
A2H049	Bloubankspruit	1.1.2.1	20	25	371	0.84
A2H050	Crocodile	1.1.2.2	14	17	148	1.44
tot A2H012 [3]			*342*	*422*	*2551*	*2.07*

Note:
1 Projection based on growth of 5.37% per year on 1983 planimetred area
2 Impervious proportion assumes one eighth of urbanised area to be paved/impervious
3 *Total* A2H012 excludes A2R001 and A2H013

WR90 gives urbanised areas by quaternary (Midgley et al., 1994b: Vol I Appendix 5.4, p.5.16). Calculation of urbanised area by quaternary (including portion of quaternary A21H) gives a value of 446.3 km²; however no year is quoted for this figure in the report. Using a baseline figure of 342 km² for the urbanised area in the *total* A2H012 catchment in 1983 (see Table 6.3 above), together with the growth rate of 5.37% over a 5 year period (from 1983 to 1988) produced very close agreement with the WR90 figure of 446.3 km². On the basis of this, the WR90 quaternary urbanisation figures were assumed to be at 1988; and, together with the 5.37% urbanisation growth rate, were used to construct the earlier urbanisation area figures (1979-1987).

The increased flow due to urbanisation (Urbflow) is of the order of 15-20% of the total flow, and about 50% on top of the naturalised flow (Natflow) (for the Crocodile River catchment, A2H012).

Point discharges
Surprising variations occur in the point loads from sewage treatment works; which one might have thought to be even more uniform that the rainfall patterns. This does not seem to be the case. This may be as a result of water restrictions being applied during drought periods; alternatively, it may be due to variations in effluent re-use.

Although the general trend appears to be exponential, the relationship is considerably more variable than expected. This lack of uniformity is very evident in a plot of effluent flows over an extended period of more than 50 years, presented by SSO et al. (1992: Vol. II, Appendix A, Fig.10). Effluent is higher in wet years and lower in drought years.

While a simple exponential curve was able to model the primary effluent flows vs time relationship over the 1979-1988 period, the model was not very significantly improved by adding a component to account for the hydrological variability. (Hydrological variability was modelled by applying a factor to the difference between Naturalised flow for a particular year and the long term average for that flow). Part of the reason for this may be that variations in water use - and hence variations in effluent flow - may have been more dependant on regulatory interventions such as water restrictions or high tariffs than simply on the magnitude of the naturalised flows. The other factor that has not been easy to determine has been the extent of effluent reuse. Every attempt has been made to account for these in the final effluent figures used; however, records of some treatment works remained incomplete (Effluent reuse may increase during drought periods).

Water restrictions were in place over the following periods (Rand Water, nd):

- *1966-67:* 19 Jan 1966 - 9 Feb 1967 (1 year ½month)
- *1969:* 28 Feb 1969 - 13 Nov 1969 (8½ months)
- *1970-71:* 15 Oct 1970 (error?) - 19 Nov 1971 (1 year 1 month)
- *1973-74:* 15 Oct 1973 - 15 Feb 1974 (4 months)
- *1979-80:* 10 Jun 1979 - 13 Feb 1980 (8 months)
- *1983-87:* 7 Mar 1983 - 31 Oct 1987 (4 years 8 months)

The shorter periods of water restriction appear to have caused a limited and temporary reduction in water use, from which water use rebounded to the pre-restriction trajectory once restrictions had been lifted. The extended 1983-87 period of water restrictions, however, caused a more significant and long term adjustment in water use patterns, from which growth in water use did *not* immediately rebound once restrictions had been lifted, although water use over the subsequent decade has again crept up towards the pre-1983 growth trajectory.

Contaminant loads:
As indicated earlier in the report, Northern Works gives a good indication of effluent contaminant loads. Using monthly averages of the flows and PO_4-P mass loads, the flow-weighted average PO_4-P final effluent concentration over the 5 year period from October 1993 to September 1998 (i.e. hydrological years 1993/94 to 1997/98) was just over 0.6 mgPO_4-P/l. Problems with effluent quality were evidently encountered at the works in the 1998/99 hydrological year, with effluent concentrations averaging over 3mgPO_4-P/l for the month of January 1999 and over 1 mgPO_4-P/l for 6 of the 7 months between October 1998 and April 1999.

Adding the data for the 1998/99 to the previous 5 years data pushes the average up to just under 0.75 $mgPO_4$-P/l, still well under the 1 $mgPO_4$-P/l level (Rimmer, 1999).

Mass loadings for the works were less variable than contaminant concentrations, with the monthly load varying between about 2.5 and 5 t PO_4-P/month over the 5 year period 1993/94 to 1997/98, but significantly exceeding that over the 6 month period in the 1998/99 hydrological year, peaking at between 20 and 25 t PO_4-P/month in January 1999. Interestingly, this 'spike' is *not* reflected in the mass loadings at weir A2H012 entering Hartbeespoort Dam.

This 'spike' appears far less marked when one compares it with the overall flows for the weir. Hydrological variability is very significantly greater than the variation - even so-called 'spikes' in the effluent data. The higher effluent figures in 1995-96 coincide with *very* high overall flows for the weir. It seems then that an estimate of the general growth of effluent should leave out the drought of 1982-85 and the floods of 1995-96 hydrological years.

Flows and loads were also obtained from various Johannesburg WWTW. Over the 9 year period (1979-1987) a constant relationship was identified between effluent flows from Northern Works + Alexandra Works and the total point source flows for the catchment as a whole: Northern Works + Alexandra works effluent = 0.41 x total point source flows for the catchment as whole. That was used to construct total point source flows over the period 1994-1998, and to determine average annual growth rates over the full period.

There appears to be a fairly constant relationship between the combined flows of Alex and Northern Works over the 10 year period from 1979 to 1988. Alex + Northern Works made up between 37% and 44% (average 41%) of the total point source loads for A2H012 (effectively for Hartbeespoort Dam). Based on this relationship, the total point source loads for A2H012 for the period 1993-1998 were estimated, based on the Northern Works loads.

What is also interesting is that the same variations in flow that occur in the Northern Works data are also reflected in other point source data for A2H012. This would seem to indicate that the variation might be due hydrological fluctuations (ie droughts and floods). The hydrological variability therefore masks any changes in flows or mass loading from the treatment works.

Putting the 1979-88 data from WR90 together with the 1993-98 data from Johannesburg, an overall growth rate of around 7.5% per year would be indicated. This is very high - significantly higher than the 5.37% per year growth rate for growth in water demand, and also significantly higher than the overall population growth rate.

There is a significant discrepancy between the sewage flows that were estimated for low income areas and the flows that are being received at sewage treatment works in A2H012. Flows in the catchment appear to be at least 180 l/cap.d, virtually double the figure for low income areas. Part of it is accounted for by commercial and industrial flows, as indicated by Hall and Watson (2000); however, more detailed investigation is required to confirm this.

Figure 6.1 below gives annual total and point source flows for the Crocodile River weir A2H012. Thin lines indicate average trend lines for each of the two components - an attempt to take out the effects of hydrological variability.

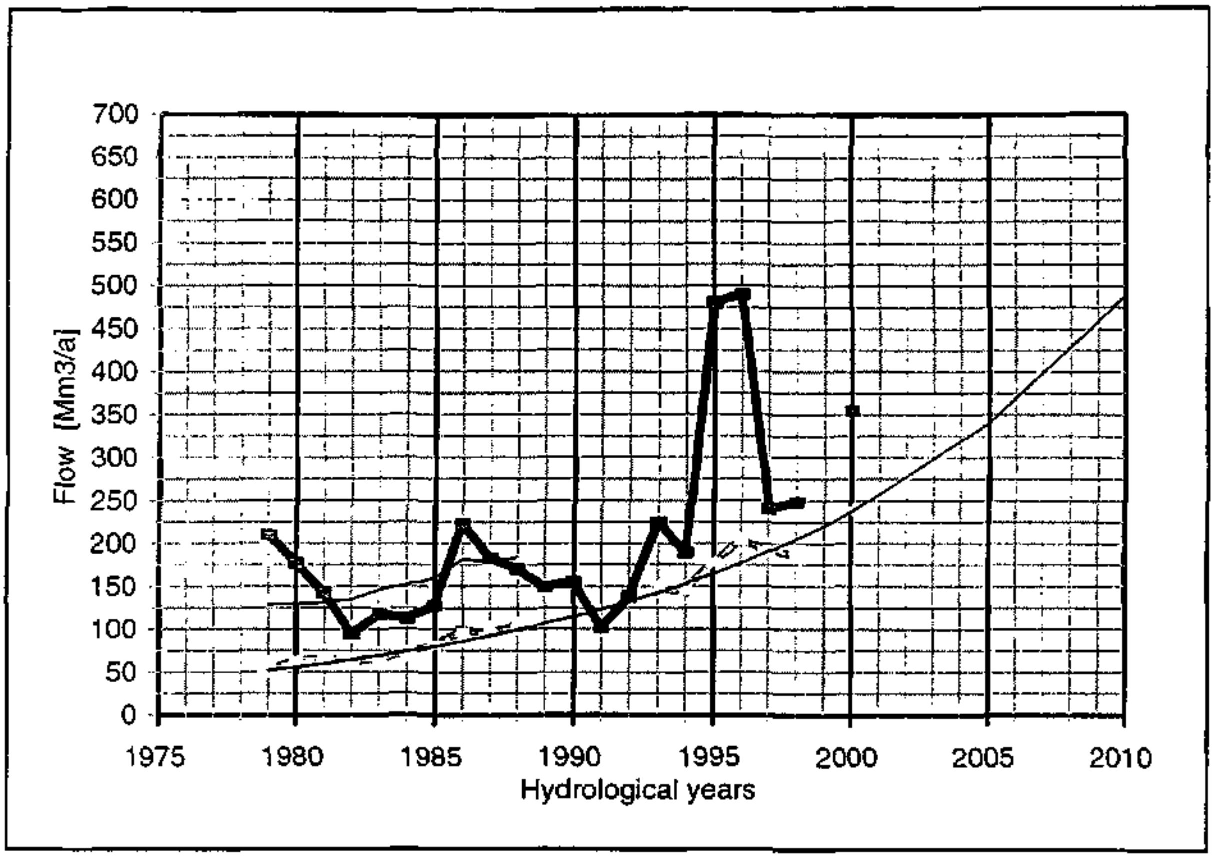

FIGURE 6.1:
ANNUAL TOTAL AND POINT SOURCE FLOWS FOR CROCODILE RIVER WEIR A2H012 FOR HYDROLOGICAL YEARS 1979-2010

The point sources were approximated most closely over the period 1979 to 1998 by a growth rate of 7.5% and a baseline point sewage flow of 60 Mm3/a in 1981 (chosen because it was a period of roughly average streamflow). Essentially what was done was to construct a model for *all* components of the flow, that could be used to extrapolate to 2000 and beyond (to 2010).

Because lake response was calculated on a monthly (rather than an annual) basis, it was necessary to construct average monthly flow and contaminant load distributions relative to the annual values.

Flow and contaminant concentration records were obtained for the two major weirs at inflow to Hartbeespoort Dam: A2H012 (Crocodile River at Kalkheuwel) and A2H013 (Magalies River at Scheerpoort) for the period hydrological year 1980 (i.e. October 1980-September 1981) to hydrological year 1998. Monthly averages were obtained by simple averaging of all flow and contaminant concentration records in a particular month to obtain monthly averages.

Monthly contaminant loads were then calculated by multiplying monthly average flows by monthly average contaminant concentrations. Monthly TP loads for Crocodile River weir A2H012 are given in Figure 6.2 below.

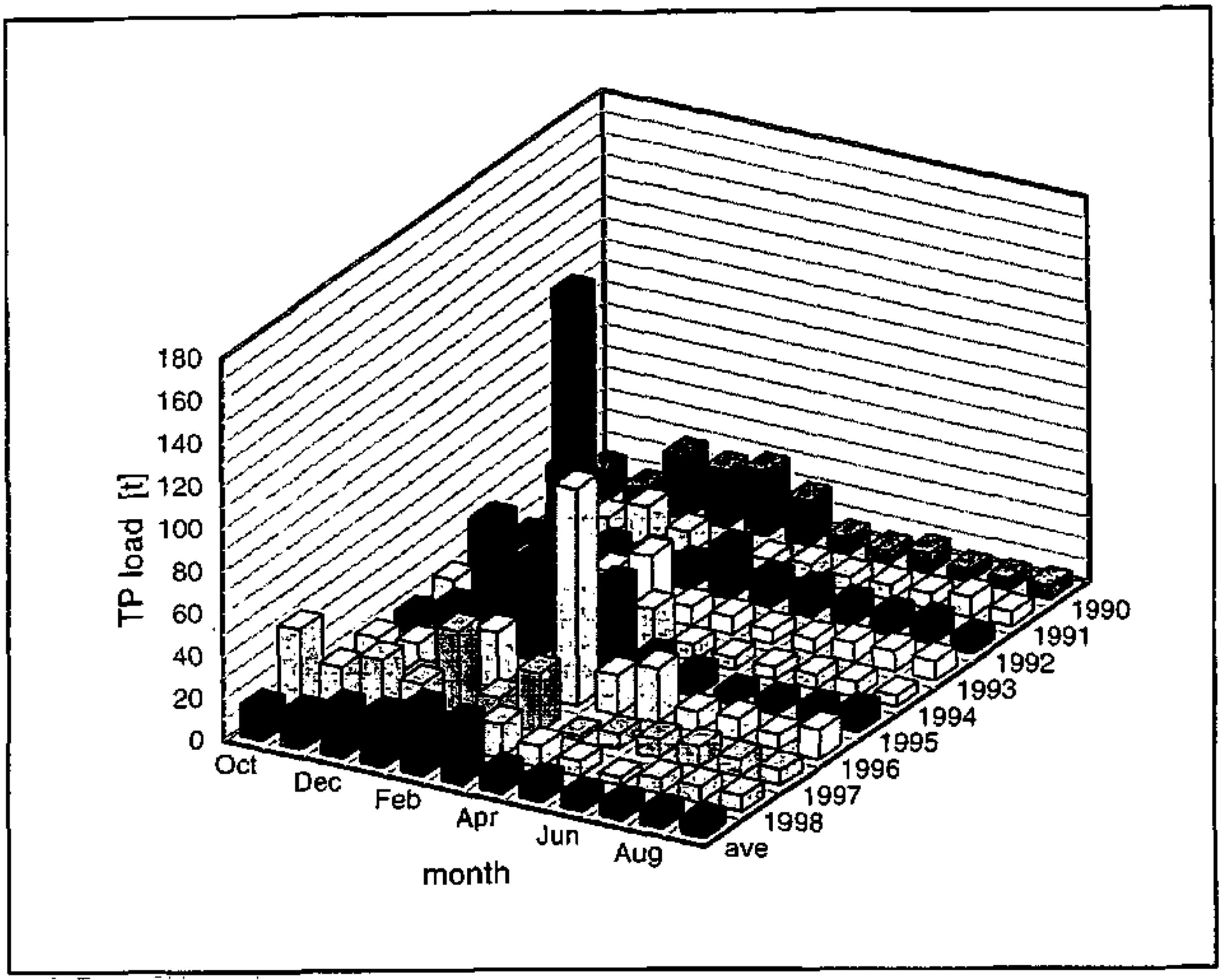

FIGURE 6.2:
MONTHLY TOTAL PHOSPHORUS LOADS [t] FOR CROCODILE RIVER WEIR A2H012 FOR HYDROLOGICAL YEARS 1990-1998

Log-log flow-load diagrams were constructed for both the Crocodile River and the Magalies River catchments, which demonstrated relatively tight relationships between both TN, TP and flow for both catchments. The Magalies River demonstrated significantly stronger relationships for both parameters against flow; and TN demonstrated a stronger relationship against flow for both catchments.

6.5 Dam balance and nutrient budget

A dam balance as well as in-lake water quality data was obtained from DWAF, and was used to calibrate the Reservoir Specific (RSEM) nutrient budget model used by Meyer and Rossouw (1992) (see p.99). This model uses two different sedimentation coefficients, applied to inflow and in-lake TP concentrations. The model is a simple mass-balance model, using monthly data. Results of actual and model results are indicated in Figure 6.3.

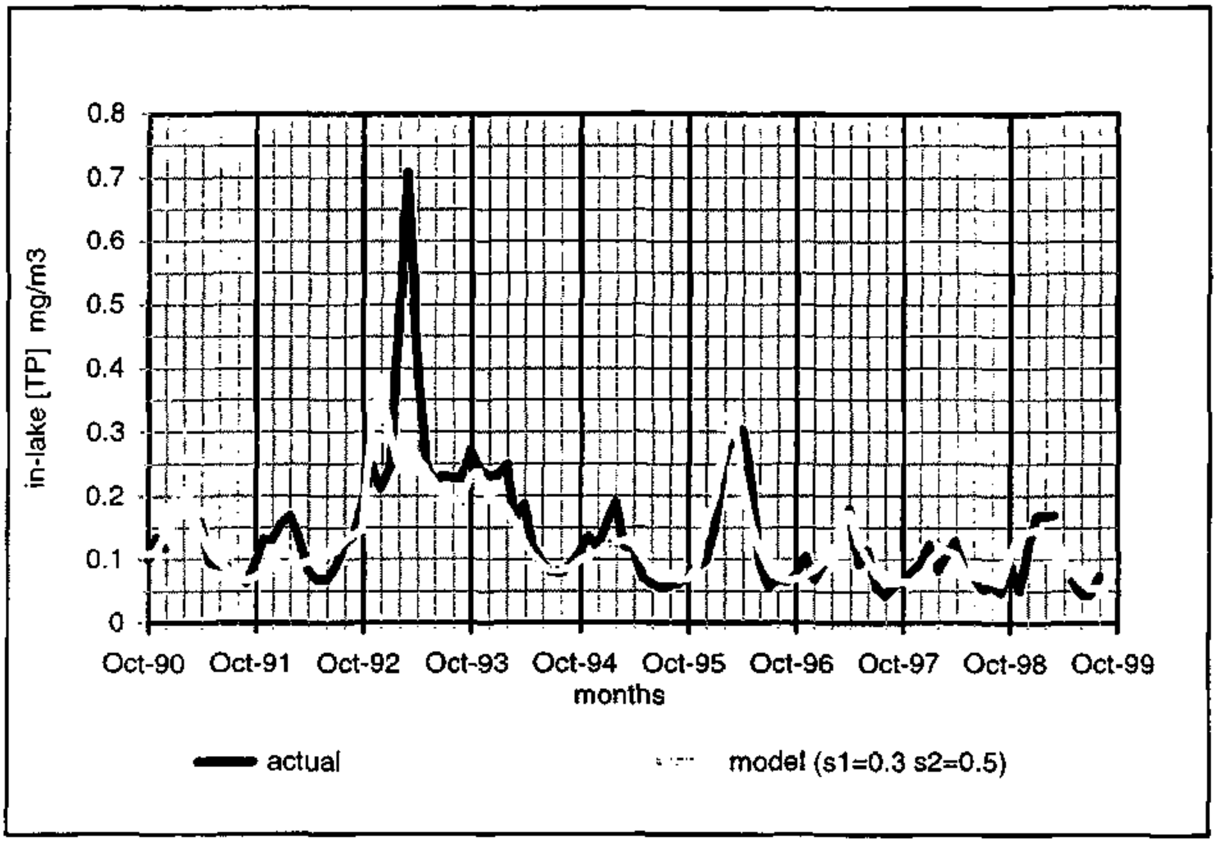

FIGURE 6.3:
NUTRIENT BUDGET FOR HARTBEESPOORT DAM 1990-1998
In-lake sedimentation factor s_1=0.3; inflow sedimentation factor s_2=0.5

6.6 Nutrient algae

The second calibration that was carried out was that of the nutrient-algae relationship. What is apparent is that the REM nutrient-algal model was able to model the algal response until February 1996. The following month, March 1996, there was a major deviation, which appears to have continued for the following years.

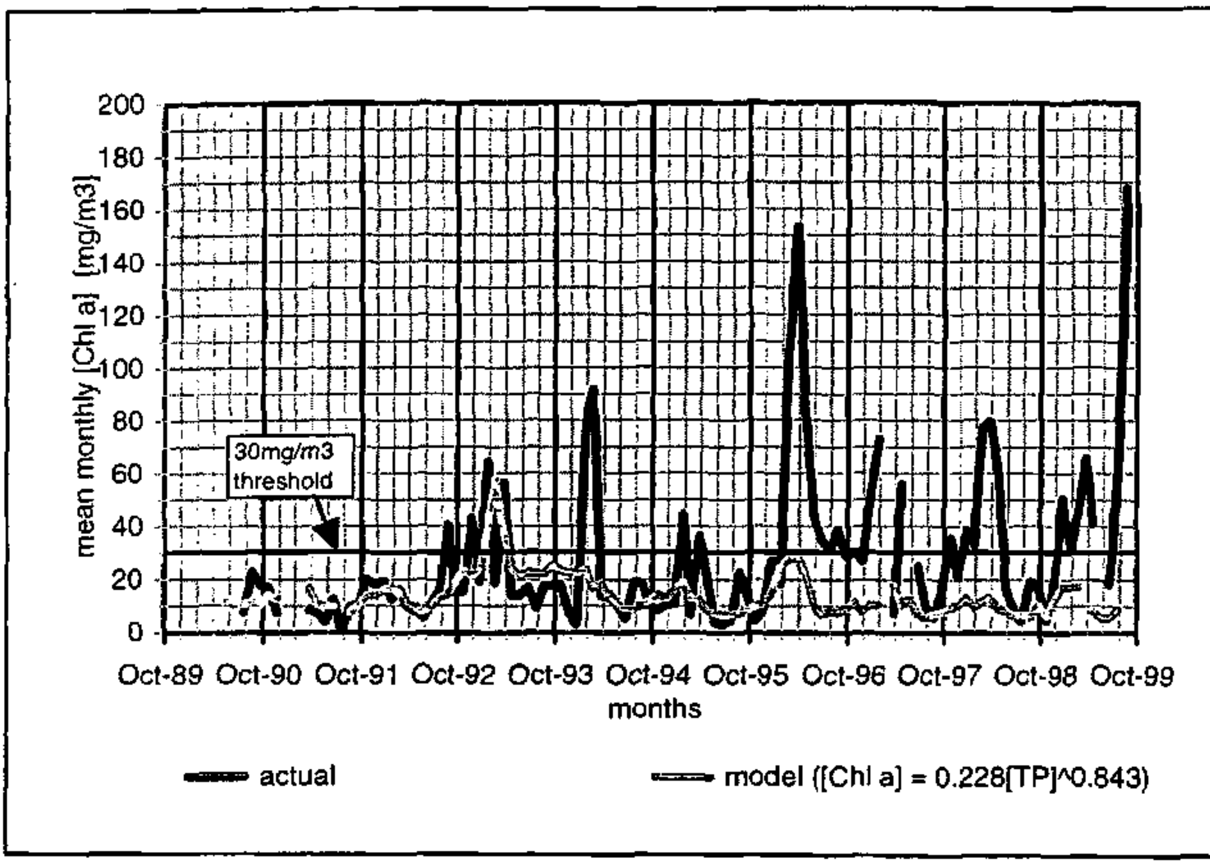

FIGURE 6.4:
NUTRIENT-ALGAE MODEL FOR HARTBEESPOORT DAM
SINGLE RELATIONSHIP

Another observation is that whereas the mean monthly [Chl a] concentrations were below the threshold value of 30 mg/m^3 for Severe Nuisance Conditions (Walmsley and Butty, 1980; Walmsley, 1984) up until February 1996, they have more regularly been above the threshold value since then.

Splitting of the data before and after February 1996, and performing separate regressions on the log-log scatterplots of the two sets revealed two distinctly different relationships, as follows:

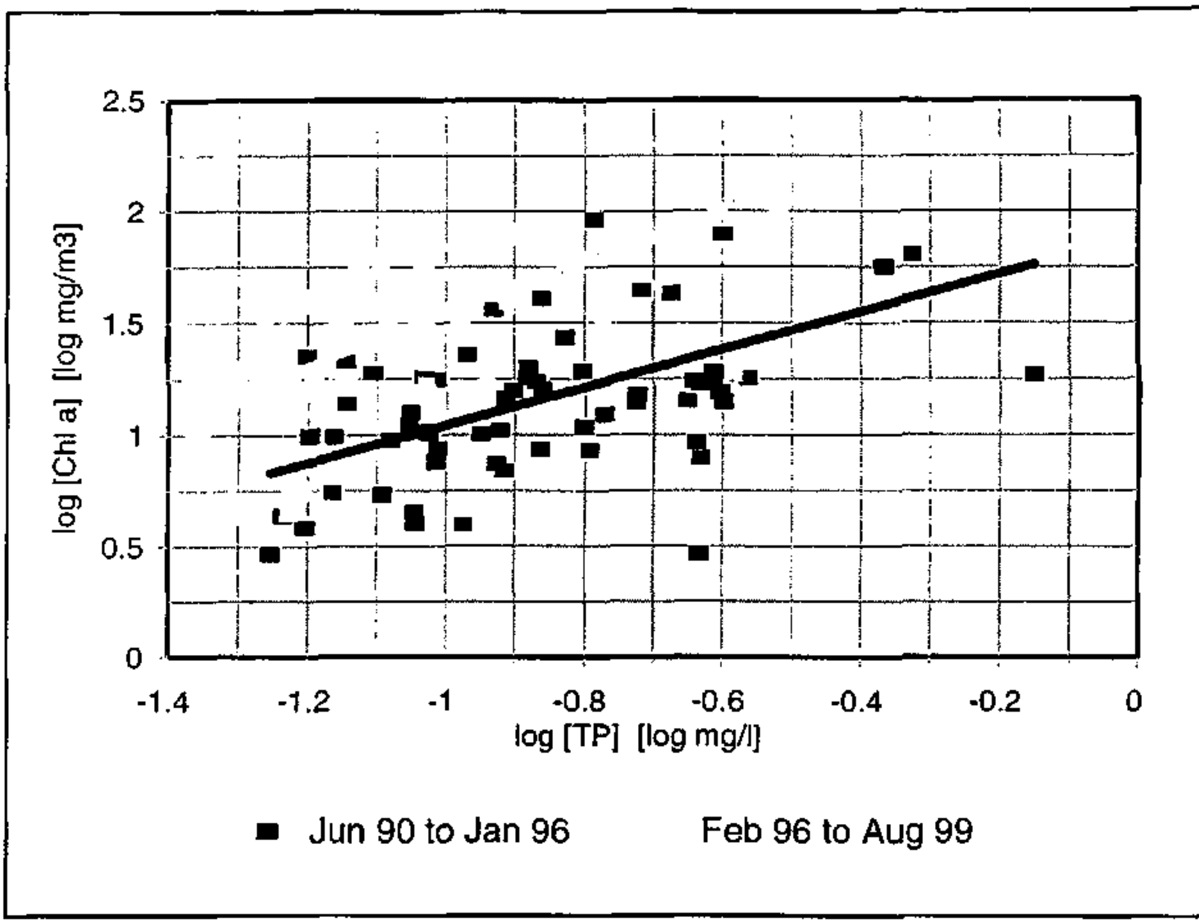

FIGURE 6.5:
NUTRIENT ALGAE LOG-LOG SCATTERPLOTS FOR HARTBEESPOORT DAM
(Separate relationships for 2 time periods)

Inspection of the data seems to indicate a distinct difference between the two time periods. Something appears to have triggered a change in algal response to the nutrient loading. A possibility would be an algal species shift. The cause of the trigger is a topic for further investigation.

A summary of the nutrient-algae relationships for Hartbeespoort Dam is given in Table 6.4.

TABLE 6.4:
NUTRIENT-ALGAE RELATIONSHIPS FOR HARTBEESPOORT DAM

Time period	*Relationship all units [mg/m3]*	*Relationship [Chl a] [mg/m3]; [TP] [mg/l]*
say 1980 to 1990	[Chl a] = 0.416 [TP]^0.675	[Chl a] = 44 [TP]^0.675
May 1990 to Feb 1996	[Chl a] = 0.228 [TP]^0.843	[Chl a] = 77 [TP]^0.843
March 1996 to Sep 1998	[Chl a] = 0.155 [TP]^1.175	[Chl a] = 519 [TP]^1.175

Plotted on normal axes, these relationships look as follows:

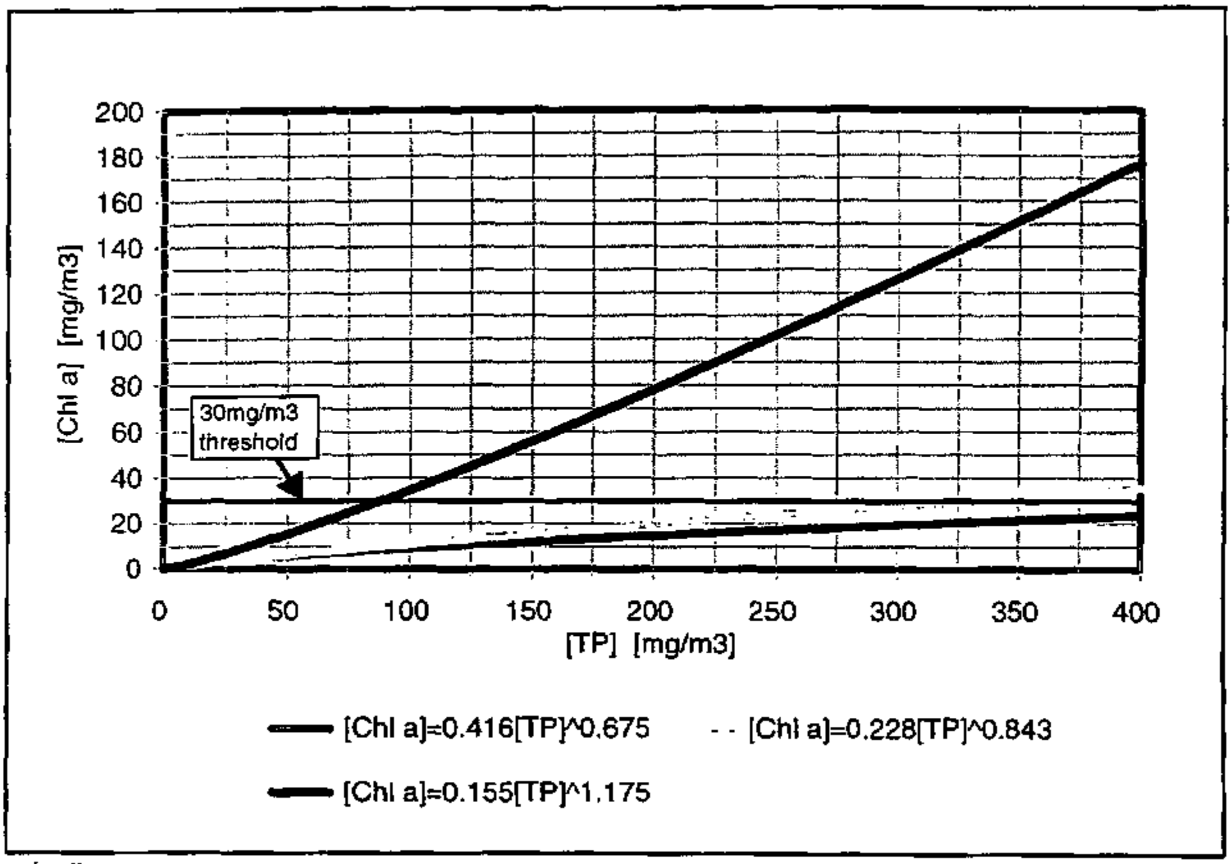

FIGURE 6.6:
NUTRIENT ALGAE RELATIONSHIPS FOR HARTBEESPOORT DAM

Using a combination of relationships to model the algal response produced a significantly improved correlation, which is shown in Figure 6.7.

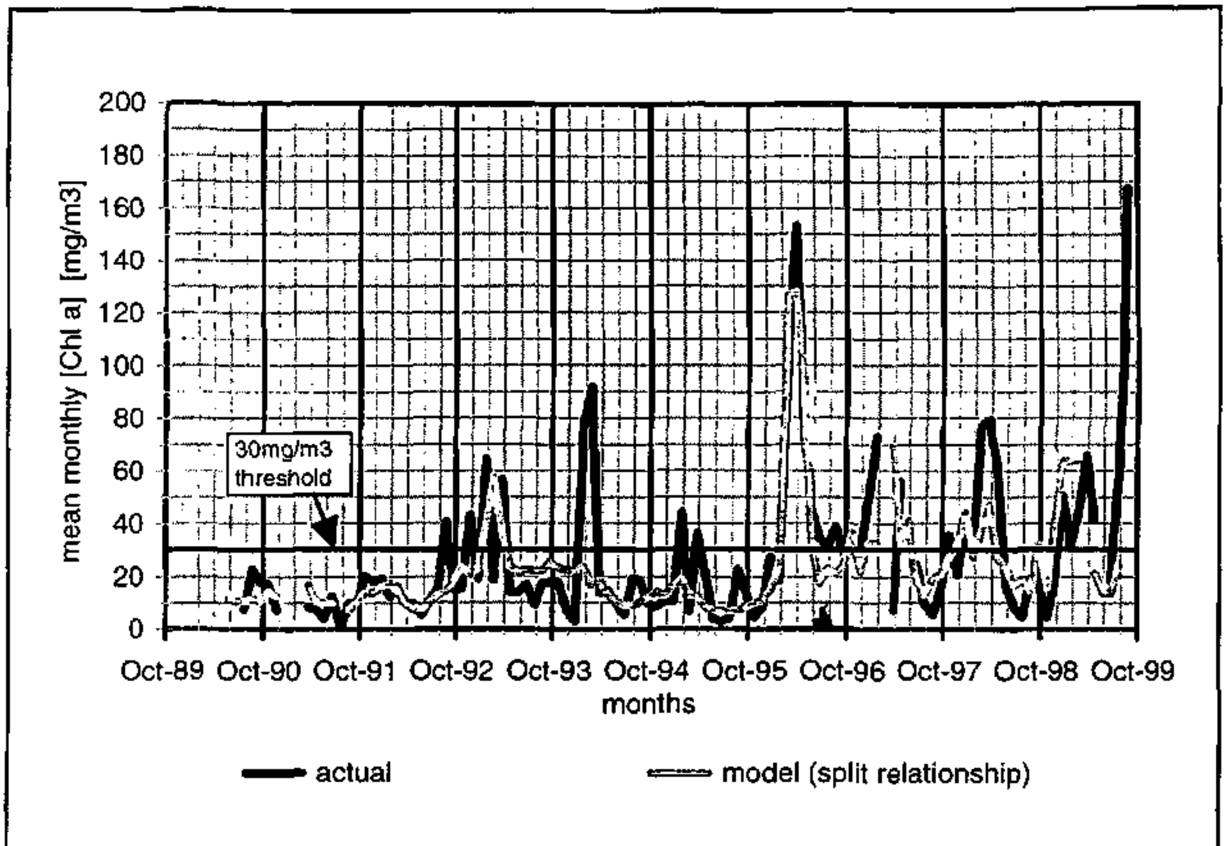

FIGURE 6.7:
NUTRIENT-ALGAE MODEL FOR HARTBEESPOORT DAM 1989-1998 SPLIT RELATIONSHIP

6.7 Extrapolation to the future

Having calibrated the models for the past, it was possible to extrapolate the models to the present and to construct a number of extreme scenarios for the future.

For population figures, SA Census data 1985, 1991 and 1996 were used, with the Urban Foundation adjustment factors applied to the 1985 census figures (Central Statistical Service, 1986, 1992; Statistics SA, 1998; Urban Foundation, 1990a). From these figures, growth rates were calculated, which were then used to interpolate between the overall figures. Growth rates were calculated by race and by magisterial district, applied separately to the different groups and then summed.

Water requirement projection demand growth rates were as follows:

TABLE 6.5:
WATER REQUIREMENT PROJECTION GROWTH RATES AS OF MARCH 1997 (Chatzistergou, 1998)

Period	*Yearly growth rate used for March 1997 projection applied to Rand Water only [%]*			*Yearly growth rate TR134 (1998) as applied to urban and non-strategic industrial [%]*		
	High	***Most Probable***	***Low***	***High***	***Most Probable***	***Low***
1996-1997	12.0	8.0	6.0	5.1	5.2	3.9
1997-1998	11.0	8.0	5.0	5.1	5.2	3.9
1998-1999	9.0	8.0	4.0	5.1	5.2	3.9
1999-2000	9.0	7.0	3.5	5.1	5.2	3.9
2000-2005	7.0	6.0	3.5	3.5	4.9	3.7
2005-2010	5.0	4.0	3.5	3.5	4.4	3.6
2010-2015	4.0	3.5	3.0	3.5	3.5	3.5
2015-2020	3.5	3.5	2.5	3.5	3.4	3.5
2020-2025	3.5	3.5	2.5	3.5	3.4	3.5
2025-2030	3.5	3.5	2.5	3.5	3.4	3.5

TABLE 6.6:
SUMMARISED WATER REQUIREMENT PROJECTION GROWTH RATES AS OF MARCH 1997 (after Chatzistergou, 1998)

Period	*Yearly growth rate used for March 1997 projection applied to Rand Water only [%]*			*Yearly growth rate TR134 (1998) as applied to urban and non-strategic industrial [%]*		
	High	***Most Probable***	***Low***	***High***	***Most Probable***	***Low***
1996-2000	10.24 say 10.25	7.75	4.62 say 4.6	5.1	5.2	3.9
2000-2010	6.0	5.0	3.5	3.5	4.65	3.65

There appears to be some sort of error in the TR134 growth figures in that the 'most probable' values are higher than both the high and low values. It is not immediately obvious by inspection of the tables which data are in error. Notwithstanding these uncertainties, it is possible to use the growth figures to extract a reasonable range of values for the purposes of the model.

A summary of the parameters used for the model for past present and future is given in Table 6.7 below.

TABLE 6.7:
SUMMARY OF PARAMETERS USED IN MODELLING THE COST OF ENVIRONMENTAL IMPACT OF SANITATION SYSTEMS IN HARTBEESPOORT DAM CATCHMENT, GAUTENG

	Parameter	*Past (1980-1998)*	*Present (2000)*	*Future (2010)*
1	*Planning*			
1.1	Population	SA Census 1980-1996 (1980 and 1985 adjusted by UF factors)	Extend at the same rates as 1991-1996; but leave white population constant; and use more moderate growth rates in place of extreme values.	Scenarios: (1) Present growth rates; assume same rates as for 1996-2000 = high (2) AIDS; assume population unchanged from 2000 = low (3) most likely (using Vaal demand study etc); overall figures for Gauteng distributed according to race group
1.2	Allocation to dam catchment	as per census data	as per adjusted population data	Scenarios: Take total Gauteng population *increase* (from 2000) and allocate as follows: (1) all to Hartbeespoort Dam catchment (2) all to Vaal Barrage catchment (3) all to Soshanguve and south-east of Pretoria (4) most likely (different percentages to the 3 areas, following GSPF)
1.3	LOS	Difference in population and water demand growth rates indicates change in LOS (and water use) Assume only WB for low-income 1980-1990 Increasing LOFLOS 1990-1995 Chemical toilets for new low-income population 1995-1998	Chemical toilets for new low-income population 1999-2000	Scenarios: (1) all new = WBc (2) all new = WBe (3) all new = LOFLOS (4) all new = VIP (5) most likely

	Parameter	*Past (1980-1998)*	*Present (2000)*	*Future (2010)*
2	*Water quality*			
2.1	Actual flow	Total adjusted streamflow DWAF 1980-98 A2H012, A2H013 1980-1998	Sum the individual components set out below	Scenarios: Sum the individual components set out below
2.2	Naturalised flow	A2H012 and A2H013 data available 1922-1989 as per WR90		Scenarios: (1) 2 x MAR = wet (2) 0.25 x MAR = dry (3) MAR = average
2.3	Irrigation	From irrigated areas and rainfall data, can estimate up to 1989 from WR90; can get more irrigated areas from SSI.		
2.4	Urbanisation	A2H012: 5.37% pa growth (corresponding to Rand Water long term water demand growth); have areas from SSI + population, therefore can estimate urbanisation percent.		
2.5	Point source	A2H012: Assume total=Nwks+Alex/0.42 7.5% growth A2H013: none		Scenarios: Dependent on LOS (for domestic) + commercial/industrial effluent flows
2.6	Grey water wash-off	Total contaminant loads as measured	Extrapolate contaminant loads from past	Scenarios: (after Ashton and Grobler, 1988) (1) 10% wash-off (2) 90% wash-off
2.7	Dam levels + operating rule	1980-1998: as per DWAF data		
2.8	Sedimentation coefficients	pre-1990: as per REM 1990-1998: s1=0.3; s2=0.6	1990-1998: s1=0.3; s2=0.6	Scenarios: (1) as per 1990-1998 = low in-lake [P] (2) as per REM = high in-lake [P]
2.9	Nutrient algae	1980-1990: REM May 1990-Feb 1996: slightly higher than REM Mar 1996-Sep 1999: significantly higher than REM	Significantly higher than REM	Scenarios: (1) REM = low (2) significantly higher than REM = existing (3) higher than existing = high

Using combinations of scenarios, such as set out in the above table, it is possible to model a range of sanitation scenarios and the consequent cost of pollution.

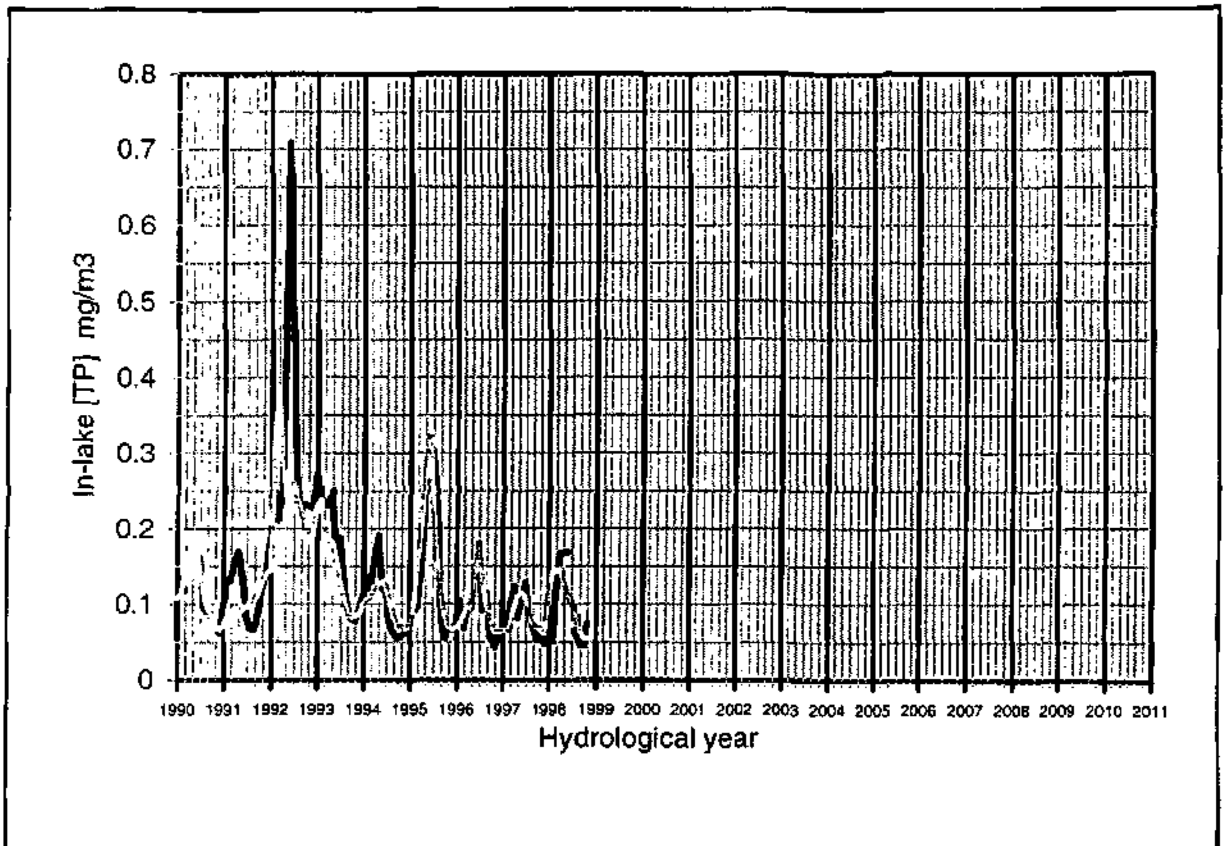

FIGURE 6.8:
IN-LAKE NUTRIENT CONCENTRATION FOR HARTBEESPOORT DAM 1990-2010

7 APPLICATION OF MODEL TO GAUTENG PROVINCE

Using the approach described for the Hartbeespoort Dam catchment, the cost of pollution from sanitation systems in other catchments can be determined. The upper limit on unit cost of treatment was indicated earlier. Catchment-specific parameters may cause the cost to vary below that limit.

To give some indication of current contamination, loads of sewage in the different catchments (from WR90) (understood to be 1989) is given below:

TABLE 7.1:
POINT SOURCE FLOWS BY IMPOUNDMENT CATCHMENT IN GAUTENG

dam	*tributary*	*catchment*	*discharger + type*	*approx volume [$10^6m^3/a$]*
Hartbeespoort	? (west)	A21F A21G	(1) Maloney's Eye -	16.0
	Crocodile (north)	A21D	(1) Krugersdorp Percy Stewart works (treated sewage) (2) Randfontein works (treated sewage)	3.3 5.5
		A21E	(1) Roodepoort Driefontein works (treated sewage)	3.4
		A21C	(1) AECI (industrial effluent; including Kelvin Power Station and Kempton Park Esther Park works treated sewage) (2) JHB Alexandra works (treated sewage) (3) JHB Northern works (treated effluent) (4) Midrand works (treated sewage)	11.7 7.5 36.9 0.7
	Hennops (east)	A21B	(1) Olifantsfontein works (treated sewage) (2) Verwoerdburg works (treated sewage)	11.9 5.8
	dam environs	A21H	(1) Pelindaba (industrial effluent) (2) UCOR/Valindaba	0.4 1.0
Rietvlei (continues into Hartbeespoort)	Rietvlei	A21A	(1) Elandsfontein Oog (natural spring) (2) Kempton Park Hartbeesfontein works (treated sewage) (3) Kempton Park Rietfontein new works (treated sewage)	1.1 4.2 12.4

dam	*tributary*	*catchment*	*discharger + type*	*approx volume [$10^6 m^3/a$]*
Bon Accord	?	A23D	(1) ISCOR steelworks (industrial effluent) (2) Pretoria Daspoort works (3) Pretoria West power station	0.5 8.2 4.9
		A23E (northern parts)	(1) Pretoria Rooiwal works? (2) Rooiwal power station?	45.1 2.8
Roodeplaat	?	A23A	(1) Pretoria Baviaanspoort works (treated sewage)	7.5
Rust der Winter	?	B31A B31B B31C	- - -	
Bronkhorstspruit (continues into Loskop)	?	B20A	(1) Delmas municipality (treated sewage)	0.6
		B20B B20C	- -	
Loskop	Wilge?	B20D	(1) Bronkhorstspruit municipality (treated sewage)	1.0
		B20F B20G B20H B20J (small portion?)	- - - -	
Boskop		C23D	(1) Venterspost Mine (mining effluent) (2) West Rand Consolidated Mine (mine effluent)	11.5 3.0
		C23E	(1) Blyvooruitzicht Mine (mining effluent) (2) Doornfontein Mine (mining effluent) (3) Driefontein Mine (mining effluent) (4) Western Deep Levels Mine (mining effluent)	2.8 3.0 22.0 1.5
		C23F C23G	- -	

dam	*tributary*	*catchment*	*discharger + type*	*approx volume [$10^6 m^3/a$]*
Vaal Barrage	Rietspruit	C22H	-	
		C22J	(1) ISCOR (industrial effluent) (2) Western Areas Mine (mining effluent)	10.2 20.0
	Klip	C22A	(1) Durban Deep Mine (mining effluent)	5.7
		C22B	(1) Boksburg (treated sewage) (2) ERPM Mine (mining effluent) (3) Germiston (Rondebult) (treated sewage) (4) Germiston (Dekima) (treated sewage) (5) Germiston (Waterval) (treated sewage)	19.4 9.0 12.0 16.4 15.1
		C22C	(1) SA Lands Mine (mining effluent) (2) ERGO Mine (mining effluent)	6.0 10.0
		C22D	(1) Johannesburg (Olifantsvlei) (treated sewage) (2) Johannesburg (Goudkoppies)	38.0 25.0
		C22E	-	
	Suikerbosrand	C21A	-	
		C21B	-	
		C21C	-	
		C21D	(1) Brakpan (treated sewage) (2) Benoni (Benoni works (treated sewage) (3) Benoni (Rynfield works) (treated sewage) (4) SAPPI (industrial effluent)	2.6 6.3 3.7 9.8
		C21E	(1) Grootvlei Mine (mining effluent) (2) Springs (treated sewage) (3) Nigel (treated sewage) (4) Tsakane (treated sewage)	3.0 4.4 2.0 2.7
		C21F	(5) Heidelberg (treated sewage)	1.7
		C21G	-	

8 CONCLUSIONS, RECOMMENDATIONS and FURTHER WORK

A key output of this study has been to differentiate between those matters which have been satisfactorily resolved for the purpose of decision-making and those which have not. The conclusions, recommendations and further work have therefore been included in a single chapter.

The project has asked: 'What recommendations can one make on the basis of the available data? What further data does one need? Where is there sufficient data and where is there insufficient data? What major questions remain unanswered? What direction do we go in from here?

8.1 Conclusions

Conclusions from this study are as follows:

Re-statement of conclusions from previous studies

The following conclusions from previous studies require re-stating:

1 *All* sanitation systems contaminate the environment to *some* extent, although characteristics of the contamination may differ between different levels of service (LOS).

More specifically:

2 The subsoil conditions of on-site sanitation systems need to be permeable enough, and the soakaways need to be big enough to ensure that effluent does not surface, but remains in the sub-surface.

3 If it does *not* remain in the subsurface, but surfaces onto the ground surface, it firstly poses a direct health risk from microbiological contaminants for the users of the sanitation system (and their immediate community), and secondly is also susceptible to being washed off the surface by rainfall directly into surface watercourses.

4 If it *does* remain in the subsurface, then there is minimal health risk from microbiological contaminants to users (and their immediate community). The microbiological contaminants are generally filtered out in the subsurface within a short distance (of the order of metres). Phosphorus is generally adsorbed in the subsurface and travels very little distance at all. Nitrogen in the form of nitrate is removed to varying degrees in the subsurface, depending on the conditions there. The remaining nitrate acts like a tracer, and remains in the subsurface. While very little nitrogen may be removed once it has been transported into a zone of the subsurface that is poor in organic material, the transport of contaminants is very slow.

5 While phosphorus tends to be removed efficiently in the subsurface for on-site sanitation systems, for water-borne systems phosphorus (even if a substantial proportion is removed in the treatment process) is discharged directly to the surface watercourse. Discharge into the surface watercourse is virtually immediate, and can be a significant source of contamination.

Methodology

1 Cost of environmental impact needs to be added to the cost of provision of sanitation infrastructure (i.e. construction, operation and maintenance) in order for a fair comparison to be made of different levels of service.

2 The method is a useful planning tool, but needs further refinement in input data. It is very important to remember what one needs data for. Data for decision-making makes

demands which can be unexpectedly at variance with scientific endeavour. A key characteristic of the method proposed in this study is the objective of getting into the *right 'ball-park'* with the costs. If they are borderline, then they require further investigation.

3 There is a strong case for environmental planning to be done at provincial level - or even more broadly - although priorities and trade-offs may need to be made at the local level.

Planning

1 In Gauteng, 60% of the population live in the Vaal Barrage catchment area; 25% in the Hartbeespoort Dam catchment area, 12% in the combined catchments of Rietvlei, Bon Accord, Roodeplaat and Boskop Dams. (Based on figures for 1990; the *proportions* are unlikely to change much in the period up to 2010). 85% of the Gauteng population therefore falls within the Vaal Barrage and Hartbeespoort Dam catchments. In terms of cost of impact, the major impact of sanitation is felt in the above catchments in the same order.

2 Almost as critical as the fact that most of the Gauteng population falls within two *impoundment* catchments is the fact that most of the population is concentrated in two *sub-catchments*: Crocodile/Jukskei/Hennops Rivers (A2H012 weir) and Klip River.

3 In terms of LOS, the provincial boundaries are critical. Low LOS are on the fringes or just beyond the boundaries of Gauteng. This highlights the difference between Gauteng and Region H. Virtually all sanitation in Gauteng is water-borne.

4 There is a temptation to suggest that because virtually all sanitation in Gauteng is water-borne, one should simply stick to water-borne sanitation throughout and not bother with a small percentage of on-site sanitation. The response to that is that it is really an anomaly of administrative boundaries. Across the boundary of the province, the situation is very different. The principles that are applied in Gauteng need to be consistent with other areas, particularly those just across the boundary. If that is not done, then one may find policies in one area undermining policies in neighbouring areas (which are under different jurisdiction; as has been the case in parts of Kwazulu-Natal where the administration has been so fragmented in the past). The need for some kind of cross-boundary consistency has been recognised by the demarcation board in the setting up of cross-boundary (i.e. provincial boundary) local authorities.

5 Because on-site sanitation currently makes up such a small percentage of the sanitation in the impoundment catchment, it is not really feasible (at the level of resolution of the data) to identify the contribution of on-site sanitation to the pollutant load with the desirable level of certainty. One could provide upper and lower bounds (from the diffuse source loads, together with theoretical analysis).

Water quality

1 Taking account of the range of permeabilities found in Ivory Park and Orange Farm, as well as the fact that the rate of movement in the *unsaturated* zone of the subsurface is significantly lower than that for the *saturated* zone, the rate of movement of contaminants in the subsurface in Gauteng can be taken to be of the order of 1 to 10m/a. The rate of movement of contaminants by wash-off from the ground surface, transport within the surface watercourse to an impoundment in Gauteng can be of the order of 50km in 2-3 days, or a month at the most. There is a difference of about 5 orders of magnitude between the two rates. Subsurface movement of contaminants, with the geological

conditions encountered in Gauteng (taking Ivory Park and Orange Farm as typical), is therefore unlikely to impact on water resources in any significant way within a 10 year frame. Surface wash-off and transport of contaminants, on the other hand, is likely to impact well within a 1 year time frame.

2 There was considerable *variability of the contaminant load data* - both from the wastewater treatment works (WWTW) as well as from diffuse sources. There was also a poor relationship between discharge from sewage treatment works and discharge into the lake - which was surprising. In particular, 'spikes' in contaminant loading from the WWTW in the Hartbeespoort Dam catchment could not be identified at the entrance to the lake (at weir A2H012), even with lag effects being taken into account. Also of note is the fact that the concentration of PO_4-P entering Hartbeespoort Dam at weir A2H012 was virtually the same as the concentration of effluent leaving the Northern works (WWTW) some 30km away.

3 The *effect of the wetlands on the Klip River* was not investigated in depth in this study. The effect of wetlands on the nutrient loading on the Vaal Barrage - certainly compared with Hartbeespoort Dam - may be very significant.

4 The *existing* (REM) models for both nutrient budget and nutrient-algae poorly described lake response in Hartbeespoort Dam over the past 10 years.

5 Accounting only for phosphorus, a (modified) nutrient-algae model adequately (for the purposes of this study) described the lake response. This implies that even if the lake is nitrogen-limited at certain select times, the effect of phosphorus is overriding.

6 By comparison with water-borne sanitation discharges - even from well-functioning WWTW meeting the special standard of 1mg/l PO_4-P - pollution from on-site sanitation is negligible. The 'wild card' is grey water; although the effect is not completely random in that if the contaminants remain in the subsurface, it isn't a problem. It needs some serious attention. A controlled experiment may be the best approach to further investigation. Pillay by her assumptions suggested that it was negligible. Ashton and Grobler in their Botshabelo study identified it as a critical question, and presented a range of scenarios.

7 Nitrate contamination of groundwater *will* occur. In Gauteng, contamination of groundwater has *already* occurred (e.g. in Soshanguve). Groundwater is certainly a strategic resource. Dolomitic areas need special consideration. However, fractured rock aquifers are small.

8 It has been assumed in this study that one is only concerned with human wastes i.e. that one is able to address the problem of inorganic salts, refractory organics, heavy metals etc by other means - and at source.

9 Because WWTW effluent standards are concentration-related (e.g. 1mg/l PO_4-P), one needs to keep an eye on growth of household water consumption (and hence sewage flow) for the full water-borne (WB) LOS. The reason is that if the flow volume doubles (for the same concentration of contaminants), then the *mass load* doubles (while still meeting the effluent standard). That can have a serious effect on the receiving impoundments. *Mass load* may well be a more appropriate measure for monitoring contaminant levels than *concentration.*

10 In terms of environmental impact, there is little difference between basic (e.g. the VIP) and intermediate on-site sanitation systems (e.g. the LOFLOS).

Costing

1 For all water treatment - both surface water and groundwater - the cost is a *step-wise function* as one moves to new processes in the treatment train, with deteriorating raw water quality.

2 *Costs of surface water treatment:* For the smaller sized - i.e. 50Ml/d - plant capacity (2000 costs) the cost sequence for different process combinations is estimated as follows:

- conventional (settling and filtration) 30c/kl
- conventional + flotation 37c/kl
- conventional + PAC 36c/kl
- conventional + GAC 50c/kl
- conventional + flotation + GAC + ozone 65c/kl

For a large capacity works (i.e. 200Ml/d) water treatment costs are about 20-25% lower than the above figures.

3 *Maximum* additional cost of surface water treatment to deal with poor quality raw water roughly *doubles* the costs of conventional treatment. For a relatively small works (50Ml/d) the magnitude of the increase (from 30c/kl to 65c/kl) amounts to about 35c/kl. For a larger works (200Ml/d), the proportional increase would remain about the same, but the magnitude of the increase would be somewhat less - about 30c/kl.

4 *Costs of groundwater treatment:* Treatment of groundwater resources is considerably more expensive than the treatment of surface water resources - with groundwater treatment ranging between R1.60/kl and R3.15/kl depending on plant capacity and process.

5 Because groundwater is generally not treated before use (in certain cases, it may be disinfected), the *additional* cost of treatment due to poor raw water quality for groundwater is suggested to be the *full* cost of treatment. This may not be entirely reasonable, but is suggested as a *very worst case* scenario for the purposes of this study.

6 Assuming this to be the case, the *additional* cost of groundwater treatment is somewhere between 4 and 9 times the *additional* cost of surface water treatment (30-35c/kl).

7 *Costs of provision (i.e. construction, operation and maintenance) of the different levels of service of water supply and sanitation* in Gauteng (2000 costs) are:

- Stand-pipe and VIP (basic) R130/cap.a
- Yard tap and aqua-privy (intermediate) R160/cap.a
- House connection and water-borne sanitation (full; *essential* use) R260/cap.a
- House connection and water-borne sanitation (full; *convenience* use) R530/cap.a

8 Assuming a maximum yield (assumed to be natural MAR) for the Gauteng portion of the catchment of the Vaal Barrage downstream of Vaal Dam - essentially consisting of the catchments of the Suikerbosrant River (C21) and the Rietspruit/Klip River (C22) - of 275Mm^3/a at an additional unit cost of treatment of 30c/m^3, the total *additional* cost of treatment will amount to R82.5, say R83million/a. For a population of 4.5 to 5million people in the catchment (in 2000), this translates to only R18, say R20/cap.a. At the lower concentrations of contaminants, it will increase the use of PAC (say 7c/kl), which amounts to less than R4/cap.a.

9 A key requirement is that the (clean) water imported from Lesotho Highlands should not be mixed with (contaminated) water from the Vaal Barrage (requiring more sophisticated treatment processes).

10 Similar calculations to those for surface water can be made for the use of groundwater resources. Assuming a maximum yield (assumed to be the Groundwater portion of the Groundwater Harvest Potential) for the Gauteng portion of the catchment of the Vaal Barrage downstream of Vaal Dam - essentially consisting of the catchments of the Suikerbosrant River (C21) and the Rietspruit/Klip River (C22) - of 125Mm^3/a at an additional unit cost of treatment of R1.90/m^3, the total *additional* cost of treatment will amount to R237.5, say R238million/a. For a population of 4.5 to 5million people in the catchment (in 2000), this translates to only R53, say R50/cap.a.

11 For the Gauteng portion of the catchment of the Vaal Barrage downstream of Vaal Dam, the sustainable yield of groundwater is about *half* that of the surface water. The additional cost of treatment of groundwater due to deteriorated raw water quality is about *five* times the equivalent additional cost of treatment for surface water. Translated to a cost per person per year, the additional cost of treatment of groundwater is therefore about 2.5 times the equivalent cost for surface water treatment. However, with current utilisation of groundwater of this catchment only about 6% (7.5Mm^3/a) of the maximum yield, this cost is still far from being realised.

12 By comparison with the costs of a higher level of service of water supply and sanitation, the maximum additional costs of treatment are small. For surface water, the additional cost of treatment (R20/cap.a) is only about 15% of the difference in cost between a basic and a full level of service (*essential* use) (R130/cap.a). If water usage for the full level of service increases towards *convenience* use, then the relative cost of treatment will drop even more. For groundwater, the additional cost of treatment (R50/cap.a) is about 40% of the level of service cost difference.

13 In summary, even *conservative* (i.e. high) estimates of additional treatment costs (either surface water or groundwater), *fully* (i.e. very conservatively) assigned to pollution from sanitation systems, are still *well less than half* the cost difference between basic and full (essential use) levels of service of water supply and sanitation (based on the particular catchments used in the analysis).

Application of model to Hartbeespoort Dam

1 From 1990 sanitation figures, there are not that many people with inadequate sanitation in Gauteng. Most are in the 'fringe' areas. These will start to be included in the cross-boundary municipalities; but if one is looking at Gauteng only, there isn't a massive problem. 90% have full water-borne sanitation.

2 Based on estimated population figures and effluent flows from WWTW, water usage for sanitation in the Hartbeespoort Dam catchment appears to be considerably higher than (about double) the figures originally estimated for that level of service. The variation in flow is large enough to warrant more than one level of service for water-borne sanitation (e.g. low level use and high level use); although it is likely that there will be less variation in per capita contaminant loads than in per capita flows. It is unclear whether these changes in water usage occur evenly, in which case more than two (say three i.e. low, medium and high) levels of service for water-borne sanitation may be necessary, or whether there is a step-wise change, in which case the two levels of service may suffice.

3 A not unreasonable flow/TP relationship, which *aggregated* both point and non-point sources, could be identified at weir A2H012. Such a flow/load relationship could *not* be established for Northern works alone; nor could it be established for weir A2H012 minus Northern works. This is anomalous. A possible explanation is that there is in-stream

sedimentation of P, and transport of this P into Hartbeespoort Dam is more dependent on general stream flow than on discharge from the WWTW. This is also supported by the fact that spikes of PO_4-P discharged from WWTW are not evident in the flows entering Hartbeespoort Dam; neither is any clear lag evident between discharge from WWTW and entry into Hartbeespoort Dam (in contrast to what Pillay found for Inanda Dam). To draw any further conclusions would require more detailed analysis.

4 The response of the lake to contaminant loads is not static. In particular, it appears that either an algal species shift or a change in the response of the algae to nutrient load can be triggered by events such as floods or droughts. These changes in lake response overshadow any changes in nutrient loading. The increased incidence of algal blooms in Hartbeespoort Dam since February 1996 has not been as a result of increased contaminant loading, but rather as a result of changed lake response, which appears to have been triggered by the high flows and contaminant loads of February 1996. Once the shift had occurred, the lake did not revert to its earlier response characteristics.

5 In terms of allocation of the cost of pollution, approximately *half* of the increased cost of surface water treatment as a result of deteriorated water quality could be attributed to sanitation systems, and most of this to full water-borne sanitation.

General comments + conclusions

1 While in themselves, most of these findings are not entirely new (virtually all of them are based on *existing* data), it is the *implication* or *significance* of a finding in one area (e.g. planning) for another area (e.g. water quality) that is particularly noteworthy.

2 Water-borne sanitation (WB) discharges directly to the surface watercourses. It is currently the major contributor to pollution (primarily phosphorus) from sanitation systems in Gauteng.

3 Even effluents meeting the effluent quality standards have a major impact on water bodies; and, added to that is the fact that a number of the sewage treatment works do not meet the standards at all times.

4 The situation in Gauteng with respect to sanitation provision and consequent pollution over the next 10 years appears to be slow to change: It appears that it is water-borne sanitation that is - and will continue - to have the major effect on lakes in Gauteng (with a bit of a 'wild card' being diffuse load washed off the *surface*). Although one can get significant changes in demographics, settlement patterns and LOS at a local (i.e. municipal) level in a relatively short space of time (say, of the order of two or three years), it takes a fairly extended period of time (say, of the order of a decade or two) to change the overall patterns of a large area such as Gauteng.

5 Unless the 'polluter pays' principle is established, there is little incentive to use a cheaper system than full water-borne systems.

6 With return flows from WWTW making up such a large proportion of the flow into impoundments such as Hartbeespoort Dam, it is becoming difficult to separate out issues of quality from issues of quantity. More specifically, some service providers may prefer to use (and treat) return flows of poor quality rather than import expensive but excellent quality water through inter-basin transfer schemes.

7 Environmental impact is one of several factors to be considered in the choice of level of service of sanitation. It is important not to confuse these different factors. Environmental impact should *not* be given as the reason for not using a particular system, when in fact the reason is motivated by other considerations, such as promotion of equity among users.

8.2 Recommendations

In the light of the above conclusions, the following recommendations are made:

1 That the method of pollution costing proposed in this study be *adopted* as an input to deciding whether or not to use on-site sanitation;
2 That policy regarding sanitation use be set at *provincial level - or higher* i.e. at national level - and that DWAF (as custodian of the country's water resources) issue permits for the use of on-site sanitation;
3 That a *workshop* be held to publicise the results of this work, and to identify priority areas for implementation and further development of the principles proposed in this study.

8.3 Further work

Critical issues that require further investigation include the following:

1 The environmental impact of grey water discharged to the ground surface;
2 The mechanisms surrounding changes in the response of algae to nutrient loads - and possible interventions to control this;
3 The stages at which new water treatment processes need to be introduced to deal with deteriorating raw water quality;
4 Quantitative estimates of the costs of loss of recreation and property value as a result of deteriorated impoundment water quality;
5 Clearer identification of the characteristics of natural resources (including both quantity and quality) and the 'ownership' of these.

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APPENDIX: SPREADSHEET MODEL OUTPUT

The output of the spreadsheet model, applied to the surface water component of the Hartbeespoort Dam catchment for hydrological year 1990 (October 1990 to September 1991) is given in this appendix.

Explanatory comments are as follows:

1 The spreadsheet is intended to be supplementary to - and illustrative of - the methodology described in the report.

2 Hartbeespoort Dam catchment consists of 2 main tributaries: Crocodile River (DWAF weir A2H012) and Magalies River (DWAF weir A2H013). Both the flow and nutrient load from the Magalies River are small by comparison with the Crocodile River.

3 Population is allocated to the two subcatchments using the allocation factors given in Table 3.9 (p.44). It may be seen that by far the majority of the population (89.7%) is allocated to full water-borne sanitation (convenience use i.e. Wbc).

4 Applying the unit flows and contaminant loads given in Table 4.16 (p.78), total flows and mass loads are calculated. Of key importance for Hartbeespoort Dam is the load of 79tP/a discharged to the surface water. Also of note is the flow of 99 Mm^3/a, which is in reasonable agreement with total point source flow for 1990 of about 110 Mm^3/a (lower line in Figure 6.1, p.129), although somewhat on the low side - especially seeing that all WB sanitation has been allocated to convenience use (i.e. high water use).

5 Actual monthly TP loads for the A2H012 weir (rather than theoretical loads), together with actual flows from the dam balance are used as input to a modified RSEM nutrient budget model (Equation 4.14b, p.19; using s1=0.3, s2=0.5) to determine the monthly P concentration in the lake. Actual P concentration are given for comparative purposes.

6 Actual in-lake P concentrations are then used in the appropriate nutrient-algae relationship given in Table 6.4 (p.133) to obtain monthly values of [Chl a]. The actual [Chl a] concentrations are also given - again, for comparative purposes.

7 In the costing section, a train of treatment processes is selected depending on the [Chl a] values relative to the threshold value of $30mg/m^3$. To produce an upper bound value of cost, the highest treatment processes (conventional treatment plus flotation, GAC and ozone) are selected at a cost of 65c/kl - 35c/kl more than the standard process train (see Table 5.5, p107, and further explanation on the following page). With actual [Chl a] of around $10mg/m^3$, this would not be necessary in practice.

8 Total additional treatment cost is then calculated for various annual volumes of treated water, which might range from the average streamflow (200 Mm^3/a, assuming an average hydrological year including all flows) to the actual flow for 1990 (slightly lower than that at 182 Mm^3/a) and down to a low value of the average naturalised run-off of the catchment assume no development (69 Mm^3/a).

9 From these values, total additional costs of treatment are obtained ranging between about R25-70m/a.

10 These costs are then allocated the sanitation in proportion to TP load (in this case, based on a sanitation TP load of 79tP/a compared with a total TP load for the catchment of 171.28tP/a - see lake response section of the model - giving a factor of 0.46. The factor of 0.46 indicates that roughly *half* of the additional cost of treatment required as a result of deteriorated raw water quality in Hartbeespoort Dam may be attributed to sanitation - and most of it to water-borne sanitation in this case.

11 Based on the population, this is converted to a cost per capita of between say R8-25/cap.a.

CATCHMENT ALLOCATION and LOS

District	1990 Gauteng	A2H012 Crocodile	A2H013 Magalies	97.7% A2H012 Crocodile	2.3% A2H013 Magalies	89.7 WBc	WBe	2.1 SEP	5.5 LOFLOS	0.0 VIP	1.2 BU	CHEM	1.4 NON
total	**6335003**			**1526621**	**36710**	**1369167**		**32454**	**84000**	**200**	**18900**		**21900**
Greater Johannesburg	**2132812**			**709841**	***0***								
Johannesburg	712593	0.5		356297		356297							
Soweto	870947												
Randburg	331796	1		331796		266842		27154			18900		18900
Roodepoort	217476	0.1		21748		21748							
Greater East Rand	**1784492**			**343958**	**0**								
Alberton	356657												
Benoni	282746												
Boksburg	194333												
Brakpan	125512												
Germiston	171432	0.5		85716		85716							
Heidelberg	71989												
Kempton Park	344323	0.75		258242		169142		5100	84000				
Nigel	76612												
Springs	**160888**												
West Rand	**632756**			**175359**	**36710**								
Krugersdorp	194843	0.9	0.1	175359	19484	172359							3000
Oberholzer	171971												
Randfontein	114840		0.15		17226								
Westonaria	151102												
Greater Pretoria	**1125398**			**297463**	**0**								
Bronkhorstspruit	39533	0.05		1977		1577		200		200			
Cullinan	32263												
Pretoria	656573	0.43		282326		282326							
Soshanguve	133827												
Wonderboom	263202	0.05		13160		13160							
Vaal	**659545**			0	0								
Vanderbijlpark	419865												
Vereeniging	239680												

FLOWS and CONTAMINANT LOADS

Unit flows and loads

		WBc	WBe	SEP	LOFLOS	VIP	BU	CHEM	NON
to surface water									
Flow	l/cap.d	200	100				2	2	
TP	gP/cap.d	0.16	0.08				0.0016	0.0016	
TN	gN/cap.d	2.5	1.25				0.025	0.025	
COD	gO2/cap.d	8	4				0.08	0.08	
to ground surface									
Flow	l/cap.d				26.5	28			20
TP	gP/cap.d				0.88	0.88			2.5
TN	gN/cap.d				3	0.6			10
COD	gO2/cap.d				30	6			100
to groundwater									
Flow	l/cap.d			200	3.5	2			
TP	gP/cap.d				0.6	0.6			
TN	gN/cap.d				3	4.5			
COD	gO2/cap.d				7	12			

Total flows and loads

		WBc	WBe	SEP	LOFLOS	VIP	BU	CHEM	NON
to surface water									
Flow	Mm3/a	99	0				0	0	
TP	**tP/a**	**79**	0				0	0	
TN	tN/a	1232	0				0	0	
COD	tO2/a	3943	0				1	0	
to ground surface									
Flow	Mm3/a				1	0			0
TP	tP/a				27	0			20
TN	tN/a				91	0			79
COD	tO2/a				907	0			788
to groundwater									
Flow	Mm3/a			2	0	0			
TP	tP/a				18	0			
TN	tN/a				91	0			
COD	tO2/a				212	1			

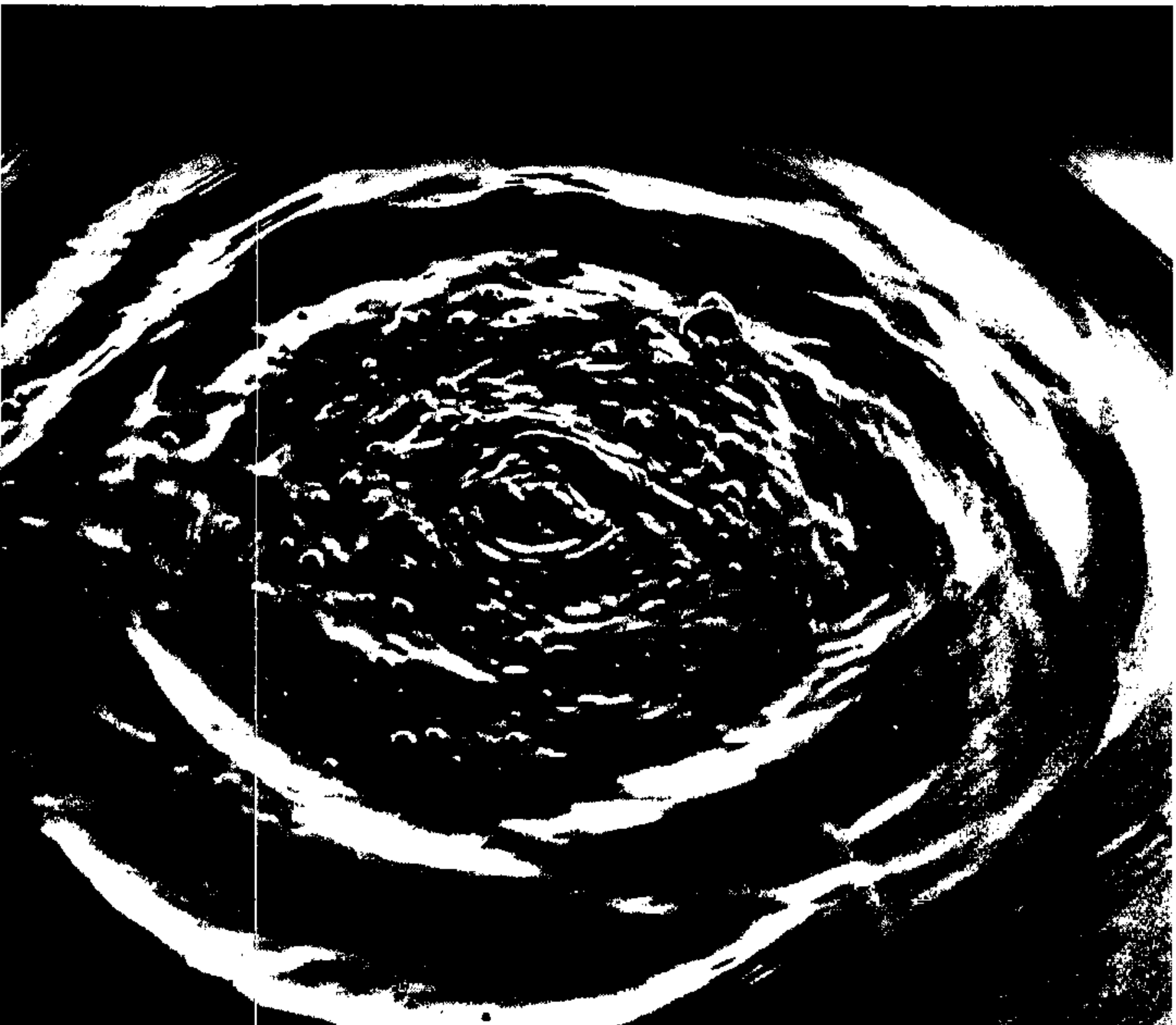
LAKE RESPONSE

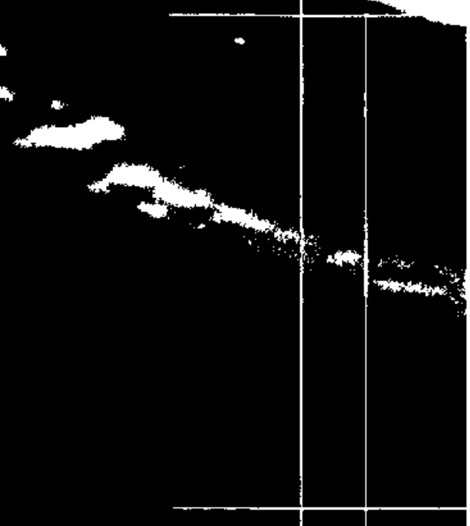
Month	est tot TP (=A2H012) TP (1) [t]	b (on first of month) contents [10^6 m^3]	c streamflow plus rain A2R001-G01 [10^6 m^3]	d calculated streamflow A2R001-E01 [10^6 m^3]	e precipitation A2R001-G02 [10^6 m^3]	f evaporation A2R001-G41 [10^6 m^3]	g gates A2R001-G24 [10^6 m^3]	h total river discharge A2R001-G22 [10^6 m^3]	i irrigation A2R001-G26 [10^6 m^3]	j=h+i total river discharge + irrigation A2R001-G22 A2R001-G26 [10^6 m^3]	k=d+e-f-j monthly change [10^6 m^3]	l=b+k (at end of month) contents [10^6 m^3]		(at end of month) Pt [t]	(ave for) month) ave Pt [t]	ave vol [10^6 m^3]	calc ave[Pt] [mg/l]	actual ave [Pt] [mg/l]	calc Chl a [mg/m3]	actual Chl a [mg/m3]
													s1=					0.11		
													0.3					0.10	10 7	4.0
Aug-90	17.83	178.693	10.261	10.261	0.000	2.055	0.000	3.138	13.579	16.717	-8.511	170.182	s2=	17.35252				0.10	10 8	7.7
Sep-90	12.17	170.182	10.556	10.431	0.125	2.855	0.000	2.791	18.566	21.357	-13.656	156.526	0.5	15.97348	16.663	163.354	0.102005	0.11	11.8	23.0
Oct-90	14.39	153.517	10.630	10.061	0.570	3.158	0.000	2.584	13.080	15.664	-8.191	145.326		16.67678	16.32613	150.926	0.108173	0.10	10.8	17.9
Nov-90	9.65	145.326	7.914	7.616	0.298	3.383	0.000	3.921	13.191	17.112	-12.581	132.745		14.58026	15.62952	139.0355	0.112414	0.14	14.3	17.4
Dec-90	28.94	132.744	19.715	17.218	2.497	3.181	0.000	4.436	4.718	9.154	7.38	140.124		23.41106	18.99566	136.4345	0.139229	0.12	12.8	7.4
Jan-91	26.53	140.123	22.484	19.435	3.049	2.909	0.000	4.463	9.051	13.514	6.061	146.184		27.26299	25.33703	143.154	0.176991			
Feb-91	30.22	146.184	31.153	29.655	1.499	2.897	0.000	4.219	4.128	8.347	19.91	166.094		32.59826	29.93063	156.139	0.191692	0.23	22.8	
Mar-91	20.95	166.093	36.525	33.811	2.714	2.588	15.438	19.821	4.959	24.780	9.157	175.25		28.82226	30.71026	170.672	0.179937			
Apr-91	7.36	175.251	12.207	12.207	0.000	2.513	0.000	4.215	5.836	10.051	-0.357	174.894		22.38533	25.60379	175.072	0.146247	0.16	16.6	8.5
May-91	5.99	174.694	10.259	10.259	0.000	1.916	0.000	3.995	9.042	13.037	-4.694	170.2		17.17111	19.77822	172.547	0.114625	0.10	10.8	7.6
Jun-91	9.27	170.200	10.498	10.446	0.052	1.295	0.000	4.081	10.904	14.985	-5.782	164.418		15.20518	16.18814	167.309	0.096756	0.09	10.2	4.1
Jul-91	5.85	164.417	10.538	10.538	0.000	1.568	0.000	4.290	11.952	16.242	-7.272	157.145		12.18745	13.69631	160.7815	0.085186	0.09	10.0	12.7
Aug-91	5.59	157.145	11.840	11.840	0.000	2.029	0.000	4.961	15.276	20.237	-10.426	146.719		9.861679	11.02456	151.932	0.072562			
Sep-91	6.53	146.718	9.091	8.960	0.131	2.060	0.000	4.357	18.559	22.916	-15.885	130.833		8.643347	9.252513	138.776	0.066672	0.06	7.5	10.0
Oct-91	9.60	130.833	12.468	11.719	0.749	2.658	0.000	4.275	14.556	18.831	-9.021	121.812		9.495695	9.069521	128.3225	0.071797	0.09		

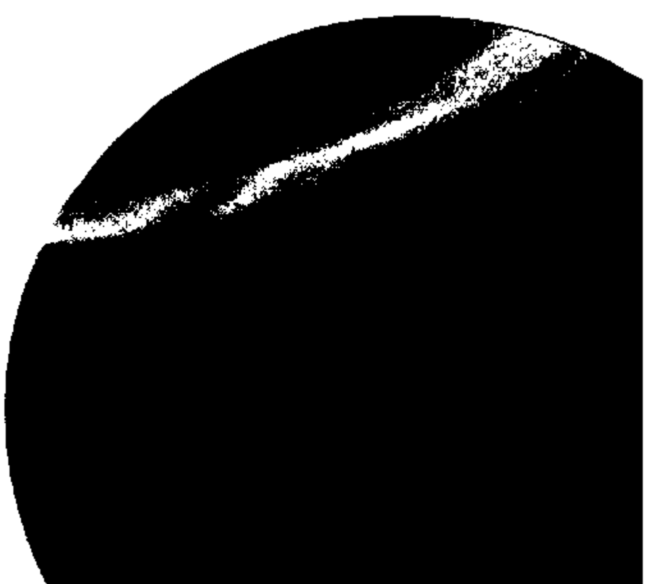
annual tol (tP/a) 171.28

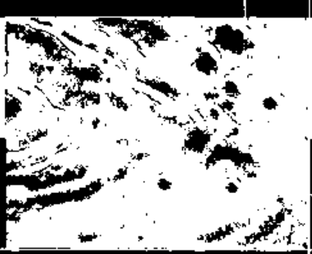
COST

	Lake algae calc Chl a [mg/m3]	Lake algae actual Chl a [mg/m3]	unit treatment cost Chla<30 conv [c/kl]	unit treatment cost Chla>=30 conv+PAC [c/kl]	unit treatment cost Chla>=30 conv+GAC [c/kl]	unit treatment cost Chla>=30 conv+flot +GAC+oz [c/kl]	add cost [c/kl]	flow ave stream [Mm3/mo]	flow act stream [Mm3/mo]	flow ave natflow [Mm3/mo]	cost ave stream [Rm/mo]	cost act stream [Rm/mo]	cost ave natflow [Rm/mo]	
			30	36	50	65								
	10.7	4.0												
Aug-90	10.8	7.7												
Sep-90	11.8	23.0												
Oct-90	10.8	17.9				65	35	16.7	10.061	5.8	5.8	3.5	2.0	
Nov-90	14.3	17.4				65	35	16.7	7.616	5.8	5.8	2.7	2.0	
Dec-90	12.8	7.4				65	35	16.7	17.218	5.8	5.8	6.0	2.0	
Jan-91						65	35	16.7	19.435	5.8	5.8	6.8	2.0	
Feb-91	22.8					65	35	16.7	29.655	5.8	5.8	10.4	2.0	
Mar-91						65	35	16.7	33.811	5.8	5.8	11.8	2.0	
Apr-91	16.6	8.5				65	35	16.7	12.207	5.8	5.8	4.3	2.0	
May-91	10.8	7.6				65	35	16.7	10.259	5.8	5.8	3.6	2.0	
Jun-91	10.2	4.1				65	35	16.7	10.446	5.8	5.8	3.7	2.0	
Jul-91	10.0	12.7				65	35	16.7	10.538	5.8	5.8	3.7	2.0	
Aug-91						65	35	16.7	11.840	5.8	5.8	4.1	2.0	
Sep-91	7.5	10.0				65	35	16.7	8.960	5.8	5.8	3.1	2.0	
								200	**182.046**	**69**	70.00	63.72	24.15	Annual total additional cost of treat [Rm/a]
											0.46	0.46	0.46	Proportion allocated to sanitation (WBc)
											32.23	29.34	11.12	Allocated total cost (WBc) [Rm/a]
											23.54	**21.43**	**8.12**	Allocated per cap cost (WBc) [R/cap.a]









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