TOWARDS AN INTEGRATED FRAMEWORK FOR THE ASSESSMENT AND MANAGEMENT OF SEDIMENT RELATED IMPACTS ON WATER RESOURCES IN SOUTH AFRICA

Report to the

Water Research Commission

by

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EXECUTIVE SUMMARY

RATIONALE

Sedimentation is the direct result of the loss (erosion) of sediments from other aquatic areas or land-based areas. Sedimentation can be detrimental or beneficial to aquatic environments. Moreover, sediment impoverishment (erosion or lack of replenishment) in an area can be as bad as too much sedimentation. Sedimentation in one area is linked to erosion or impoverishment in another area and is a natural process of all water bodies (i.e. lakes, rivers, estuaries, coastal zones, and even the deep ocean). This indicates that sediment management and control should be an integral consideration in any water resources development and protection strategy, as opportunities for truly effective solutions may also be inter-related. Further, as the natural processes which determine the movement of water or sediments (or both) do not respect administrative boundaries, a holistic, river catchment-wide approach is frequently more appropriate than a local or national approach. Improved integration between relevant sediment management and water management objectives is therefore an important aim, and opportunities which contribute to both sets of objectives should be identified and exploited.

Assessment and management of sediment related impacts on water resources is complex and multivariate, involving a careful balance of science, politics and economics. As is true for most such complex issues, there is not a single correct way to address the problem, but rather the approach should be driven by the ecological, political and socio-economic goals of all interested parties. Moreover, because the choices made have far-reaching implications, it is useful for countries, regions or communities to develop standard integrated approaches for assessment and management of sediment related impacts to meet agreed-upon goals.

Although local and site-specific sediment related impacts are still likely to be the main scales at which interventions are made (i.e. dredging of a particular river reach), they need to be placed within a broader context and with full appreciation and consideration of their impacts within the catchment. By considering the catchment as the prime morphological unit and scale for effective assessment and management of sediment related impacts, one of the most important requirements in the planning and decision-making processes, is the establishment of an integrated framework appropriate for sedimentation assessment, and management. Integrated sediment management frameworks can help to understand the interactions, intersections, and information exchanges necessary to manage sediment sustainably. In the broadest sense, the conceptual framework should identify the relevant key environments (subsystems) within a catchment, and the interrelationships between the environments. In particular, in the sediment management process the conceptual framework should help managers identify and evaluate the:

1. various uses and users that interact with sediment in a catchment, and the relevant impacts;
2. various environments within a catchment, and how they are impacted by sedimentation;
3. sources of sediments and associated contaminants; and
4. pathways, storage and fluxes of sediments and contaminants between these environments.

Sediment management frameworks for most catchments in the world have not yet been developed, or are not yet well established. This hinders sustainable management of sediments within the catchment. Globally, the need for Integrated sediment management frameworks has been recognised, however, very few countries have such frameworks in place. **Figure 1** shows that as in 2011 all African countries lacked sediment management frameworks, except for Angola which falls in the category of countries with some sediment management framework, regulations, or project examples. Neglecting to manage sediment in a sustainable way, either by lack of adequate sediment management strategies, or the cursory inclusion of sediment in generic policy and legislation, can result in costs to both society and the environment.

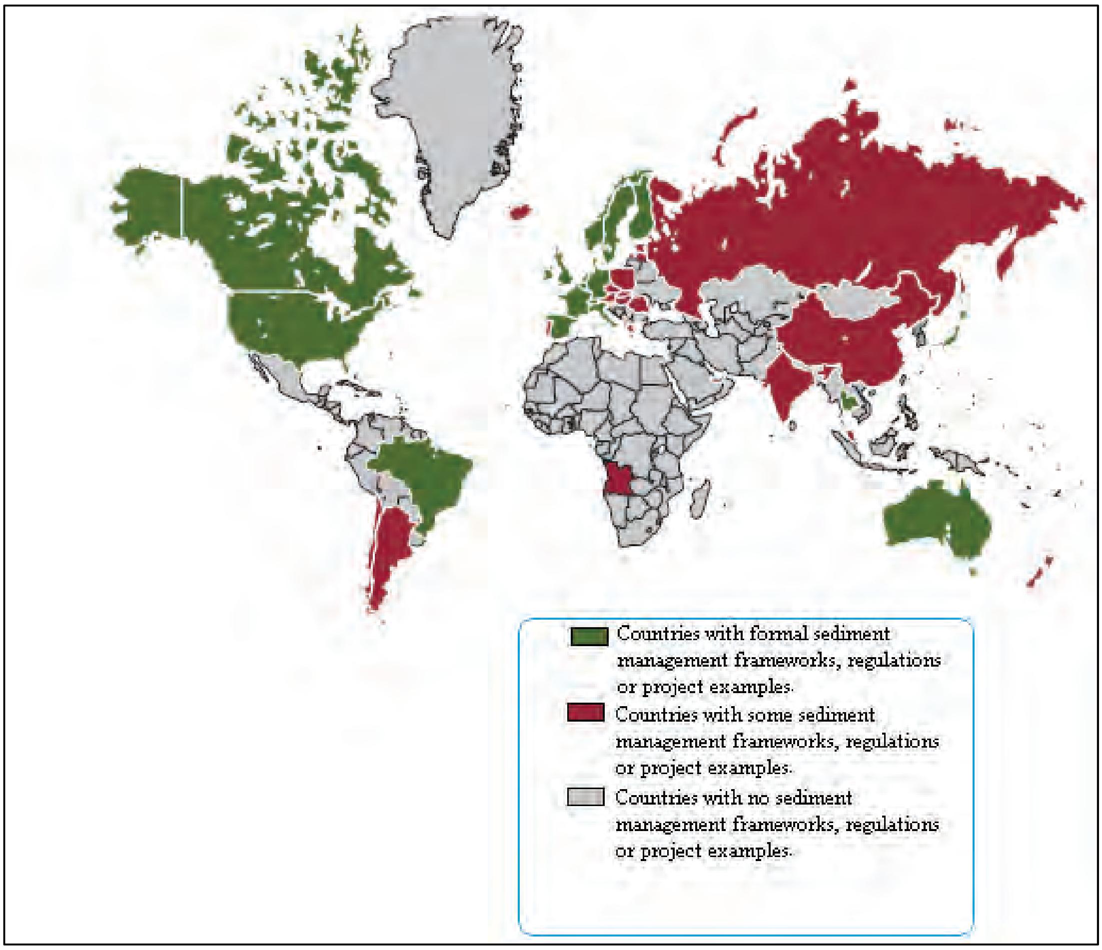

Figure 1: Global map showing countries with and without sediment management frameworks (Sparado, 2011)

PROJECT OBJECTIVES AND AIMS

South Africa does not have a sediment management framework in place, nevertheless, a number of studies have been and or are being undertaken around sedimentation. These studies have dealt with site(problem)-specific cases regarding sedimentation; however, with the movement towards integrated management of water resources, it is necessary to collate the results of these studies to come up with a holistic understanding of the impacts. This requires an integrated framework which will ensure that the assessment, and management methodologies for each site-specific are consistent with each other, and can therefore be easily integrated. Hence, the purpose of this project was to develop an Integrated Framework for the assessment and management of sediment related impacts on water resources in South Africa. The framework was to incorporate source specific interventions, particularly aimed at regulating the activities responsible for sediment production coupled with strict monitoring. The main objectives of the project are:

1. To assess and review existing knowledge on sedimentation and management practices and frameworks in South Africa. This will cover sedimentation, impacts on major rivers and navigation pathways, aquatic ecosystems, water supply systems (Lakes, rivers, reservoirs, dams), hydroelectric facilities, etc., from the quantity (yield), quality, efficiency, and sustainability perspectives.
2. To identify and evaluate available models for integrated sediment assessment and management on a catchment scale. The models will be assessed for their ability to perform sediment assessment and prediction, sediment impact and risk assessment as well as decision support. Based on the outcome a model will be selected for use/improvement or recommendations will be made on development requirements for such a model. The model is expected to represent mathematically the main functions and uses of sediment, and the natural and anthropogenic influences and their impacts. The model will also be expected to cater for information and decision support system that houses the catchment data, and allows managers to analyse different scenarios for decision making.
3. To develop a conceptual framework for the integrated assessment and management of sediment related impacts on water resources. Because sediments production are hydrologically, land cover, slope and soil type controlled the framework will be developed to, account for these factors at the catchment scale. The sediments impacts will be assessed, ranked, prioritised and managed on the same scale. The framework will present the best process-based solution which takes account of the present source of sediments and institutional management frameworks.
4. To develop a pilot study solution on a catchment scale that demonstrates the use of the framework, and sediment assessment and management model as part of the information and decision support systems. The case study will include the application of the framework to depict relationships between the actors (both natural and anthropogenic) in the catchment; the application of the model to predict and assess sediment transport and impacts of sedimentation on the environment, hydrology and society; application of the information and decision support system to demonstrate how decision can be made the modelling results and/or under different possible scenarios in the catchment.

REVIEW OF METHODS AND MODELS

A review of sediment management methods and models was conducted for the purpose of assessing their ability to perform sediment assessment and prediction, sediment impact and risk assessment, as well as decision support. The review was based on literature and available models documentations. Integrated sediment modelling encompasses understanding the fate of a contaminant from its source point to its point of destination. It is widely known that the whole process of sedimentation from production, transportation and deposition of sediment is very complex because of the variables that are involved in their occurrence. In South Africa it has been indicated that water as a transporting medium plays a critical role, thus this report dwells mainly on sediment transport by water.

The review considered sediment generation and transport at the catchment level, transport through the river system, and transport and deposition of the sediments at the reservoir because of the various dominant processes that make each component stand alone. The methods and models that have been developed in South Africa for sediment transport have been reviewed, as well as the various established methods that have been developed in the world.

In South Africa sediment yield and transport have been extensively studied and three main techniques have been used successfully, namely sediment yield maps from statistical approaches (Rooseboom *et al.,* 1992), reservoir sediment surveys (Rooseboom *et al.*, 1992, Batuca and Jordaan, 2000) and river sampling. The latter two methods assess or measure the amount of sediment in the reservoir or river, but do not necessarily evaluate processes in the upstream catchment. However these measurements can be used to calibrate and validate mathematical models. Transport at the river channels in South Africa has been investigated, and Rooseboom (1974) developed a transport formula of total sediment based on the stream power concept, which is widely in South Africa in sediment studies.

There are other various methods that have been developed to transport cohesive or non-cohesive sediments in river systems, and some of these methods have been incorporated in models either in 1D, 2D, or 3D to solve for sediment transport in the rivers or reservoirs. A number of models have been reviewed in this study; in 1D MIKE 11, HEC-6,GSTAR, and FLUVIAL, in 2D MIKE 21, TABS-MD, CCHE2D, SED2D WES, and HSCTM-2D, in 3D ECOMSED, and Delft-3D. This is not an exhaustive list; however these models were reviewed as they are widely used in the world.

What the review of these methods and models revealed was that the choice of the appropriate technique, required to estimate the sediment impact of a water resource system should include not only an assessment of the investigation aims and catchment condition, but also the potential impacts of system failure. It is recognised that while visual and qualitative assessments are appropriate for systems with low risk and minimal change to an otherwise stable system, and can be accomplished with the aid of primarily judgment based tools, however, as the systems of interest becomes more complex and where there is a higher risk to life and property, more analytical approaches such as the Non-equilibrium sediment transport methods are strongly recommended. Many analytical techniques are available that typically require the calculation of hydraulic parameters for the range of natural discharges, such as velocity and shear stress. All of these techniques require data determined from field observations and measurements, as well as calculations.

As the risk and uncertainty increase, the use of more detailed models is also recommended. These also vary in complexity from the relatively simple Lane's stream balance approach, to the more elaborate computer models. However, the use of increasingly complicated models is not necessarily recommended. On its own, a more complicated analysis will not necessarily be sufficient or more accurate. The reliability of any model is dependent on the skill and experience of the assessor, as well as the input data. Engineering judgment becomes more critical with increasing risk, and the required field work and data collection become more labour intensive. Therefore, the suitable assessment column should be regarded as a cumulative recommendation that increases with increasing risk. Further, since each stream system is unique, assessors should review the assumptions and data requirements, and consider their own experiences when determining the appropriate technique to use.

Table 1 illustrates typical assessment techniques for estimating the impacts of sediment on different project types and catchment conditions.

Table 1: Selection guidance for sediment impact assessment technique (USDA, 2007)

Study Type	Site/catchment Assessment	Risk to life, property	Suitable sediment impact Assessment
Bank Stabilization No significant change to cross section, slope, or planform	Relatively stable catchment and site	Low	Confirm that there is no significant change in the local hydraulic conditions from pre- to post project and note catchment stability
Bank Stabilization No significant change to cross section, slope, or planform	Moderately active catchment and site	Moderate	Assess stable channel grade at design flows. Field check indications of future channel evolutionary change
Bank Stabilization No significant change to cross section, slope, or planform	Moderately active catchment and site	High	Rating curve comparison of above and through site
Channel Stabilization Small change to cross section, slope, or planform	Moderately active catchment and site	Low	Rating curve comparison of above and through site, as well as pre- and post-project
Channel Stabilization Small change to cross section, slope, or planform	Moderately active catchment and site	Moderate	Sediment budget analysis
Channel Stabilization Small change to cross section, slope, or planform	Active catchment and site	High	Long-term numerical modelling

REVIEW OF SEDIMENT MANAGEMENT FRAMEWORKS

Table 2 gives a summary of the characteristics of the reviewed sediment management frameworks. This was meant to aid in selecting the appropriate frameworks for application in South Africa. Most of the frameworks can be applied on site-specific and river catchment scales. All frameworks except for the conceptual framework for river-catchment-scale sediment management do not show the level at which stakeholder participation should be undertaken within their structures.

Heise *et al.* (2004) noted that for effective and successful sediment management it is essential that the relevant stakeholders participate in the entire process, on both the local and catchment scales, during assessment, development and implementation of sediment management plans. In South Africa, stakeholder participation in water resources management has been emphasized in the National Water Act (NWA) of South Africa (Act 36 of 1998) and National Water Resources Strategy (DWAF, 2004b). DWAF (2004a) further provides guidelines for stakeholder participation in integrated water resources management (IWRM) in South Africa. Stakeholder participation in IWRM should, therefore, be based on a well-defined process leading to clear benefits to participation. As such, stakeholders need to be able to express their needs, but also to see how these needs are going to be progressively realized by on-going participation. The guidelines include a detailed procedure for stakeholder participation in IWRM.

Table 2: Characteristics of the reviewed sediment management frameworks

Framework	Scale of application	Addresses management of	Stakeholder participation	Case study example	Reference(s)
Conceptual framework for river-catchment-scale sediment management	Site-specific and river catchment	Quantity and quality	Yes	Ns	Apitz and White (2003)
Sediment budget conceptual framework	Site-specific and river catchment	Quantity	No	Long Island, New York, and Ocean City Inlet, Maryland	Rosati (2005)
Sediment risk ranking conceptual model	Site-specific and river catchment	Quantity and quality	No	WFD River Catchment, UK	Apitz *et al.* (2009)
A risk-based framework for contaminated sediment	Site-specific and river catchment	Quality	Yes	Canada and Ontario*	Chapman and Anderson (2005)
Contaminated sediment decision tree/framework	Site-specific	Quality	No	Piraeu, Greece	Katsiri *et al.* (2008)
Driving Force-Pressure-State-Impact-Response (DPSIR) framework	Site-specific and river catchment	Quantity and quality	Yes	Northfolk Broads, England	White and Apitz (2008), Cranford et al. (2012)
Adaptive Management framework	Regional and river catchment	Quantity and quality	Yes	Perdido Pass, Alabama, US	Lillycrop *et al.* (2011)
Sediment evaluation framework	Regional	Quantity and quality	Yes	Pacific Northwest (the states	U.S. Army Corps of Engineers *et*

Framework	Scale of application	Addresses management of	Stakeholder participation	Case study example	Reference(s)
				of Washington, Oregon, and Idaho	*al.* (2006)
Technical management framework	Regional	Quality	Ns	US Corps navigation dredging	U.S. Army Corps of Engineers and USEPA (2004)

Ns= Not specified

THE FRAMEWORK

Although there is a need to develop sediment management frameworks that can be used in any catchment, it is important to remember that each catchment is different and the complex role that sediment plays means that different objectives, pressures, impacts and mitigation measures will need to be considered in different catchments, and even in different sites within a given catchment (Apitz *et al.,* 2009). Thus, a conceptual model may assist in identifying the need for site-specific assessment or catchment-scale assessment. In order for river catchments to be used as sediment management units, it is vital to have a conceptual model of river catchment functioning that links different areas in space and time, and allows potential consequences (impacts) of drivers to be evaluated (White and Apitz, 2008).

The selection of the appropriate framework should be based on the specific aim(s) of the study and whether the framework fulfils the requirements of sustainable integrated sediment management and IWRM principles. This means an appropriate framework should be able to address sediment related problems at a river catchment scale while involving stakeholders in decision making throughout the whole process. The aim of the study may either be managing the quantity and/or quality of sediments in a river catchment. Thus, frameworks that can be applied on river catchment scale, for example, the conceptual framework for river-catchment-scale sediment management or the DPSIR framework can be used in a study that is aimed at managing the quantity and quality of sediments. If a framework is appropriate for a particular river catchment but it does not clearly incorporate stakeholder participation, it can be extended so as to include stakeholder participation and still be used in that particular river catchment.

In developing the framework, three key Modules/building-blocks were identified as follows:

1. Objectives and Scale Selection Module
2. Tools Assessment and Selection Module
3. Strategies formulation and Selection Module

The ultimate goal for the development of the Integrated Sediment Management Framework is to manage sediments sustainably. To be able to manage sediments sustainably there is a need for a sediment management plant (SMP) on a catchment scale, and this must also be incorporated into a catchment management strategy. An SMP is required to achieve a balance between fulfilling sediment management objectives, and the need to secure human activities and legal requirements (Netzband, 2006). To be effective, the SMP must be technically sound and practical, environmentally sensitive, politically realistic and financially feasible and sustainable (Noble Consultants *et al.,* 2012). Developing a sediment management plan (SMP) will provide guidelines for more effective management of sediment resources, recognizing they are part of a regional system involving natural processes (Gulf of Mexico Foundation, 2009). The SMP seeks to achieve the following four objectives:

1. Identify erosion/deposition problem areas in the catchment;
2. Identify principal sources of sediment in the catchment;
3. Identify alternative methods of reducing erosion rates; and
4. Evaluate and recommend methods to reduce impacts resulting from sediment erosion and deposition.

Figure 2 shows a simplified guideline showing the steps to be followed in the development of SMP.

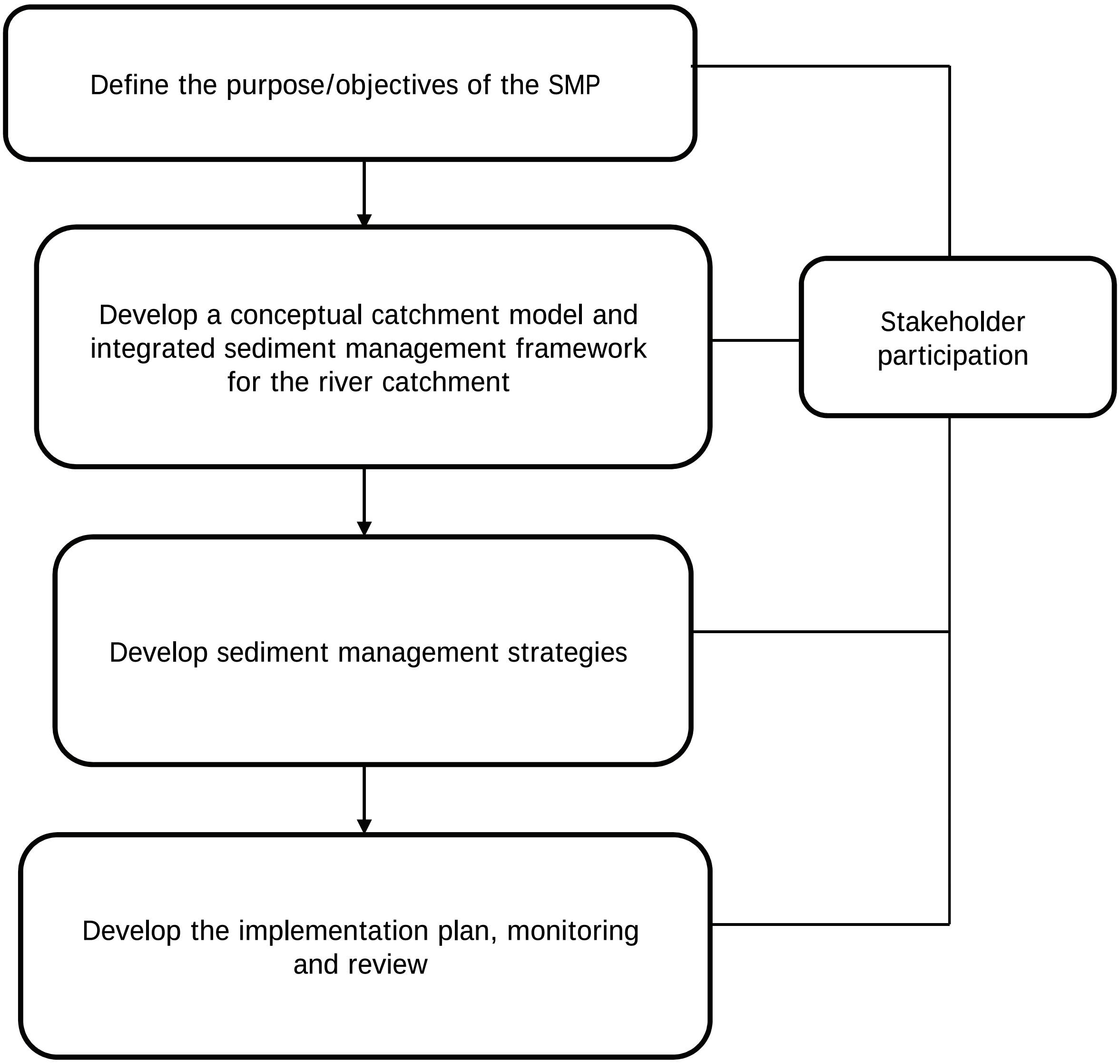

Figure 2: Guideline for developing SMP

CASE STUDY

The Department of Agriculture and the Water Research Commission (WRC), amongst others, have funded a number of soil erosion and sedimentation research projects in South Africa. These studies have given birth to a variety of models, methods and maps useful in the prediction and management of soil erosion and sedimentation. This knowledge has in most cases been integrated on a national or continental scale, i.e. the continental (Africa) soil erosion risk map, the erodibility classes of South Africa, Sediment yield map of South Africa, etc. However, our ability to develop cost-effective land and sediment management strategies is still limited by sources of error in spatial data, ranging from natural variability to issues of accuracy and precision in mapping techniques. In addition, the spatial problem is coupled with a wide variety of mapping techniques that are equally valid but give different results. These Methodological problems point to the need to establish a proper framework to guide and standardize regional soil loss and sedimentation modelling and mapping efforts. The purpose of these project was therefore, to develop such a framework, which should outline the different erosion processes, interactions and deposition processes likely to dominate at different scales.

In this context, regional modelling should combine the simplicity required for application on a regional scale with appropriate incorporation of the most important processes. At the regional scale, it appears that the inherent erodibility of the soil and parent material are the overriding erosion and sedimentation risk factors in South Africa, and not the slope gradient, as determined in the United States. Furthermore, the framework needs to describe the most feasible erosion and deposition assessment and techniques, as well as input data sets, for application at different scales. Hence, in reality, a case study to demonstrate the effectiveness of such a framework would have to be done on a national scale. However, before a large amount of money and effort can be spent on such a national demonstration, it is most preferable to demonstrate on a particular case, and in such a case, such demonstration would essentially be a demonstration of the logic behind the framework.

Therefore, this case study was not geared towards intensive first order modelling, but to use existing information or results from previous studies with minimum adjustment to demonstrate the proposed framework's logic. Hence the objectives of the case study can be summarised as follows:

1. Identify users, their objectives and their contribution to sedimentation problems based on the developed framework
2. Select a suitable model/method for the estimation of soil erosion and sedimentation yield for Welbedacht reservoir based on the developed framework approach
3. Estimate erosion and sedimentation for various natural and anthropogenic scenarios
4. Use the results to design integrated catchment sedimentation management strategies for Welbedacht reservoir based on the developed framework.

The case study was undertaken as part of a Masters degree by Mr Thomas Chabalala at the Tshwane University of Technoloy.

The study aimed at demonstrating an integrated approach to sedimentation processes and management for the reservoir. Firstly, it intended to determine the various sources and rates of sediment transport. Secondly, to select a model for integrated catchment sedimentation processes, and lastly, to apply the model developed to design integrated catchment sedimentation management strategies for Welbedacht reservoir.

In an attempt to accomplish the objectives outlined above, RUSLE model developed by Wischmeier and Smith (1978) was selected for this research. The data was analysed and used in RUSLE model to compute annual soil loss in a catchment. Based on the findings of this study, the following conclusions and recommendation can be drawn:

1) The results obtained indicated the total annual soil loss of approximately 602.58 ton per hectare per year since 1992 to 2011 for scenario without conservation measures, which leads to a value of about 30.13 ton per hectare per year when divided by the number of years over which was computed.
2) It further shows that agricultural practices contribute the greatest volume of sediment, with the bulk coming from cultivated land at 273 ton per hectare per year. The next most extensive sediment sources are forest and built-up which includes urbanization and construction areas contributing 103.3 ton per hectare per year, followed by thicket bush land and forest plantations contributing 80.0 and 16.6 ton per hectare per year each. Grassland, degraded land, mining and quarry contribute 3.9, 9.8 and 5.3 ton per hectare per year respectively.
3) After application of soil conservation practices to RUSLE model, the results shows sediment yield coming from cultivated land decreased from 273 to 67.1 ton per hectare per year, while sediment from built-up and forest decreases to 59.5 ton per hectare per year and 0.62 ton per hectare per year respectively. Total average annual soil loss in the catchment decreased to 141.7 ton per hectare per year (to about 24% or rather a decrease of 76%). This leads to a value of about 7.09 ton per hectare per year when divided by the number of years over which it was simulated.
4) Applying this reduction to the Welbedacht storage assuming a linear relationship would mean that Welbedacht would have only lost about 57% of storage compared to 87%. This is an indicative figure, it should be noted that most of the storage was lost within the first three years, hence the assumption of a linear relationship is used here only to indicate a potential reduction.

5) The overall results showed that the Framework can be a useful tool to logically getting to an optimal solution for an area in question.
6) The proposed Integrated Catchment Management Strategies for Welbedacht catchment are:

   - Soil conservation measures such as contour banks, tillage practices, and terracing must be implemented to reduce the high rates of soil erosion, especially in the cultivated land.

   - Construction site stabilization activity, such as mulching, sediment catchments, seeding of grasses and planting of trees need to be implemented during and after constructions to protect the vulnerable soil from erosion.

CONCLUSIONS

The research found that there are no documented sediment management frameworks in South Africa. However, there are various legislations concerned with water and environmental protection that may indirectly include sediment management. These include the NWA No. 36 of 1998 and National Environmental Management Act (NEMA) No. 107 of 1998. Section 21(g) of the NWA stipulates that the disposal of waste in a manner which may detrimentally impact on a water resource is a water use. According to DWAF (2008) the waste includes any solid material or material that is suspended, dissolved or transported in water (including sediment) and which is spilled or deposited on land or into a water resource in such a volume, composition or manner as to cause, or to be reasonably likely to cause, the water resource to be polluted.

Therefore, a conceptual Integrated Sediment Management Framework was designed and presented in this report. The Integrated framework essentially provides a platform whereby sediment management tools/models/frameworks, etc. can be brought together such that their results are consistent when applied by different people. The Developed Integrated framework is therefore not meant to be a replacement of the existing frameworks, as it has been shown that each of the frameworks has their focus and strong points which if logically brought together can enable management to assess the holistic situation by combing the results from the various frameworks.

It has been shown that integrated sediment management is effective on river catchment scale, it is therefore crucial to develop sediment management frameworks for different river catchments in South Africa while following the basic concepts outlined in the existing/reviewed frameworks. Thus, it is essential for each river catchment to have its own integrated sediment management framework.

The selection of the appropriate framework should be based on the specific aim(s) of the study and whether the framework fulfils the requirements of sustainable integrated sediment management and IWRM principles. This means an appropriate framework should be able to address sediment related problems at a river catchment scale while involving stakeholders in decision making throughout the whole process. The aim of the study may either be managing the quantity and/or quality of sediments in a river catchment.

The development of the sediment management framework should be based on the catchment area contributing runoff. Any framework that can meet these criteria can be tested for use in SA river catchments. Frameworks such as sediment budget conceptual model can also be tested if stakeholder participation is incorporated within them. However, issues such as data requirements and availability should be considered while selecting or adopting a specific framework. These are dependent on the scale of application (size of the river catchment) and the aims of the study.

RECOMMENDATIONS

Based on the conclusions it is recommended that:

1. In a South African context, the unavailability of a national guiding principles on sediment management is seen as a challenge to the implementation of the integrated Sediment management framework, and it is therefore recommended that as a first step South Africa should develop high level policies to guide the various organs of the state in managing sediments sustainably.
2. Management of sediments spans a number of independent institutions, hence for an integrated approach to be successful, there must be an institutional co-operation strategy and a committee that will facilitate engagements between the various institutions. Hence further research should be geared towards identifying the key role players in sediment management and development a co-operation strategy.

3. Sediment Management Plans should be developed and incorporated into the catchment management strategies as a matter of urgency.
4. Researchers, policy-makers and community education have to go hand-in-hand to face the problems of land degradation and soil erosion as the successful implementation of soil conservation measures and road drainage control is only possible through a combination of socio-economic, political, and scientific considerations.
5. There must be community education and awareness about the long term consequences of human interference into their natural environment as people understand their present impact on the future productivity of their land.
6. There must be a development of conditions to be used in initial site selection for the project such as select a site that is suitable rather than force the terrain to conform to development needs. This will ensure that development features follow natural contours.
7. Further studies should be undertaken in view of improving the relevance of the Framework for all catchments in South Africa. What would also be important would be to add an economic model to assist with the choice of strategies relative to the implementation cost.

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LIST OF ABBREVIATIONS

AM	Adaptive Management
CSM	Conceptual Site Model
DDD	dichlorodiphenyldichloroethane
DDE	dichlorodiphenyldichloroethylene
DDT	dichlorodiphenyltrichloroethane
DERSMPW	Delaware Estuary Regional Sediment Management Plan
DPSIR	Driving Force-Pressure-State-Impact-Response
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
GICF	Generic Integrated Conceptual Framework
IWRM	Integrated water resources management
MAP	Mean Annual Precipitation
MCDA	multi-criteria decision analysis
NEMA	National Environmental Management Act of South Africa (Act 107
NWA	National Water Act of South Africa (Act 36 of 1998)
RCMP	River Catchment Management Plans
SA	South Africa
SAV	Submerged Aquatic Vegetation
SEF	sediment evaluation framework
SMP	sediment management plans
U.S.	United States
WMAs	Water management Areas
WRC	Water Research Commission

1 INTRODUCTION AND OBJECTIVES

1.1 THE NEED FOR AN INTEGRATED SEDIMENT CONCEPTUAL FRAMEWORK

The wide range of economic activities and the hydrological complexity of many river catchments, both in terms of the functioning of the soil-sediment system and links between water quality, quantity and economic activities, make integrated management of river catchments difficult and challenging (SedNet, 2007). The sediment balance in catchments and river catchments is altered by human activities, producing social, economic and environmental repercussions (ISI, 2012). This makes sediment management an important component of sustainable water resources management.

The dynamic nature of river sediments calls for a new approach to sediment management that explicitly addresses transport, quantity and quality throughout the framework (Apitz and White, 2003). Integrated sustainable sediment management, which is a comprehensive approach for addressing the long-term management and conservation of sediments within a catchment, to maintain current and future beneficial uses while addressing regional, environmental, economic, and social objectives (Mastin, 2011), is thus required in river catchments. **Figure 3** shows an example of integrated sustainable sediment management in a catchment. It shows integrated activities aimed at minimizing sediment generation by reforestation, vegetion buffers in agricultural fields and establishment of parks; treatment and confinement of contaminated sediments; and ensuring beneficial use of sediment by channelling it for beach nourishment while minimizing the volume deposited in the river at the same time.

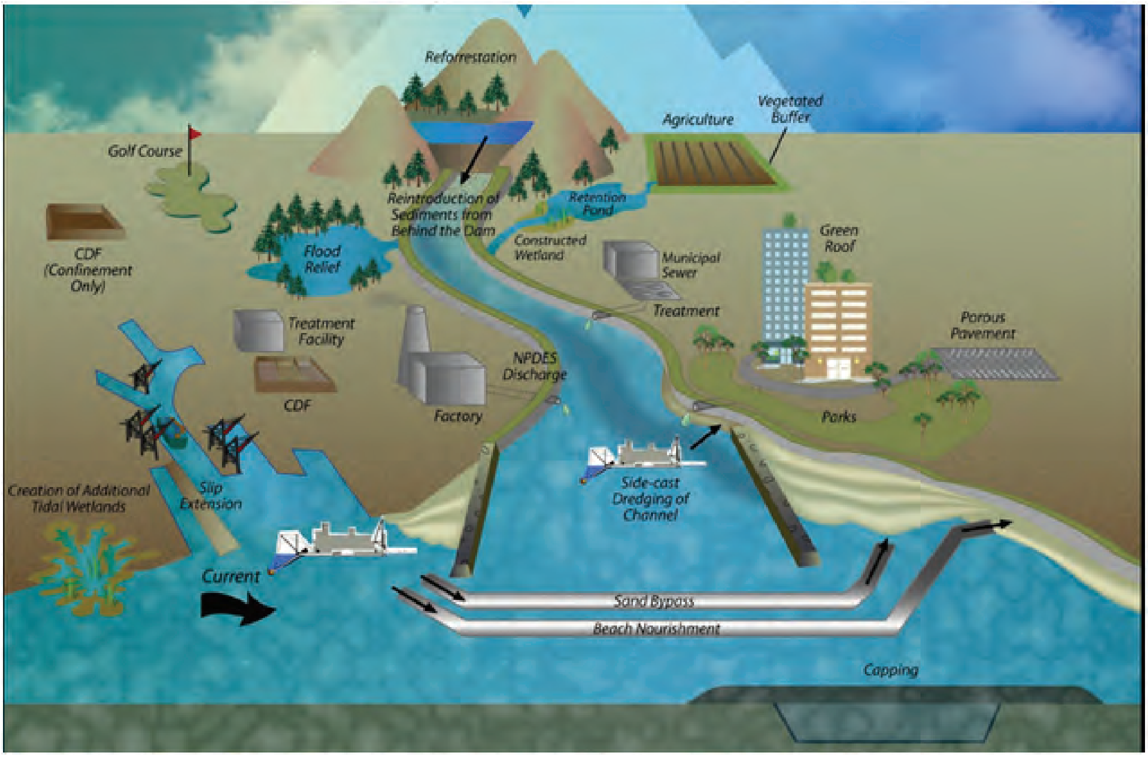

Figure 3: Integrated sustainable sediment management in a catchment (Mastin, 2011)

Integrated sustainable sediment management can be achieved through the use of sediment management frameworks which help to understand the interactions, intersections and information exchanges necessary to manage sediment sustainably. Effective sediment management requires a holistic approach taking into account system understanding, integrated management of soil, water and sediment, trans-boundary cooperation, upstream-downstream interrelationships and stakeholder involvement (SedNet, 2009) and partcipation.

Sediment management frameworks for most river catchments in the world have not yet been developed or are not yet well established. This hinders sustainable management of sediments within the river catchments. For example, Smith (2011) reported that existing sediment management in the Delaware estuary is unsustainable due to lack of regional sediment management framework. Tavolaro (2008) reported that the policy and regulatory frameworks required to improve regional sediment management throughout the Harbor Estuary does not exist and many sediment-related problems remain unaddressed or under-addressed.

Sparado (2011) conducted a review on countries with and without sediment management frameworks and produced a global map showing their distribution (**Figure 4**). **Figure 4** shows that all African countries lack sediment management frameworks, except for Angola which falls in the category of countries with some sediment management framework, regulations, or project examples. The study did not find any documented sediment management frameworks in South Africa from the 18300 internet searches that were conducted. Neglecting to manage sediment in a sustainable way, either by lack of adequate sediment management strategies, or the cursory inclusion of sediment in generic policy and legislation, can result in costs to both society and the environment (SedNet, 2002).

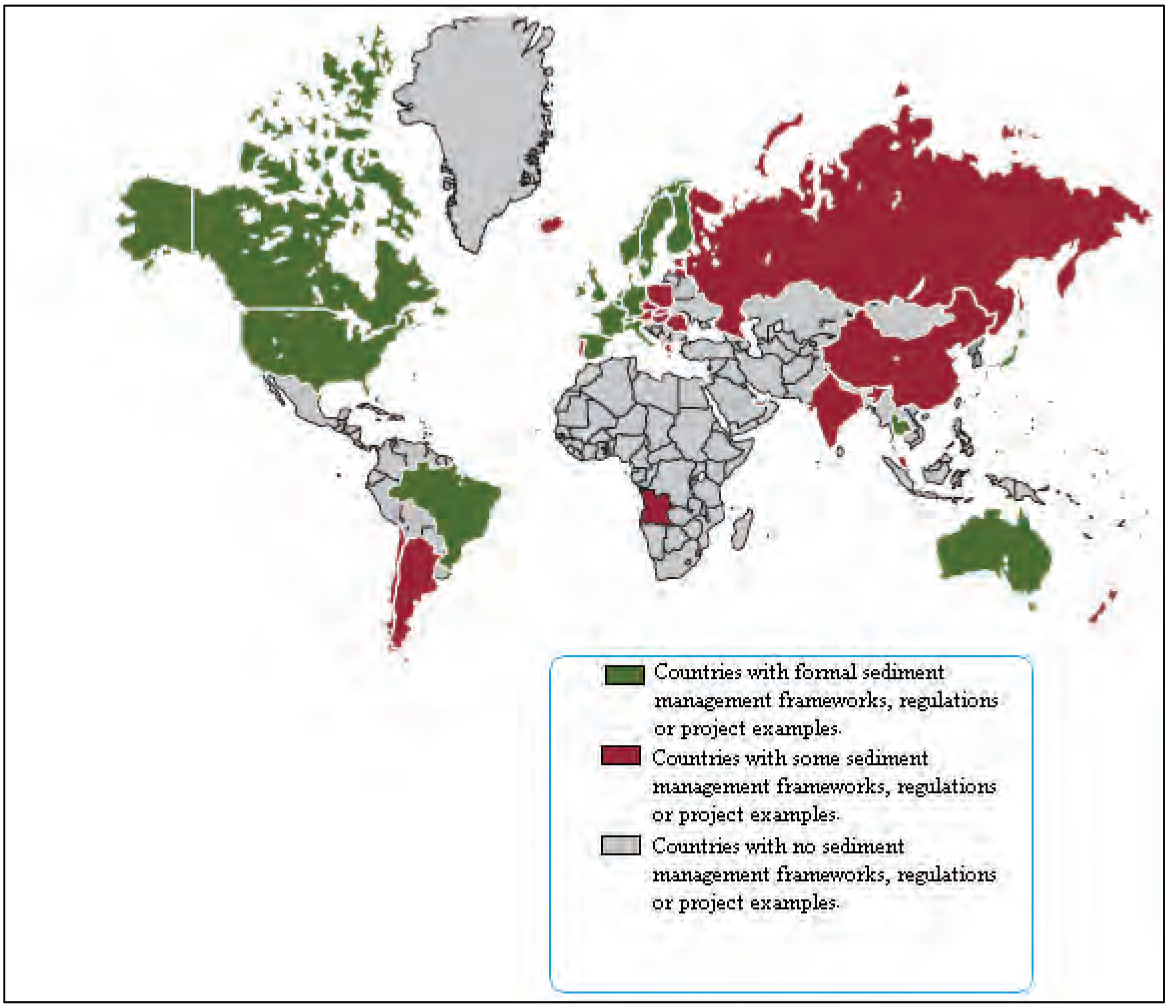

Figure 4: Global map showing countries with and without sediment management frameworks (Sparado, 2011)

Although local and site-specific sediment related impacts are still likely to be the main scales at which interventions are made (i.e. dredging of a particular river reach), they need to be placed within a broader context and with full appreciation and consideration of their impacts within the catchment. By considering the catchment as the prime morphological unit and scale for effective assessment and management of sediment related impacts, one of the most important requirements in the planning and decision-making processes, is the establishment of an integrated framework appropriate for sedimentation assessment, and management. Integrated sediment management frameworks can help to understand the interactions, intersections, and information exchanges necessary to manage sediment sustainably. In the broadest sense, the conceptual framework should identify the relevant key environments (subsystems) within a catchment, and the interrelationships between the environments. In particular, in the sediment management process the conceptual framework should help managers identify and evaluate the:

- various uses and users that interact with sediment in a catchment, and the relevant impacts;
- various environments within a catchment, and how they are impacted by sedimentation;
- sources of sediments and associated contaminants; and
- pathways, storage and fluxes of sediments and contaminants between these environments.

1.2 OBJECTIVES OF THE PROJECT

South Africa does not have a sediment management framework in place, nevertheless, a number of studies have been and or are being undertaken around sedimentation. These studies have dealt with site(problem)-specific cases regarding sedimentation; however, with the movement towards integrated management of water resources, it is necessary to collate the results of these studies to come up with a holistic understanding of the impacts. This requires an integrated framework which will ensure that the assessment, and management methodologies for each site-specific are consistent with each other, and can therefore be easily integrated. Hence, the purpose of this project was to develop an Integrated Framework for the assessment and management of sediment related impacts on water resources in South Africa. The framework was to incorporate source specific interventions, particularly aimed at regulating the activities responsible for sediment production coupled with strict monitoring. The main objectives of the project are:

1. To assess and review existing knowledge on sedimentation and management practices and frameworks in South Africa. This will cover sedimentation, impacts on major rivers and navigation pathways, aquatic ecosystems, water supply systems (Lakes, rivers, reservoirs, dams),

hydroelectric facilities, etc., from the quantity (yield), quality, efficiency, and sustainability perspectives.

2. To identify and evaluate available models for integrated sediment assessment and management on a catchment scale. The models will be assessed for their ability to perform sediment assessment and prediction, sediment impact and risk assessment as well as decision support. Based on the outcome a model will be selected for use/improvement or recommendations will be made on development requirements for such a model. The model is expected to represent mathematically the main functions and uses of sediment, and the natural and anthropogenic influences and their impacts. The model will also be expected to cater for information and decision support system that houses the catchment data, and allows managers to analyse different scenarios for decision making.
3. To develop a conceptual framework for the integrated assessment and management of sediment related impacts on water resources. Because sediments production are hydrologically, land cover, slope and soil type controlled the framework will be developed to, account for these factors at the catchment scale. The sediments impacts will be assessed, ranked, prioritised and managed on the same scale. The framework will present the best process-based solution which takes account of the present source of sediments and institutional management frameworks.
4. To develop a pilot study solution on a catchment scale that demonstrates the use of the framework, and sediment assessment and management model as part of the information and decision support systems. The case study will include the application of the framework to depict relationships between the actors (both natural and anthropogenic) in the catchment; the application of the model to predict and assess sediment transport and impacts of sedimentation on the environment, hydrology and society; application of the information and decision support system to demonstrate how decision can be made the modelling results and/or under different possible scenarios in the catchment.

2 LITERATURE REVIEW

2.1 OVERVIEW

The purpose of **chapter 2** is to set the scene for the rest of the report in terms of literature reviewed on this project, and it is therefore placed in wider context of sediment and its management. The chapter presents some concepts on what sediment is and what it is composed of. Some of the main functions and uses of sediment, and the natural and anthropogenic influences and impacts on these, are also described. These considerations naturally lead to an assessment of how to manage sediment so as to balance the needs of nature and society, and to a discussion on the river catchment as an appropriate management unit to do this. The Chapter has therefore been divided into four main components as follows:

1. Chapter 2.2 – Sediment movement and behaviour;
2. Chapter 2.3 – Causes of sediment;
3. Chapter 2.4 – Impacts of sediment; and
4. Chapter 2.5 – Sediment management.

2.2 SEDIMENT MOVEMENT AND BEHAVIOUR

In river catchments, sediment can be transported by a variety of mechanisms including: flowing water; wind; gravity-driven processes such as mass movements and bank collapse; flowing glaciers and ice; animals and humans; and machinery (such as tractors). In perennial river channels, sediment transportation is by flowing water (i.e. the river), but it is important to recognise that other processes are important outside the channel, and that these processes can supply sediment to the channel. Thus, wind processes may be important in mobilising and transporting sediment from exposed soil on fields, or fine material stored as talus on hillslopes towards river channels. Wind and flowing water are important for transporting and delivering fine sediment (i.e. clay-, silt and sand-sized material) from land to rivers, but the sediment load of a river also consists of coarser material such as gravels and boulders. This coarser component is delivered to the channel by, for example, mass movements (such as landslides, rockfalls and debris flows) and the collapse of channel banks, and these processes may or may not involve flowing water (Owens, 2008).

Thus, there are many different sources of sediment in river catchments, and different mechanisms and pathways by which they are delivered from the source to the river channel, and these are described in more detail in the following subsections. In addition to the fluvial sources of sediment in river catchments, in the downstream, estuarine and near-coastal parts of a 'river catchment', sediment is also supplied from estuarine, coastal and marine sources. In many cases, these nonfluvial sources may be dominant for the downstream parts of the catchment. Coastal and marine sediment sources are also important for other river systems, and have important implications for how sediment is managed in the lower reaches of the river, including harbours (Owens, 2008).

Within aquatic systems, there is usually a simple distinction between the suspended load and bedload. The former is essentially sediment that is transported suspended within the water column, and typically consists of material <2 mm in diameter. The latter is that portion which moves by rolling, sliding and saltation and is therefore usually transported close to the channel bed. Bedload material is coarser and/or denser than the suspended load, the former being typically >2 mm in size, and has different hydrodynamic and chemico-physical properties than the finer, suspended load. There are more complicated classifications of the sediment load of a river with, for example, divisions of the suspended load into washload and suspended bed-material load components. For simplicity, however, a separation into suspended sediment and bedload is usually sufficient, although it is important to recognize that the distinction between the two loads is time and space dependent, as material transported as bedload during one event may be transported in suspension during another event with greater flow velocity (Owens, 2008).

Sections 2.2.1 to 2.2.4 below gives more detailed information on the 1) Definition of sediment, 2) Sediment functions, 3) Sediment transportation and deposition, and 4) Sediment yield and production.

2.2.1 DEFINITION OF SEDIMENT

Sediment means different things to different people and consequently there are a variety of different terms and phrases used to describe 'sediment'. 'Mud', 'dirt' and 'sludge' are terms that are often used by the public or non-scientific community when referring to 'sediment', although mud is also a term used by certain groups of scientists when referring to fine-grained organic and inorganic material (i.e. clay- and silt-sized material), as opposed to coarse-grained 'sediment'. For many, especially managers and regulators, sediment is synonymous with dredged material. It is perhaps here that some of the problems and issues of sediment management arise, i.e. the lack of appreciation and agreement on what sediment is (Owens, 2008).

In terms of definitions of sediment, there are several. A useful definition is that put forward by the European Sediment Network, SedNet (www.sednet.org): *Sediment is suspended or deposited solids, of mineral as well as organic material, acting as a main component of a matrix which has been or is susceptible to being transported by water* (Owens, 2008).

This definition is what many would regard as appropriate. However, it is not fully inclusive, and does fail to recognise other forms of transportation such as wind and ice (e.g. glaciers), and indeed it can be argued that sediment movement by people, animals, machinery, etc. is relevant. Also, sediment need not necessarily move in suspension. Large sediment particles may move by rolling, saltation or sliding. This helps to highlight the problem of understanding and defining what is meant by sediment. Thus the definition stated above is a good working definition in the water sector and for this project in particular, but it is important to bear in mind the caveats just described.

2.2.2 SEDIMENT FUNCTIONS

Sediment and its movement through river catchments from source to sink are important for several reasons and these include (Owens, 2008):

1. as part of the global denudation cycle;
2. for global biogeochemical (including carbon) cycling;
3. for transferring nutrients and contaminants from terrestrial to freshwater to marine and coastal systems;
4. for being (i.e. sediment itself) and creating (e.g. beaches, channel islands, saltmarshes) aquatic habitats and landforms;
5. by helping to maintain a high level of biodiversity within aquatic systems through the creation of diverse sedimentary environments;
6. for providing an important natural resource (e.g. aggregates, fertile soil on floodplains); and
7. for the functioning of coastal ecosystems and the evolution of deltas and other coastal landforms.

The link between sediment (amount, type and dynamics) and the ecology of aquatic systems is important, as various ecological metrics are useful as an integrated measure of the health of a system. Studies have shown that biotic assemblages in rivers may be influenced by sediment amount and composition. Conversely, other studies have shown how in-stream vegetation influence sediment deposition, thereby illustrating the important inter-relationship between aquatic biota and sediment dynamics. The variations in sediment particle size and structure provide important habitats for different types of aquatic life. This variation in sedimentary habitats at different spatial scales is important for maintaining biodiversity within aquatic systems by providing suitable conditions for spawning, shelter, food sources, etc. (Owens, 2008). Biodiversity must therefore be considered when considering the impacts of sediment on water resources, and this is in line with the requirements of the NWA.

2.2.3 SEDIMENT TRANSPORTATION AND DEPOSITION

Sediments undergo different processes of transportation and settling. This causes the water systems to possess different kinds of deposition at different position. These differences are controlled by the effects of the sediment particle size, hydraulic condition and sediment transportation methods. Due to different behaviour of sediment particles in transportation and deposition, they have a different impact on sediment deposition pattern, and storage losses for reservoirs. Thus, it is important to treat each type separately, so as to understand how they are transported and deposited. Due to the existence of different kinds of sediment particle in the stream flow, several transporting and depositing kinds occur. In general, sediments are divided into two major parts; bed-load and suspended load. They exist in a stream inflow at different ranges and different quantity with respect to the time and space. The increase or decrease of any type of sediment has direct reflection on the deposition pattern. **Sections 2.2.31 and 2.2.3.2** describes sediment transport, and types of sediment deposition.

2.2.3.1 Sediment transport

Sediment transport is, in general, the transport capacity or detachment limited. Transport capacity limitation means that the amount of sediment water can carry at a given flow conditions is the limiting factor, and the supply of sediment is abundant. Detachment (supply) limitation means that the transport rate is determined by how much sediment is available and how much can be detached regardless of how "strong" the flow is.

Transport capacity limited conditions are generally easier to solve, because sediment transport can be determined directly from flow conditions. Detachment limited conditions require a better parameterisation of soil surface properties that inhibit erosion.

2.2.3.1.1 Sediment transport capacity and sediment load

The transporting capacity is determined by the characteristics of the river channel and other factors. Every sediment particle that passes a given stream cross-section must satisfy the two conditions below (Msadala, 2009):

- It must be eroded somewhere in the catchment above the cross section; and
- It must be transported by the flow from the place of erosion to the cross section.

It can be concluded from the above conditions that the rate of sediment transport depends on the transport capacity of the stream, and availability of sediment. Further, the amount of transported material in the stream would therefore depend on two groups of variables (Msadala, 2009):

1. Characteristics and quantity of material made available for transport (characteristic variables): catchment topography, geology, rainfall intensity, magnitude and duration, weathering, vegetation, surface erosion, sediment supply from tributaries, mineralogy, soil type and land use; and
2. Sediment transport capacity (defining variables): channel geometry, width, depth, shape, wetted perimeter, slope, vegetation, roughness, velocity distribution, turbulence and uniformity of discharge.

The sediment that is transported by the river has varying sizes in terms of diameter. In regions where the sediment transported in the river is relatively coarse consisting of sand, gravel or coarser particles it is possible to hydraulically determine the sediment yield. Sediment yield is the quantity of sediment that has been mobilised from a known catchment area size which is passing through a river channel's reference point in a given time interval. Sediment quantitative analysis is sometimes expressed as total sediment load in a stream. The sediment transport capacity is determined as function of hydraulic conditions and the shape of the stream cross section (Msadala, 2009).

2.2.3.1.2 Sediment concentrations and fluxes

There have been numerous studies that have estimated sediment fluxes *(sediment mass transported past a specific location per unit time)* in river catchments, over a range of temporal and spatial scales. Most studies have been concerned with fluxes over relatively short periods of time, such as during high-flow events and over periods of a year or years, often as part of river monitoring programmes. Sediment flux data rarely span more than a few decades at best, although there are records extending back for about 100 years or so for some rivers. Most sediment is transported during high discharge events such as those caused by precipitation, snowmelt (e.g. freshets), and water released from dams (natural and artificial impoundments) (Owens, 2008).

There are also situations when high sediment fluxes in rivers are not related to variations in water flows in rivers, and in these situations sediment is delivered to river channels from landslides and other mass movements, channel bank collapse, or anthropogenic disturbances such as mining and dredging activities. Suspended sediment concentrations in flowing water vary by orders of magnitude, from essentially zero at low flow conditions (i.e. base flow) to > 10 g/l during peak transport conditions (i.e. storm events and freshets) in some flowing water systems. In other systems, such as lowland chalk rivers, suspended sediment concentrations may always be relatively low, i.e. <100 mg/l. Values during extreme events, such as volcanic eruptions and glacial lake outburst floods, can be even greater: such events probably also result in the highest specific sediment yields although the occurrence and duration of such transport events are relatively limited (Owens, 2008)

Similarly, bedload fluxes range from essentially zero for most of the time to values over 10 kg/s/m during high-magnitude events (Owens, 2008). Although sediment fluxes are generally greatest from highly disturbed agricultural and deforested catchments, sediment fluxes and yields from urban catchments can also be high. Sediment fluxes vary temporally as well as spatially in response to various natural and anthropogenic driving forces.

2.2.3.2 Types of sediment load deposition

The river flow usually carries a wide range of the sediment particle sizes and they are transported either as a bed load or as a suspended load. Bed load transport rates are usually expressed as being related to excess dimensionless shear stress raised to some power. Excess dimensionless shear stress is a non-dimensional measure of bed shear stress about the threshold formation. Suspended load is carried in the lower to middle parts of the flow, and moves at a large fraction of the mean flow velocity in the stream. These are transported deeper into the reservoir either by non-stratified flow forming a uniform deposition at the middle of reservoir, or by stratified flow depositing at lower part of the reservoir forming a muddy lake. Generally the suspended load is divided into two parts; one comes from the bed of the river, and the other load from the catchments area as wash load (Bashar et. al, 2010).

Sediment-deposition can be classified into three categories based on the location of deposition, with inclusion of the sedimentation in backwater reaches as part of the sedimentation. These categories are 1) Back water deposition, 2) Delta deposition and 3) Bottom set deposition, and these are further discussed in the following subsections.

2.2.3.2.1 Back water deposition

This type of deposition occurs in the river before it enters the reservoir. After changing the water level in the river by the effect of back water curve, the velocity of water will be reduced. Subsequently a small part of the coarse sediment will deposit in this region till it reaches the reservoir delta deposition. It is considered as a transition between the original river bed and delta formation. In theory, the backwater deposit should grow progressively, into upward and downward direction of the river, because it extends with changes of bed forms. However this growth is limited, because the stream adjusts its channel by eliminating meanders, forming a channel having an optimum width-depth ration or varying bed form roughness. These factors make stream transports its sediment load through the reach with evolution done in one direction.

2.2.3.2.2 Delta formation

This is caused by rivers that enter a reservoir, lake or sea. The process involves deposition of sediment of large sand sizes due to the reduction of stream sediment holding capacity. The morphology and sedimentary sequences of a delta depend on the discharge regime, the sediment load of the river, and the relative magnitudes of tides, waves, and currents. Also, the sediment grain size and the water depth at the depositional site are important for the shape of the deltaic deposition patterns. This complex interaction of different processes and conditions results in a large variety of different patterns according to the local situations (Seybold *et. al.,* 2007). Wright and Coleman (1975) described depositional facies in deltaic sediments and concluded that they result from a large variety of interacting dynamic processes (climate, hydrologic characteristics, wave energy, tidal action, etc.) that modify and disperse the sediment transported by the river.

2.2.3.2.3 Bottom-set bed deposition

Bottom deposition of the reservoir is formerly by transporting and depositing the fine sediment, which is carried by the water to the middle and end of the reservoir in suspension stage. This type of deposition is mainly composed of clay and silt fraction, which are transported in the reservoir water body either by the turbulent suspension or by turbidity currents. Its deposition starts beyond the delta upstream the dam wall site. The shape and configuration of the deposit is affected by the process of transporting and depositing of suspended material. There are two main ways of transporting fine sediment into the reservoir body. First is by suspension action of sediment particle. In this case they travel beyond the delta towards the reservoir body either by the action of electro-magnetic of small particles or by turbulence action of flowing water. The second way is by gravity action on the sediment-laden water which enters to the bottom of the reservoir in the form of turbidity current (Bashar *et. al*, 2010).

2.2.4 SEDIMENT YIELD AND PRODUCTION

The displacement of sediment by water depends on the amount and erosivity of the rainfall, slope of the terrain, soil erodibility, and the extent of ground cover. These factors can be further grouped into those that affect: (1) the availability of sediment (i.e. soil erosion hazard and land cover), and (2) the washoff of this sediment (i.e. rainfall erosivity, Mean Annual Precipitation (MAP) and slopes)."Washoff" and "Availability" are in fact common to all nonpoint source problems. Qualitative assessments of these factors can be combined to identify areas of high, medium or low sediment availability and washoff potential. For example steep slopes, combined with high energy rainfall and a high MAP yield a high washoff potential, while erodible soils, poor ground cover and certain land uses yield a high sediment availability. High washoff potential together with high sediment availability in turn identify areas with a high sediment production potential (Moolman, 2004).

Sediment yield varies both in time and space. Knowledge of the extent of the temporal and spatial variability in sediment yields is significant in the context of resource allocation for sediment control measures. Most sediment transport occurs during the months of the year in which the river has high water flows, and this period can contribute up to 90% of the annual load (Msadala, 2009). The determining factors for an increase or decrease in sediment yield with time depend on the site-specific conditions. In some circumstances, annual variability in sediment yield can just be a reflection of the variability in precipitation and runoff.

The information on sources of sediment yield within a catchment can be used as perspective on the rate of soil erosion occurring within that catchment. Soil erosion prediction in turn allows policymakers to assess the current status of the land resource and the potential need for enhanced or new policies to protect soil and water resources

(Flanagan *et al.,* 2002). Water erosion is a powerful factor in landscape evolution. As a result of enhanced erosion, soil fertility is decreasing considerably and rivers, canals and reservoirs are experiencing accelerated siltation. In addition, the products of erosion, i.e. sediments, act as a vector and potential store of contaminants. The urgent need to understand and control soil erosion arose at the boundary of the 19-20th Centuries and remains important today (Bobrovitskaya, 2002).

2.3 CAUSES OF SEDIMENTS

2.3.1 OVERVIEW

Every human action within a catchment has an effect on the sediment movement and dynamics. Sediments and soils washed from the catchment silt up drainage channels and creeks and eventually end up in the river, lake, wetland, dam or sea. Sediments found in a river catchment are an accumulation from many different sources. While no one source is solely responsible for the problem, the combined effect of all contributing factors amounts to a huge influx of sedimentation which affects the balance of the ecosystem.

A quantitative understanding of both natural and anthropogenic sediment sources is needed to accurately assess and predict the adverse effects of sediments on aquatic ecosystem (Ramos-Scharrón and MacDonald, 2007). Sedimentation will occur constantly at the boundaries closer to the source. The highest amounts of sediments are deposited during conditions of high sediment concentration along with low wave activity (Van Proosdij et al., 2000). As the water moves further away from the source, the concentration of sediment will decrease. Therefore, the points further from the source, or further inland, tend to not receive as much sediment load (Friedrichs and Perry, 2001). Net deposition of sediment on a marsh is therefore, a function of the availability of sediment and opportunity for deposition. The increase concentration of sediment will increase the opportunity for deposition (McDonald, 2003). **Sections 2.3.2** and **2.3.3** discusses the anthropogenic, and natural causes respectively.

2.3.2 ANTHROPOGENIC CAUSES

2.3.2.1 Overview

The term anthropogenic designates an effect or object resulting from human activity. Human activities have significantly enhanced sedimentation as well as sediment loss. Sediment producing activities can be land-based (i.e. agriculture, forestry, construction, urbanization, recreation) and water-based (i.e. dams, navigation, port activities, drag fishing, channelization, water diversions, wetlands loss, other large-scale hydrological modifications). Sediment impoverishment or loss is generally due to retention behind dams, bank or beach protection activities, water diversions, and many of the aquatic activities. Morphological changes (physical changes over a large area) to large aquatic systems can also result in major changes in natural sediment erosion and sedimentation patterns. As an example, the change in the size and shape of a water body will result in new water flow patterns leading to erosion or sediment removal from sensitive areas.

Land use impacts on sediment loads are commonly seen as resulting in increased sediment loads and therefore as an inadvertent effect of human activity. However, the active implementation of soil and water conservation and sediment control programmes in river catchments can have the reverse effect and result in reduced sediment loads, or at least reduce the increases associated with land clearance and surface disturbance. Anthropogenic causes are generally classified according to three groups, i.e. development, agriculture and desertification, and these are discussed further in the following subsections.

2.3.2.2 Development

While the construction of buildings, services and roads are necessary, it is important to minimize the removal of the vegetation cover that holds the soil in place in the catchment. Erosion during and after construction of roads, highways, and bridges can contribute large amounts of sediment and silt to runoff waters, which can deteriorate water quality and lead to fish kills and other ecological problems. Heavy metals, oils, other toxic substances, and debris from construction traffic and spillage can be absorbed by soil at construction sites and carried with runoff water to lakes, rivers, and bays. Runoff control measures can be installed at the time of road, highway, and bridge construction to reduce runoff pollution both during and after construction. Such measures can effectively limit the entry of pollutants into surface waters and ground waters and protect their quality, fish habitats, and public health. In there are no measures in place, rain can erodes exposed soil and carry it to the drainage lines and creeks, where it is finally deposited into the river system. Urban development usually means more paved and sealed areas. More water runs off these hard surfaces and at a greater speed, increasing erosion when the water reaches unsealed areas.

Construction and maintenance standards of the unpaved roads are generally poor. Road drainage structures (i.e. ditches, culverts, or cross-drains) are sparsely located, even on extremely steep segments. As a result of the high rainfall erosivity and poor drainage design, deep rills commonly develop on road surfaces, especially on the steeper segments. These steeper segments typically have to be regraded every year or so to allow passage by standard passenger cars. Eroded soil from construction sites is carried to streams and lakes where it causes (1) excess turbidity that harms aquatic life, increases water-treatment costs, and makes the water less useful for recreation; and (2) sedimentation that clogs drainage ditches, stream channels, water intakes, and reservoirs, and destroys aquatic habitats (USGS, 2011).

There is planning that can be undertaken to prevent runoff pollution from road, highway, and bridge construction. However, an erosion and sediment control plan during development needs to be integrated to other plans that are aimed at managing sediments.

2.3.2.3 Agriculture

Agriculture, including commercial livestock and poultry farming, is the source of much organic and inorganic sediment that pollute surface waters and groundwater. These contaminants include both sediment from erosion cropland and compounds of phosphorus and nitrogen that partly originate in animal wastes and commercial fertilizers. Animal wastes are high in oxygen demanding material, nitrogen and phosphorus, and they often harbour pathogenic organisms. Wastes from commercial feeders are contained and disposed of on land; their main threat to natural waters, therefore, is from runoff and leaching. Control may involve settling catchments for liquids, limited biological treatment in aerobic or anaerobic lagoons, and a variety of other methods (SIEWF, 2008).

2.3.2.4 Desertification

Desertification is another source of sediment increase. It is said that about “one fifth of the world’s population is threatened by the impacts of global desertification. Its effects can be seen all over the world. Today, a third of the earth’s surface is threatened by desertification, which adds up to an area over 40×10^6 km^2 of the planet.” The cause of desertification is human activities such as over-cultivation and poor irrigation practices combined with climate change. Fertile soils become barren patches of land and washed away by wind or water and deposited in water systems as sediments (Takeuchi, 2004).

2.3.3 NATURAL CAUSES

2.3.3.1 Overview

Natural sources of sediments include erosion of bedrock, soil and decomposition of plants and animals. Natural sediment mobilisation is an important process in the development and maintenance of coastal habitats, including wetlands, lagoons, estuaries, sea-grass beds, coral reefs, mangroves, dunes and sand barriers. In the following subsection three different causes (i.e. soil erosion, tree throw, and climate change) of natural sedimentation are discussed.

2.3.3.2 Soil erosions

Soil erosion occurs when soil is removed through the action of wind and water at a greater rate than it is formed. Erosion occurs when the land surface is left bare in regions that are arid enough, as a result of low rainfall, to allow the soil to dry out, and flat enough to allow the wind or water to carry the soil away over several consecutive days. Land may become susceptible to wind and water erosion through grazing animals, which remove the protective plant cover, and whose hooves break up the soil, especially round watering points. Arable land that has been left bare is also a major problem (NDA, 2006).

Wind and water erosion on agricultural and non-agricultural lands removes 4 billion tons of soil annually. Two thirds of this amount is moved by water and one-third by wind. In forested areas erosion can occur by a wide variety of processes, including soil creep, dry ravel, mass movements including slumps and slides from slope failure, and biogenic transport (for example, animal burrowing or tree throw). In most undisturbed forests erosion rates and sediment yields are typically low. Unpaved roads, rural and urban development, and forest management activities will usually increase erosion rates, but the net effect on waterways and aquatic habitat is highly variable. Sometimes much of the sediment eroded from a site may not make it to the stream depending on the force acting upon them. In such cases, an increase in erosion may have relatively little adverse effect on stream channel morphology and aquatic ecosystems. On the other hand, erosion is likely to remove much litter and some of the surface mineral soil layer. Both of these are sources of onsite nutrients and organic matter, in which case loss by erosion will have a direct, adverse effect on site productivity. Drainage from roads and developed areas often flows directly into the stream network, and the increase in runoff and/or sediment can adversely affect downstream resources and aquatic ecosystems (Cipra *et al.,* 2003).

Surface erosion, due to wind or water, is definitely the most important source of sediment production wherever vegetation does not provide a sufficient cover of the soil from the rainfall impact, and morphological conditions are such as to foster the removal of particles by wind or overland flow. This means that surface erosion is particularly active in cropland areas, especially where the type of soil is more vulnerable, yet erosion-control measures and correct cultivation practices have not been applied. In many temperate countries, an extremely high rate of surface erosion took place in historical times, following the rapid expansion of cultivated areas and before sustainable land management was adopted (Di Silvio, 2008). Wind can move sediment grains over long distances when they are carried through the air. Sediments also can be blown along expanses of land, such as beaches, mudflats, or construction areas.

A major challenge in the management of ungagged catchments is not only the estimation of hydrological balances but also of material fluxes, in particular those of sediment. This is especially critical where the delivery of sediment may compromise the physical function (e.g. due to siltation or channel diversion) or ecology (e.g. via the delivery of associated plant nutrients or contaminants) of the receiving water body (Grant *et al.,* 2003).

2.3.3.3 Tree throw

Root throw is defined as tree uprooting when the root plate is upheaved along with any attached sediment. Root throw is recognized as an important near-surface process affecting infiltration, air capacity and remixing of organic material and is also an important sediment transporting agent on forested hill slopes. Root throw results in vertical and horizontal displacement of sediment attached to the roots (called the root plate). The disturbed sediment often remains attached to the root plate for a period of time after root throw. Subsequent root plate disintegration due to weathering and decay of the roots leads to vertical fall of sediment, which may remain in situ or move horizontally and/or vertically due to gravity and inertia (Gallaway *et al.,* 2009)

Although tree throw provides a dramatic example of bio-turbation by plants, roots do not have to be ripped out of the ground to move sediment. The prosaic but unremitting process of root growth and decay also contributes to a downslope flux of soil. The mechanics of sediment transport by this process are similar to shrink-swell in clays and frost heave, where there is an initial expansion normal to the ground surface, followed by a vertical collapse. In the case of roots, expansion is provided by root growth that can apply axial pressures up to 1.45 MPa and radial pressures up to 0.91 MPa. These pressures are substantial and suggest that root growth could push up a column of soil approximately 100-m thick (assuming, of course, no internal deformation within the soil). When the root decays through the continual process of root turnover, the void left by the root is eventually filled by soil caving in from above (Gabet *et al.,* 2003).

2.3.3.4 Climate Change

Climate change may affect the sediment generation and transportation processes and the consequent sediment flux in a river. anthropogenic causes of sediments mentioned above can also interact with climate change resulting in changing sediments load. In most rivers, however, it is likely to prove difficult to disentangle the impact of climate change or variability from changes resulting from other human impacts, and existing evidence suggests that, in most cases, these human impacts are at present likely to be more significant. Equally, however, the clarity of the signal reflecting the impact of human activity could be reduced by climatic variability, for example where it is superimposed on changes associated with variation of the Southern Oscillation Index and associated shifts between El Nino and La Nina conditions (Walling, 2008).

Lawler *et al.* (2003) were, nevertheless, able to report a clear example of the impact of recent changes in atmospheric circulation on the suspended sediment fluxes from two glacierized river catchments in Iceland. In this case, there was negligible anthropogenic disturbance of the catchments and any trends were attributed to climate variability. To date, few studies have provided definitive evidence of the impact of recent climate change in causing changes in the sediment loads of the world's rivers and there is clearly a need to establish the importance of this driver in both absolute terms and in relation to other more direct impacts of human activity. To link changing sediment fluxes to their causes, independent time series of land use and climate changes need to be documented (Walling, 2008).

2.4 IMPACTS OF SEDIMENTS

2.4.1 OVERVIEW

There are both positive and negative environmental and socio-economic effects of sediments. The positive aspects of sediments can be accentuated and the negative impacts lessened by appropriate planning and management regimes in a river catchment.

In this chapter the negative and positive impacts of sediments on both the environment, and socio economics are discussed.

2.4.1.1 Negative impacts of Sediments

The construction of reservoirs, especially large reservoirs, greatly changes the natural river conditions and causes a number of environmental and ecological problems related to sedimentation. On the one hand, the sediment carried by flow largely deposits in the reservoir because of the reduction of flow velocity, and diminishes the benefits of the reservoir. On the other hand, the flow released from the reservoir carries much less sediment than the natural flow and scours the downstream river channel. Engineers and planners should pay close attention to these problems in the planning and design stages and try to find available measures or operations to mitigate the damaging effects of the reservoirs as much as possible (Xiaoqing, 2003).

Worldwide sedimentation is a serious problem and considered as salient enemy. The sediment trapped in a reservoir limit the life of the reservoir (Takeuchi, 2004) and diminishes benefits for irrigation, hydropower generation, flood control, water supply, and navigation (Bashar *et al.,* 2010). Other environmental impacts of sedimentation include the following: loss of important or sensitive aquatic habitat, decrease in fishery resources, loss of recreation attributes, loss of coral reef communities, human health concerns, changes in fish migration, increases in erosion, loss of wetlands, nutrient balance changes, circulation changes, increases in turbidity , loss of submerged vegetation, and coastline alteration.

Further, as sediments deposition propagates upstream and up tributaries, it raises local groundwater table, reduces channel flood capacity and bridge navigation clearance, and affects water division and withdrawals. On the other hand, the reduction of the sediment load downstream can result in channel and tributary degradation, bank erosion and in changes of the aquatics habitats to these suited to a clearer water discharge (Bashar *et al.,* 2010).

2.4.1.2 Positive Impacts of Sediments

Sediments bring a number of challenges to the environment and so as to human's life. However, it does not always cause trouble and can sometimes even be utilized as a precious resource. Sediment eroded from upstream catchments normally contains organic manure, fertilizers and other matter (Xiaoqing, 2003). Loamy soils and soils with lots of organic matter are the type of soils that are primarily used by farmers who need to plant crops. Farmland irrigated by water with sediment may have higher production levels because of fertility in the sediment. Sediment may also be diverted to warp and improve lowlands. The sediment may also be used as construction material for earth embankments and dikes for flood control. It is a good local material, with the advantages of low costs, short transportation, and convenience. In some developing countries, the sediment dredged from rivers, lakes or reservoirs is used to make bricks (Xiaoqing, 2003).

Sedimentation in reservoirs can also have positive impacts downstream of a dam. Reservoirs greatly reduce the quantity of suspended solids, especially in catchments disturbed by deforestation and development. This reduces the cost of water treatment and can be beneficial to aquatic ecosystems sensitive to elevated suspended solids levels. Many recreational uses, such as fishing, also benefit from reduced suspended sediment and enhanced water clarity (Utah Division of water resources, 2010).

Sediments transported by rivers carry important nutrients and organic material such as algal cells and finely divided organic detritus. “Modification of the production and transport of this organic material by the dam-reservoir system can have important ecological consequences downstream. Reservoirs can greatly reduce the downstream transport of detrital organic material used as a food source in the downstream ecosystems. Conversely, reservoirs with a prolonged detention period can discharge water enriched with limno-plankton (tiny freshwater plant and animal life).” (Utah Division of water resource, 2010).

Table 3: Major Impacts of sediments (Environment Canada, 2005)

Pertinence Sector Action or Mechanism Impacts			
MAJOR IMPACTS			
Major rivers and navigable waterways	Navigation	• Deposition in rivers or lakes. • Dredging (streams, reservoirs, lakes or harbours).	• Decreases water depth making navigation difficult or impossible. • Releases toxic chemicals into the aquatic or land environment.
Aquatic ecosystems	Fisheries/ aquatic habitat	• Decrease light penetration. • Higher suspended solids concentrations. • Absorbed solar energy increases water temperature. • Carrying toxic agricultural and industrial compounds • Settling and settled sediment.	• Affects fish feeding and schooling practices; can reduce fish survival. • Irritate gills of fish, can cause death, and destroy protective mucous covering in fish eyes and scales. • Stress to some fish species. • Release to habitat causes fish abnormalities. • Buries and suffocates eggs. • Reduces reproduction.
Lakes, rivers, reservoirs as water supplies	Water supply	• Increased pump/ turbine wear. • Reduced water supply usability for certain purposes • Additional treatment for usability required	• Affects water delivery, increases maintenance costs. • Reduces water resource value and volume. • Increased costs.
Hydroelectric facilities	Hydropower	• Dams trap sediment carried downstream. • Increased pump/turbine wear	• Diminishes reservoir capacity. • Shortened power generation lifecycle. • Higher maintenance, capital cost

Pertinence Sector Action or Mechanism Impacts			
MAJOR IMPACTS			
All waterways and their ecosystem	Toxic chemicals	• Become attached or adsorbed to sediment particles	• Transport to and deposited in other areas • Later release into the environment.

2.4.2 ENVIRONMENTAL IMPACTS OF SEDIMENTS

Human impact in the fresh water environment has not been a big issue in South Africa as it has been in the Northern Hemisphere, with its big commercial interests in freshwater fisheries. Recent surveys do however indicate problems in this regard. Sediments from drainage catchment erosion are the greatest single factor contributing to the problem. The accelerated accumulation of sediments in aquatic ecosystems leads to a decline in surface water quality and biodiversity. Adverse impacts on aquatic ecosystems result from excessive sedimentation and turbidity. Sediments fill the interstices of gravel and cobble stream bottoms, greatly decreasing the spawning areas for many fish species and the habitat for macro-invertebrates, which serve as food for many fish species (USGS, 2005).

The environmental impacts of sedimentation include the following: loss of important or sensitive aquatic habitat, decrease in fishery resources, loss of recreation attributes, loss of coral reef communities, human health concerns, changes in fish migration, increases in erosion, loss of wetlands, nutrient balance changes, circulation changes, and increases in turbidity, loss of submerged vegetation, and coastline alteration. Improper sediment management results in the destruction of aquatic habitat that would have otherwise depended on their presence.

2.4.2.1 Effects on invertebrates

Elevated levels of Suspended and Bedded Sediments have been shown to have wide ranging effects on both pelagic and benthic invertebrates. Effects can be classified as having a direct impact on the organism due to abrasion, clogging of filtration mechanisms thereby interfering with ingestion and respiration, and in extreme cases smothering and burial resulting in mortality. Indirect effects stem primarily from light attenuation leading to changes in feeding efficiency and behaviour (i.e. drift and avoidance) and alteration of habitat stemming from changes in substrate composition, affecting the distribution of in faunal and epibenthic species (Berry *et al.*, 2003).

Reduced feeding activity as a response to increased levels of suspended sediments has also been reported for copepods and daphnids. Invertebrate drift is directly affected by increased suspended sediment load in freshwater streams and lakes. Increases in suspended sediments (e.g. 120 mg/l) can result in increased drift, significantly altering the distribution of benthic invertebrates in streams. Alteration in the quality and quantity of deposited sediments can affect the structure and function of benthic macro faunal communities by increasing substrate embeddedness and altering substrate particle size distributions. Increased embeddedness can result in decreases in aquatic insect densities and small increases in siltation can directly affect caddis fly pupa survival. Several studies have examined the effects of the burial of estuarine invertebrates (Berry *et al.,* 2003).

2.4.2.2 Effects on Coral reefs

The increased sedimentation resulting from coastal development is a major source of coral reef degradation. Excessive sedimentation can adversely affect the structure and function of the coral reef ecosystem by altering physical and biological processes. High sediment loads can smother tissue resulting in bleaching in the short-term and death in the long-term. Excessive sedimentation can affect the complex food web associated with coral reefs, killing not only corals but other reef dwelling organisms (e.g. sponges) which serve as food for commercially important fish and shellfish. Declines in tropical reef fisheries in the Caribbean and the Pacific are believed to be partially due to increased sedimentation rates. Increased sedimentation is also one of several factors which affect coral recruitment. Coral larvae will not settle and establish themselves in shifting sediments. Consequently, increases in sedimentation rates can alter the distribution of corals and their associated reef constituents by influencing the ability of coral larvae to settle and survive (Berry *et al.,* 2003).

2.4.2.3 Effects on Aquatic plants

Some populations of aquatic macrophytes have experienced dramatic losses over the past two decades, a decline largely attributed to changes in underwater light climate due to increases in suspended sediment concentrations (Best *et al.,* 2001). Turbidity limits the growth and distribution of aquatic plants by reducing available light. The large-scale declines of Submerged Aquatic Vegetation (SAV) reported in Chesapeake Bay are believed to be directly related to increasing amounts of nutrients and sediments entering the Bay. To address the unacceptable Bay-wide decline in SAV the United State Environmental Protection Agency Chesapeake Bay Program office established water clarity criteria. Water clarity criteria are based on the light requirements for SAV growth and survival. The criteria take total suspended solids (particulate matter and chlorophyll a) into account, as well as epiphytic growth and salinity regime. Submerged Aquatic Vegetation is also subject to burial, although different species have different tolerances for sediment accretion, and different sediment entrainment qualities. These different tolerances can result in changes in species composition in addition to overall loss of SAV as a result of increased siltation. It is not always possible to separate out the effects of burial from the other effects of increased sediment input, e.g. reduced light penetration (Berry *et al.,* 2003).

2.4.2.4 Effects on fish

The effects of increased Suspended and Bedded Sediments resulting in increased embeddedness, on salmonids in particular, have been well documented. An increased supply of fine sediment to a stream can cause the gravel interstices of a stream bed to be filled in. This process can cause reduced hatching due to the reduction in flow through the stream bed and the resulting decrease in dissolved oxygen. It can also cause reduced larval survival because of armouring of the sediment surface which traps the larvae. Increased sedimentation in other habitats (e.g. estuaries) can cause burial of eggs. Even a small amount of deposited sediment can cause a problem. Winter flounder eggs, for example, will suffer reduced hatching success if buried to only one half an egg diameters (Berry *et al.,* 2003).

2.4.2.5 Effect on wildlife

There are very few published reports on the effects of Suspended and Bedded Sediments on aquatic-dependent wildlife (i.e. birds and mammals). For the most part, aquatic-dependent wildlife are more mobile than the fish, invertebrates and plants and therefore aquatic-dependent wildlife can avoid most of the direct effects of increased Suspended and Bedded Sediments. A heron or an osprey, for example, can avoid more turbid areas, and choose areas of clearer water. If and when the water clears in the area, the bird can return. If increases in Suspended and Bedded Sediments are wide-spread and long-term, however, they might cause a problem for aquatic-dependent wildlife that consumes aquatic prey. Most of the studies of the relationship between turbidity and aquatic-dependent wildlife involve field studies with birds. Turbidity makes it difficult for water birds to forage effectively (Berry *et al*., 2003).

2.4.3 SOCIO-ECONOMIC IMPACTS OF SEDIMENTS

Sediment is socio-economic, environmental and geomorphologic resources, as well as, a tool of nature. However, changes in sediment quantity and quality can have a significant impact on a range of social and economic systems. The deposition of sediment in irrigation canals and its subsequent built-up of aquatic weeds results in losses in production of great magnitude. On the other hand, the cost of sedimentation includes loss of hydropower potential since method of sediment removal involves measures that lower the head and interfere with generator operation. The most serious effect, however, is the loss of agricultural production. The problem of sedimentation has been reflected downstream in terms of sediment deposition in the reservoirs and the irrigation canalization networks, causing flood risks, crops damage, pumps intakes blockage, low production, navigation and hydropower generation difficulties with socio-economic impacts (Ahmed, *et al.*, 2005) .

2.4.3.1 Loss of storage capacity

Reservoir sedimentation and the consequent loss of storage capacity affect reservoir benefits, such as flood control, water supply, irrigation, navigation, power generation, fishing and recreation. In arid and semi-arid regions, reservoir sedimentation problems become most acute where the loss of storage capacity by reservoir sedimentation is above 1- 2% per year and the lifetime of most reservoirs is only 20 to 30 years. The Welbedacht Reservoir in South Africa, completed in 1973 with a 152.2 million m^3 storage capacity, lost most of its storage capacity (66%) within the first 13 years of its existence (Rooseboom *et al.*, 1992).

In Italy, an analysis of 268 reservoirs distributed over the country with a mean age of 50 years showed the following loss of reservoir storage capacity: 1.5% of the reservoirs were completely filled by sediment, 4.5% had lost 50% of their storage capacity, and 17.5% had lost 20 per cent of their storage. The Ichari Reservoir in India silted up to crest level of the spillway in two years. The Austin Reservoir lost 41.5% of its total storage volume from 1893 to 1897, and the dam gave way in 1900. The new Lake Austin of the Colorado River in Texas lost 95.6% of its capacity in 13 years, the Habra Reservoir in Algeria 58% in 22 years, and the Wuchieh Reservoir in Taiwan 98.7% in 35 years. The Indus River carries about 74 billion m^3 of water and 300 million tons of suspended sediment per year into the Tarbela Reservoir. In the six years after its commissioning in 1974, it accumulated about 950 million m^3 of sediment in the upper 30 km of the delta (Wu, *et al*., 1996).

2.4.3.2 Downstream navigation

When a reservoir is built on a river, much of the sediment is stored in the reservoir. The flow released from the reservoir carries much less sediment than the natural flow, which interrupts the sediment balance and results in scouring in downstream reaches and a lowering of the water level. For a navigable river, this may result in insufficient water depth during the low flow seasons (Xiaoqing, 2003).

2.4.3.3 Damage to agricultural land

Sedimentation damage to agricultural land resources can be related to over wash of infertile material, impairment of natural drainage, and swamping due to channel aggregation, associated floodplain scour and bank erosion. The best and most differentiated flood damage information in South Africa is available through the damage surveys undertaken after the major floods in 1974. Damage due to erosion products is not identified separately. Deposition of sediment is probably the most widespread form of flood damage in the dryer regions of South Africa (Braune and Looser, 1989).

2.4.3.4 Health

Sediments take up the active storage of reservoir, which means that such reservoir can be a breeding space for diseases vectors such as mosquitoes which spread malaria. Other water-borne diseases can emerge due to the water not flowing freely as well as contaminants associated with sediments can be deadly. Thus the community water availability is reduced due to poor water quality conditions.

Various pollutants are commonly found in urban and suburban storm water. Runoff from roofs, roads, and parking lots can contain significant concentrations of copper, zinc, and lead, which can have toxic effects in humans. Insecticides are frequently found in fish in at level considered harmful to wildlife, raising concerns about carcinogenic effects and disruption of hormonal systems in humans.

In the initial stage of reservoir sedimentation, the deposition of sediment can actually improve the water quality by absorbing pollutants. According to observations carried out at Guanting Reservoir, one ton of sediment can absorb 700 g of dissolved lead. Mud deposited on the reservoir floor displays strong adsorption of arsenic, of which the concentration on the floor is 10 to 100 times higher than that in water. Similarly, the concentration of chromium on reservoir floors is about 20 000 times higher than that in water. Thus, deposited sediment as well as the layer of water near the floor will be progressively polluted. Pollutants increasingly accumulate in the lower part of the reservoir. In time, they become highly concentrated that this part of the storage becomes in itself a source of pollution (Xiaoqing, 2003).

2.5 SEDIMENT MANAGEMENT

2.5.1 OVERVIEW

The concept of Integrated Water Resource Management recognises the need to manage water resources in an integrated manner and on a catchment scale. For over a century, hydrologists and geomorphologists have recognised that the movements of water and sediments are controlled by processes which operate at the catchment scale. The management of sediments in rivers has a long history and has, until recently, tended to deal with local issues, usually associated with either (a) excessive amounts of sediments in rivers, reservoirs and harbours and associated removal and dredging activities or (b) issues of sediment deficit and the effects of this on habitats (including river banks, floodplains and deltas) and building structures. The main driver has normally been a specific local issue such as the need to maintain navigation, water storage or conveyance capacity, or, less frequently, the need to move contaminated sediment from a particular area or to restore habitat. Alongside this there is a long history of beneficial use of sediment, such as extraction of gravel or sand for the construction industry. Over recent years, increased awareness of the quality, as well as the quantity, aspects of sediment have led to increasingly stringent controls on sediment related activities, and in particular on disposal of dredged material (White and Apitz, 2008).

According to White and Apitz (2008), sediment management actions are normally taken as a result of sediment quantity imbalances; however, the issues that make such management complex are often related to sediment quality. A wide range of contaminants have low solubility but high sorption potential, meaning that they bind to sediment particles, and in particular to the finer grained clay and silt particles. Because of the intermittent way in which sediments, and their associated contaminants, move through the river catchment and river system, contaminated sediments can be delayed within the sediment supply and transfer chain for decades or even centuries, remaining within alluvial floodplains or buried in sediment deposits. When these sediment stores are disturbed, through extreme flow events, channel migration, alterations to the flow duration curve or direct physical disturbance, contaminants, some of which may not be currently used or may be banned from use, can be remobilised. There is thus a legacy problem, where sediments are acting as the memory of previous polluting activities in the river catchment (White and Apitz, 2008).

Sediment management is necessary to ensure that the requirements governing utilisation or protection of water courses are met, and also to protect sediments as natural elements of water courses. Completely natural water courses which are not subject to human influence or requirements do not need sediment management (HTG, 2004). From a societal point of view, sediment is managed in the landscape for a variety of reasons, including:

- to maintain urban drainage and sewerage systems;
- 'maintenance dredging' in river channels, estuaries, ports, harbours, etc. to maintain shipping transportation;
- to maintain the life-span of reservoirs and for operational reasons;
- to ensure the efficient flow of water in watercourses and reduce flooding;
- to maintain or improve terrestrial and aquatic habitats (i.e. fisheries, coral reefs, etc.);
- to maintain geomorphological features, sometimes for aesthetic or recreational needs (such as gravel bars, beaches, etc.); and
- to maintain or improve water quality.

Sediments are absolutely necessary for aquatic plant and animal life. Managed properly, sediments are a resource; improper sediment management results in the destruction of aquatic habitat that would have otherwise depended on their presence.

Appreciation of sediment as part of a dynamic river catchment system, and of sediment as a 'memory' of previous activities, leads to the conclusion that it may not be most effectively managed at an individual site. Sediment also needs to be more explicitly considered in a range of activities within river catchments which may affect the river sediment regime whilst being targeted towards quite different ends. It is thus important to consider sediment management within its wider environmental, economic and social context. In order for river catchments to be used as sediment management units, it is vital to have a conceptual model of river catchment functioning that links different areas in space and time, and allows potential consequences (impacts) of drivers to be evaluated (White and Apitz, 2008).

2.5.2 SEDIMENT MANAGEMENT AT A RIVER CATCHMENT SCALE

2.5.2.1 Why manage sediment at the river catchment scale?

While the tendency is to think of each sediment issue in relative isolation, and manage these accordingly, each sediment function or use is both dependent on other functions in time and space, and in turn influences many other sediment functions and uses. Thus if we are to manage sediment for the needs of nature (i.e. for maintaining fish habitats) and/or society (e.g. dredging for maintaining navigation), then this needs to be undertaken with a full appreciation and consideration of management impacts on nature and society within the river catchment. Thus the river catchment scale represents the most convenient and meaningful management unit for river management, be it for water and/or sediment (Owens, 2008).

Following on from the discussion in the previous sections, there are several reasons, many of which are inter-related, as to why sediment management should either be at the river catchment scale or be part of a broader management programme at this scale (i.e. for soil-sediment-water management). The following sub-sections consider some of these and are based on Owens (2008).

2.5.2.1.1 Interventions have implications

Decision-making needs to be placed within the context of a river catchment because a local or site-specific intervention will in most cases impact other parts of the catchment, either upstream or downstream of the intervention. This is because a river catchment operates and functions as an open system with interconnected subsystems (hillslopes, floodplains, river channels, lakes, harbours, etc.). By altering one subsystem or part of a subsystem there will be impacts on other parts of the system. Thus, in order to manage the system in a sustainable way, this needs to be done at the most appropriate scale. For rivers, the management scale of the system is the river catchment scale because the size and topography of the river catchment, and the activities within it, control the sources, pathways and fluxes of water, sediment and contaminants (Owens, 2008).

2.5.2.1.2 Multiple functions, uses and users of sediment

Most river catchments throughout the world are highly populated and/or modified by human activities, and thus society has many uses of sediment and/or has various impacts on sediment behaviour which place pressure on the various functions that sediment performs. Thus site-specific sediment intervention or management will have impacts on other functions, uses and users of sediment. It is therefore necessary to consider, and to some extent evaluate, all users and uses of sediment within a river catchment. The river catchment scale is the most appropriate scale for decision-making involving multiple interested parties because the catchment topography defines the area in which most sediment functions operate and in which many sediment users reside. Thus the actions of a farmer or land owner will influence soil erosion and sediment delivery within the catchment in which the land is located, and thus downstream sediment functions and uses such as fishing and dredging, but their actions are unlikely to influence such functions and uses in adjacent catchments (Owens, 2008).

2.5.2.1.3 Source control as the best solution

In most cases, source control will be the optimal long-term solution: environmentally, socially and economically. Most sources of sediment, and many sources of contaminants, are derived from diffuse sources. Most diffuse sources of sediment operate across large areas and may be dispersed throughout all or most of the river catchment, such as those sources associated with agricultural land. The controlling of such diffuse sources necessitates a river catchment scale approach in order to: identify all or most of the sources of the sediment and contaminants; for conducting meaningful risk assessment and evaluation; and to be able to implement remediation and mitigation options that are appropriate for controlling diffuse sources spread over a large area (Owens, 2008).

2.5.2.1.4 The dual issues of quantity and quality

Recently, in many countries, sediment management has had to consider the dual issues of sediment quantity and sediment quality. The latter has become particularly important in recent years due to the introduction of guidelines and legislation associated with the removal and disposal of contaminated sediment, especially in marine and estuarine environments. Of fundamental importance for water, and indirectly sediment, management is the focus on the river catchment as the main unit of assessment and management, and the development of River Catchment Management Plans (Owens, 2008).

2.5.2.2 The need for catchment sediment management plans

Where necessary the River Catchment Management plan should be supplemented by a Sediment Management Plan which takes into account the underlying needs and represents part of an agreed maintenance plan linked to the measures necessary to achieve the sediment quality targets. In doing so, the various conditions of the catchment area must be taken into account. In general it will be necessary to differentiate between inland watercourse and tidal/coastal areas. The components of a sediment management plan for a particular river catchment should include the following (HTG, 2004):

- Basic objectives and requirements within the context of the River Catchment Management Plan;
- Evaluation/monitoring of sediment quality;
- Action to reduce input of contaminants;
- Action to reduce erosion and control sedimentation processes;
- Action to provide and maintain water depths, discharge conditions, the maintenance of wetland areas, shallow water areas and retention spaces, and clean up measures;
- Framework for the disposal of sediments in water, *i.e.* relocation, or possibly sub-aquatic confined disposal; and
- Options for beneficial use of removed sediment, including on land.

Management options include sluicing sediment through a dam, mechanical sediment removal, and in some cases, dam removal. Sluicing and releasing sediment downstream is achieved by lowering the reservoir water surface to expose the sediments and the incoming stream flow carries the sediments through openings in the dam. Removing reservoir sediment using mechanical methods (dredging or excavation) can be very costly. In removing a dam, potential sediment impacts (erosion, transport, and deposition) could occur in the reservoir and in the river channel. The water discharged from a reservoir typically has a reduced sediment load and this affects channel and habitat conditions downstream of a dam. There are benefits to restoring the sediment supply to the downstream channel but potential negative impacts, such as increased flooding potential and temporary destruction of habitat could occur. However, these potential sediment impacts can be reduced or avoided with an effective sediment-management plan (USBR, 2008).

2.5.2.1 Requirements to manage sediment at the river catchment scale

Having established that the river catchment scale represents the most appropriate scale or unit for management, it is necessary to obtain the relevant information required to make decisions so as to manage sediment effectively and, ideally, sustainably. Some key requirements in the decision-making process for sediment management at the catchment scale include (Owens, 2008):

1. Identifying the drivers for sediment management. In other words, why does sediment need to be managed? There are a variety of drivers and pressures that operate at different spatial scales. In most situations, sediment management is influenced and guided by legislation and policy. At the river catchment scale, it is likely that there are many types of legislation and policy relevant for soils, water and waste where sediment plays a key, if often unstated, role. There are also non-regulatory drivers, such as agri-environment schemes, which influence how and why sediment is managed at a local and regional level. While local, site-specific management actions do not necessarily require an understanding and appreciation of all types of legislation, at the river catchment scale they become relevant and need to be assessed in order to identify those that are relevant.
2. Identifying the sources, pathways and transport processes of sediment and contaminants within the catchment of interest. This is a prime need for sustainable and effective sediment management, by providing an understanding of how the sediment-contaminant system is behaving, and is a central requirement for source control as a management option. What is clear is that, at the catchment scale, there are multiple sources of both sediment and contaminants, and that these sources supply sediment and/or contaminants at different parts of the catchment and over different timescales.
3. Using appropriate tools to assemble the relevant information and data needed for informed decision-making by managers. In many respects, the selection of which 'tool' to use in order to obtain the necessary information is dependent on the management question being asked, such as: What are the main sediment and contaminant sources? Where are they located in the catchment? How will a particular management option (i.e. dredging) affect future sediment fluxes in the catchment? There are many tools and techniques (such as monitoring, modelling and tracing techniques) that are available. Such tools provide much of the basic information that is required by many of the other aspects of the decision-making process. Thus, for example, tracing techniques provide information on sediment sources and pathways, while system modelling is often used to inform policy

development through scenario analysis. Specific tools and approaches available to help river catchment managers with decision making that are particularly relevant at the river catchment scale are risk assessment and cost-benefit analysis. These are specific tools that can be used to assess and evaluate the various management options available to managers.

4. Involving stakeholders in the decision-making process, from start to finish. This is now recognized as an important part of environmental management where there are various interested parties, often with conflicting interests and goals, and when there are several management options available. Indeed, stakeholder participation, and appropriate communication, is becoming increasingly incorporated within environmental legislation.
5. Because of the complexity of trying to manage sediment at a large scale, such as a river catchment, it is often useful to develop a framework (or nested frameworks) which incorporates many of the requirements and considerations listed above, as well as other important issues.

2.5.3 SEDIMENT MANAGEMENT STRATEGIES

There are a variety of different influences and impacts on sediment within a river catchment, and therefore reasons why sediment is managed. What becomes clear, when we look at (a) the multitude of functions and uses of sediment and (b) those factors that influence and impact on these functions and uses, is that: there are many functions and influencing factors; the interactions between them are complex; and they operate at different spatial locations within a river catchment and operate at different time scales (Owens, 2008).

For water managers to make effective sediment management decisions, they need to predict potential river channel and in-reservoir impacts (USBR, 2008). Abatement or control of sedimentation can be successful if implemented on a broad land area or catchment scale and is directly related to improvement in land-use practices. Agriculture and forestry (logging) improvements where soil loss is minimized are not only technically feasible: They can be carried out at a moderate cost and with net benefits. Improved land-use practices are the primary measures to control sediment sources: terracing, low tillage, modified cropping, reduced agricultural intensity (e.g. no-till buffer zones), and wetlands construction as sediment interceptors (Owens, 2008).

Wetlands that separate upland areas from aquatic areas serve as natural filters for the runoff from the adjacent land. Wetlands thus serve to trap soil particles and associated agricultural contaminants. The construction of natural buffer zones and wetlands replenishment adjacent to logging areas are effective techniques. Catchment construction activities such as port expansion, water diversions, channel deepening, and new channel construction must undergo a complete environmental assessment, coupled with predictive sediment re-suspension and transport modelling, so alternative courses of action and activities to minimize the negative impacts of sedimentation may be chosen.

When considering management strategies it is important to realise that urban areas contribute more than twice as much sediment per hectare during rain periods. Instruments to assess the amount of sediment coming from urban areas and construction sites needs to be set up. Data collected from these sediment samplers can be used to develop and implement effective management plans for the control and management of sediment loads from developing and existing urban areas.

Erosion and sediment control investigations should follow a well-documented stepwise process, and with all assumptions and goals clearly stated. The recommended procedure for investigating requirements of a development includes the following steps (QDIEA, Undated):

- Step 1 – Identify issues and concerns
- Step 2 – Develop goals and objectives
- Step 3 – Erosion potential study
- Step 4 – Investigate and evaluate alternatives
- Step 5 – Select Best Management Practice (BMP)
- Step 6 – Develop an Erosion and Sediment Control Program
- Step 7 – Implement and maintain the Program
- Step 8 – Monitor Program and review BMP guidelines

2.5.4 SEDIMENT MANAGEMENT AND RESEARCH – SA PERSPECTIVE

South Africa has been involved in sedimentation research/studies since the 1960s. These researches have addressed issues ranging from the heavy metals in sediments, impact of agricultural sediments to methods that can be used to control reservoir sedimentation. Researches that have been conducted are detailed below.

In 1966, Schwartz and Pullen (1996) developed a guide to the estimation of sediment yield in South Africa which formed the base study to the sediment yield in South Africa. Then, other methods of sediment yield estimation and determination started to be studied. Roberts (1973) developed a method of estimating mean annual sediment yields in ungauged catchments; followed by Rooseboom *et al.* (1979) assessing changes in the sediment load of the Orange River during the period 1920 to 1969; Boucher and Weaver (1991) stated that Doornkamp and Tyson (1973) examined the overall pattern of sediment yield of South African rivers, and calculated suspended sediment yield using Fournier's equation. In 1973, Rooseboom (1978) described sediment discharge in Southern African Rivers using a detailed data base of sediment production for a range of catchments; Le Roux (1985) undertook a qualitative study using maps as a visual means of comparing sediment production to other environmental variables; then Rooseboom *et al*. (1992) developed a sediment yield map of Southern Africa.

Braune (1984) researched about the density of sediment in South African reservoirs; Grobler *et al.* (1987) did a review of sediment and water quality interaction using the Vaal River system as the reference and then Schultz (1988) integrated studies to generate runoff, solutes and sediment in tributary catchment of the Great Fish River and James (1987) conducted a distribution of fine sediment deposits in compound system; Le Roux (1990) conducted a study based on the rate of sedimentation of 87 major storage for spatial variations in the rate of fluvial erosion (sediment production) over South Africa; Rooseboom *et al.* (1992) researched on sediment transport in rivers and reservoirs.

Whyte and Swartz (1997) determine design parameters for the combined process of sedimentation and flotation for the removal of suspended solids from effluents in the pulp and paper industry; and determine the optimum ratio sedimentation to flotation for the effective removal of suspended solids; Basson and Rooseboom (1997) conducted a study on ways of dealing with reservoir sedimentation. This study was followed by a detailed study that focused on one method of dealing with reservoir sedimentation in 1999, *dealing with reservoir sedimentation – Dredging*. Rooseboom (2002) wrote a paper which details how to extract water from sediment-laden streams in South Africa. Van Zyl and Lorentz (2003) conducted a study to verify the performance of selected models on the impact of farming systems on sediment yield in the context of integrated catchment management; Schumann (2003) conducted a study to develop management of marine sedimentation in South African estuaries with special reference to the Eastern Cape.

Hay et al. (2005) developed a guide aimed at improving our understanding about sediments and sedimentary processes in South African estuaries, and how these processes might be managed; Sharpe and James (2006) studied the deposition pattern of sediment from suspension emergent of vegetation and found out that longitudinal deposits from suspension within emergent stems is enhanced by increased flow depth and reduced by increased sediment grain size and stem density; Brick *et al.* (2006) reviewed various international diversion methods and technologies to apply for sediment control at river abstraction works in South Africa. It was found that methods developed in Western Europe for example to control sediment extraction are less effective in South Africa due to the different climatic conditions and sediment characteristics.

Greenfield *et al.* (2007) analysed the quality of sediment in Nyl River system in the Limpopo Province. The results clearly indicate that the metals do not appear to pose an environmental problem in the system and also indicate that all metal concentrations fell within the lower end of the Sediment Quality Guideline Range; Grenfell and Ellery (2009) investigated how streamflow variability impacts upon sediment transport using the Mfolozi River as a case study. It was found that suspended sediment transport was supply-limited in the Mfolozi River, and that differential sediment supply was probably related to rainfall seasonality, variability in precipitation and high rates of catchment evaporation. These same factors are responsible for variability in streamflow.

Armitage and Rooseboom (2011) determined the link between Movability Number and Incipient Motion in river sediments; Gordon and Muller (2010) reviewed international methods for derivation of sediment quality guidelines and how can they be best applied in South African to develop guidelines for sediment quality in South Africa’s freshwaters.

Assessing metal contamination of sediment is complicated since metals are a ubiquitous, naturally occurring component of sediment, their concentrations in un-contaminated sediment can vary by orders of magnitude over relatively small spatial scales, and naturally occurring and anthropogenically introduced metals tend to accumulate in the same areas. South Africa has been actively involved in researches relating to metals in sediment and these include:

- Definition of baseline metal concentrations for assessing metal enrichment of sediment from the south-eastern Cape coastline of South Africa by Newman and Watling (2007).

- Note on the concentrations and bioavailability of selected metals in sediments of Richards Bay Harbour, South Africa by Wepener and Vermeulen (2005).
- Heavy metals (Cd, Pb, Cu, Zn) in mudfish and sediments from three hard-water dams of the Mooi River catchment, South Africa by van Aardt and Erdmann (2004).
- Survey of heavy metals in the sediments of the Swartkops River Estuary, Port Elizabeth South Africa by Binning and Baird (2001).
- Comparison of supercritical fluid extraction and Soxhlet extraction for the determination of DDT, DDD and DDE in sediment by Naude *et al*. (1998).
- Determination and partitioning of heavy metals in sediments of the of the Vaal system by sequential extraction by Gouws and Coetzee in 1997.
- Determination and specification of heavy metals in sediments of the Hartbeespoort Dam by sequential chemical extraction by Coetzee (1993)
- Grobler and Davies (1979) studied the availability of sediment phosphate to algae in 1979 followed by a study that concentrated on sediments as a source of Phosphate: a study of 38 impoundment by 1983
- Metal enrichment of sediment in inland water – the Hartbeespoort Dam by Wittman and Forstner (1975) forming the base of metal studies in sediments in South Africa.
- In 2002 Wade *et al.* conducted a study to assess the radionuclides accumulated in sediments of the Mooi river catchment and it was found that the main radionuclide is Uranium. Then Coetzee (2004) assessed sources, pathways, mechanisms and risks of current and potential future pollution of water and sediments in old-mining areas of the Wonderfonteinspruit Catchment. The results of this study indicate that uranium poses a hazard to water users in the catchment because of its chemical toxicity

In order to develop an integrated framework for the assessment and management of sediment related impacts on water resources in South Africa, it was very important to group and summarise the results of these studies.

3 SEDIMENT MANAGEMENT OBJECTIVES AND TOOLS

3.1 OVERVIEW

Sediment management objectives are narrative statements that describe the desired future sediment quantity and quality conditions at a site or a region. Sediment management objectives should address economic, societal, as well as environmental problems associated with sedimentation. Sediment management objectives must reflect the ecosystem health objectives and be expressed in terms of specific ecological functions (McDonald *et al.*, 2003). The objectives should define the ecological, regulatory and socio-economic goals for both the river catchment (and its outlet to estuaries and the sea) and specific parcels of sediment (Apitz and White, 2003). Sediment management objectives include minimization of losses in reservoir capacity and minimization of risks associated with flooding. Reservoir sediment management objectives can be regional and/or site-specific and they vary from region to region or from site to site.

Gordon (1998) described the process of formulating management objectives which include determining the reasons for the present condition of the ecosystem, establishing a general description of the desired condition of the ecosystem and steps that seek to increase the specificity of visions/goals by translating them into statements of measurable conditions. The study further gave examples of how management objectives can be used in decision-making.

Reservoir management objectives include meeting regulatory criteria, maintaining economic viability, ensuring environmental quality and securing quality of human life. Joziasse *et al.* (2007) gives a detailed description of different aspects of social and societal driving forces of sediment management objectives. Sediment management objects and their driving forces summarized in **Table 4** are partially based on information obtained from Heise *et al.* (2004) and Joziasse *et al.* (2007).

Table 4: Sediment management objectives and driving forces

Objective	**Driving force**
Meeting regulatory criteria	International convention, transboundary rivers- Sedimentation impacts may reduce downstream water releases from reservoirs at transboundary rivers
Maintaining economic viability	Stabilization of societal income, public employment and regional importance-This can be hampered by sediment if it decreases water depth to a critical level for navigation, if poor sediment quality or enhanced re-suspension cause economic losses from, e.g. fishery or tourism, or if the sediment dynamics or storage result in flooding or undesirable erosion.
Ensuring environmental quality	Environmental ethics and demand of recreational areas- Sediment may be managed to reduce the risk of the deterioration of the ecological function of a river system (for example maintenance of ecological water requirements), accompanied by the reduction of species and the destruction of habitats, degradation of water quality and the impairment of human health in direct (recreation activities) or indirect contact (fish and drinking water consumption) with the affected water body.
Securing quality of human life	Public welfare and safety-Sediment accumulation may facilitate flooding and endanger human safety, and reduce reservoir storage capacity which reduces water availability for supply thereby impacting on quality of human life; dredging activities or land disposal sites planned in the neighbourhood may alter the accustomed surroundings.

Table 5 gives a summary of examples of sediment management objectives formulated for different sites or regions. **Table 5** shows that sediment management objectives can be formulated to address the management of sediment related impacts on water resources, which is the thrust of the current study. An example of such impacts includes reduction of storage capacity of reservoirs which impacts on water resources availability and promotes flooding. Some of the sediment management objectives stated in Kashawai (2005), Ashton Coal Mine (2005) and Kantoush and Sumi (2010) serve as examples of objectives that can address the management of sediment related impacts on water resources.

Table 5: Summary of examples of sediment management objectives formulated for different sites or regions

Region/Site	Sediment management objectives	Source
Mekong River Catchment	• Minimise sediment trapping behind the dam • Maximise sediment transport through the reservoir and past the dam wall • Maintain the seasonal distribution of sediment transport • Maintain the natural grain-size distribution of transported sediment	MRC (2009)
Government of Japan	• To prevent disaster • To conserve river and coastal environment like ecosystem and sightseeing, etc. • To manage river and coast in appropriate manners	Kashiwai (2005)
British, Columbia	• Maintain and/or restore sediment quality conditions such that sediments do not adversely affect the survival, growth, or reproduction of sediment-dwelling organisms (as indicated by the results of long-term toxicity tests) • Maintain and/or restore sediment quality conditions such that sediments do not adversely affect the structure of benthic macroinvertebrate communities (as indicated by the results of benthic surveys) • Maintain and/or restore sediment quality conditions such that sediments are not contaminated at levels that would result in the accumulation of contaminants in the tissues of aquatic organisms to levels that would adversely affect aquatic dependent wildlife or human health.	McDonald *et al.* (2003)
Malaysia	• Minimize erosion and sedimentation • Reduce impacts from other chemical constituents associated with materials usage or other contractor activities within a construction site • Install appropriate measures to reduce impacts on downstream waterways from the finished project and provide a commitment that these measures will be maintained	Ooshaksaraie *et al.* (2009)
Ashton Coal, New South Wales	• To minimise the impact of construction and operational activities on erosion and the sedimentation of disturbed land, watercourses and water bodies. • To minimise the loss of topsoil from areas disturbed by mining activities.	Ashton Coal (2005)
Broads wetland, United Kingdom	• Reduce sediment load to the waterways through partnership working • Balance sediment inputs with future planned dredging (following removal of the current sediment backlog) • Define waterway specifications, and hence the dredging requirement and having done so evaluate and minimise its environmental impact • Maximise beneficial reuse of sediment • Target and prioritise expenditure • Adopt a risk-based approach to planning works • Influence wider legislation and policy for sustainable and integrated management on a catchment scale	Broads Authority (2007)
Alpine Reservoirs in Japan and Europe	• To prevent siltation of intake facilities and aggradation of upstream riverbed, accompanied by sedimentation processes in reservoir, in order to secure the safety of the dam or river channel • To maintain storage functions of reservoirs, and realize sustainable water resources management for future generations • From a perspective of comprehensive sediment management in a sediment transport system, to release sediments from dams	Kantoush and Sumi, (2010)

3.2 SEDIMENT MANAGEMENT TOOLS/STRATEGIES

The process of making decisions and taking actions on sediments (including no action), take into consideration a wide range of factors (Apitz and Power, 2002). Sediment management is needed to secure human activities and environmental objectives, and is subject to different legal requirements. The issues faced by sediment managers are complex; the problems involve a large number of variables, the systems involved are dynamic, and the uncertainties associated with them are large and often dominate the decision-making process (Apitz, 2008). To balance all this, sediment management plans (SMP) should be developed. The institutional provisions of the Water Framework Directive, like River Catchment Management Plans (RCMP), can provide the necessary platform and instruments. Management plans have to consider the high natural variability of sediment dynamics and should not compromise the ability of the system to respond. An adaptive, site-specific management approach is needed which allows for variations within a given range. It has to be acknowledged that dynamic systems contain elements of uncertainties (Netzband *et al.*, 2007).

The most important motive to use strategies for controlling reservoir sedimentation is the preservation of reservoir storage (especially if appropriate sites for replacement are unavailable), though impacts upstream and downstream of the reservoir have also gained more consideration (Sloff, 1997). The premise behind decision making for management is that, the effects of management actions are predicted and compared to the effects of other actions, including no action. Using past experience, research, scenario studies, models and pilots, the responses to various actions can be quantitatively predicted, and the “best” actions selected based upon the chosen set of criteria. Whilst this premise may be relevant for the simplest of problems, attempting to manage the effects of multiple stressors on complex ecosystems at various scales may become increasingly difficult (Apitz, 2008). Selecting the best sediment management option is a complex and often controversial task (Apitz *et al.*, 2005).

According to Apitz and Power (2002) sediment management strategies can be categorized into five broad groups which are selected based upon an evaluation of site-specific risks and goals:

1. No action. This category is only appropriately applied if it is determined that sediment pose no risk.
2. Monitored natural recovery. This is based on the assumption that while sediment pose some risks, it is low enough that natural processes can reduce the risks over time in a safe manner.

3. In situ containment. In this process, sediment contaminants are in some manner isolated from target organisms, though the sediments are left in place. It does not require landfill.
4. In situ treatment
5. Dredging or excavation. In this process, physical and mechanical methods are applied and these processes may require landfill.

US Department of Interior (2006) gives a summarized comparison of sediment management alternatives adopted from ASCE (1997) as shown in **Table 6.**

Table 6: summarized comparison of sediment management alternatives (ASCE, 1997)

Sediment management alternative	Advantages	Disadvantages
No action	• Low cost.	• Continued problems for fish and boat passage. • For storage reservoirs, continued reservoir sedimentation, loss of reservoir capacity, and reduced sediment supply to the downstream river channel.
River erosion	• Potentially low cost alternative. • Sediment supply restored to the downstream river channel.	• Generally, largest risk of unanticipated impacts. • Temporary degradation of downstream water quality. • Potential for river channel aggradation downstream from the reservoir.
In situ treatment/mechanical removal- all or a portion of the reservoir sediment would be removed and transported to a long-term disposal site.	• Generally low risk of reservoir sediment release. • Low impacts to downstream water quality. • Low potential for short-term aggradation of the downstream river channel.	• High cost. • Disposal site may be difficult to locate. • Contaminated sediments, if present, could impact on ground water at the disposal site.
Stabilization- sediment would be stabilized in the reservoir by constructing a river channel through or around the reservoir sediments.	• Moderate cost. • Impacts avoided at other disposal sites. • Low to moderate impacts to downstream water quality. • Low potential for short-term aggradation of the downstream river channel.	• Long-term maintenance costs of the river channel through or around reservoir sediments. • Potential for failure of sediment stabilization measures. • Reservoir area not restored to natural conditions

The information required to evaluate or compare each of the sediment management options is different and any assessment should be designed to evaluate and support management goals and potential remedial options (Palmieri *et al.*, 2001; Apitz and Power, 2002).

Sediment management strategies can also be divided into three groups: measures in the catchment area, in the reservoir and at the dam (Althaus and De Cesare, 2006; De Cesare *et al.*, 2011; after Schleiss and Oehy 2002) (**Figure 5**).

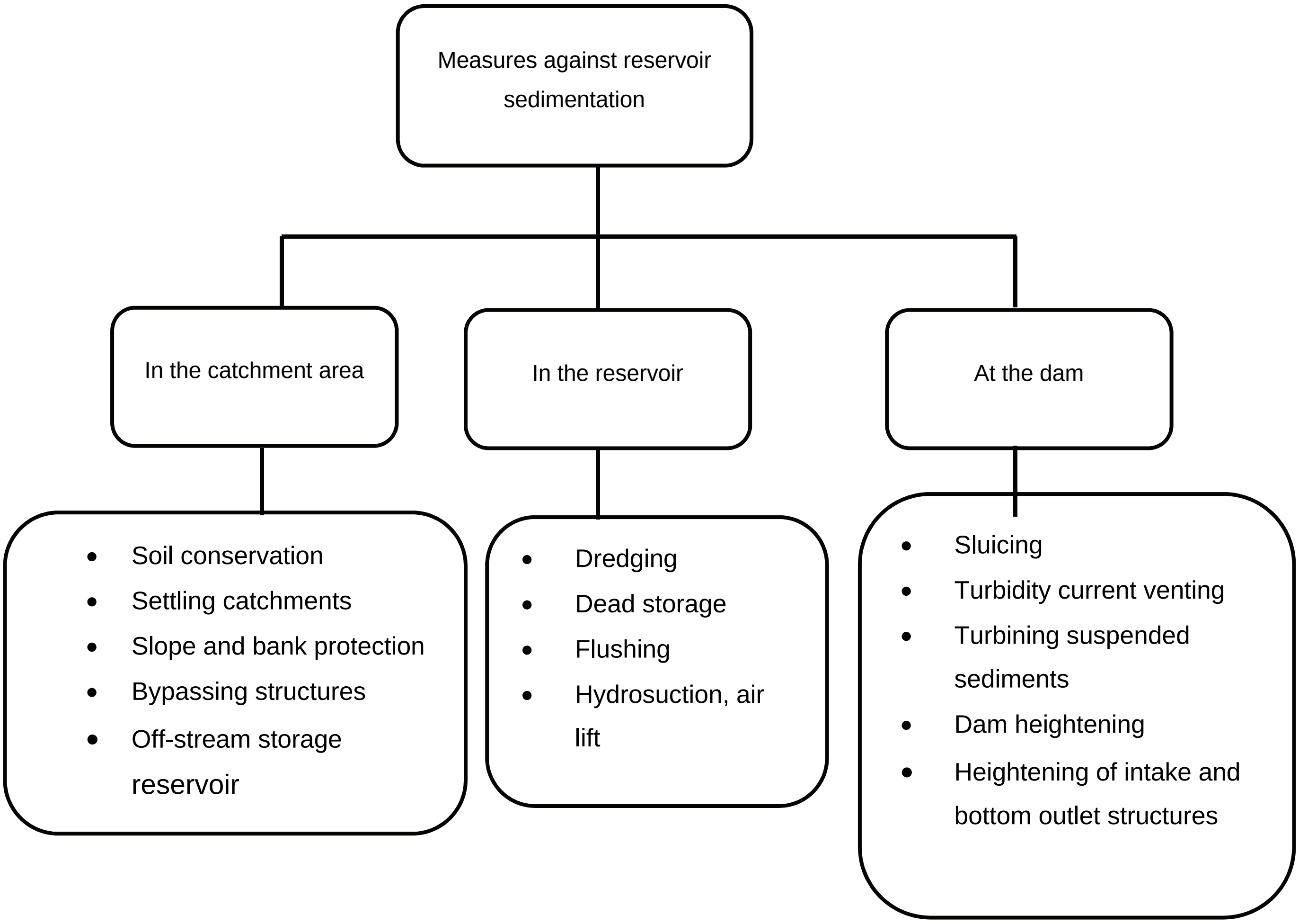

Figure 5: Measures against reservoir sedimentation (source: Schleiss and Oehy, 2002)

Reservoir management methods/strategies shown in **Figure 5** have extensively been reviewed in literature. Examples of relevant literature include Lahlou (1996), Basson and Rooseboom (1999), Palmieri *et al.* (2003), Basson (2004), Hartmann (2004), Sawadogo (2008), Utah Division of Water Resources (2010), amongst others. The methods/strategies are summarised as follows:

- Measures in the catchment area
- Soil conservation
- Settling catchments
- Slope and bank protection
- Sediment bypass

- Off-stream storage
- Measures in the reservoir
- Dredging
- Flushing
- Hydrosuction
- Dead storage
- Measures at the dam
- Sluicing
- Density/turbidity current venting
- Dam heightening
- Turbining suspended sediments

3.3 SELECTING FEASIBLE SEDIMENT MANAGEMENT STRATEGIES/METHODS

Choosing or ranking environmental management strategies can be a complex and difficult problem, yet it is among the most important decisions an environmental manager will make (Linkov *et al.*, 2005). The actual choice of the most convenient strategy is a complex process involving hydrology, hydrogeology, morphology and dam engineering (US Department of Interior, 2008), cost and effectiveness. The cost and applicability of sediment management strategy will vary from one site to another and no single measure can be suggested because of the large number of variables involved in reservoir sedimentation (Sumi and Hirose, 2002).

The ultimate success of sediment management activities should be judged by gains in ecosystem quality (Krantzberg *et al.*, 2000). The results will always be site-specific and no standardization is possible apart from the basic principles on which the solution is based (US Department of Interior, 2008). At sites with multiple water bodies or sections of water bodies with differing characteristics or uses, or differing levels of contamination, project managers have found that alternatives that combine a variety of approaches are frequently the most promising (EPA, 1999). In response to the above, a number of studies have assessed the use of models, frameworks and decision support tools for selecting the most feasible sediment management options.

Harb and Zenz (2011) illustrated the need for a decision support system to select the most feasible method. The RESCON model is an Excel based computer program designed to assess the engineering feasibility and determine the selection of a desirable sediment management strategy subject to environmental and social safeguards specified by the user (Kwashima *et al.*, 2003). It only considers no sediment removal, flushing, hydrosuction, traditional dredging and trucking sediment management options. The detailed description of the model including its structure can be found in Palmieri *et al.* (2003) and Kawashima *et al.* (2003).

Alvarez-Guerra *et al.* (2010) used stochastic multicriteria acceptability analysis to integrate explicit consideration of uncertainty and stakeholder preferences. The proposed methodology for decision-making in sediment management is shown in **Figure 6**.

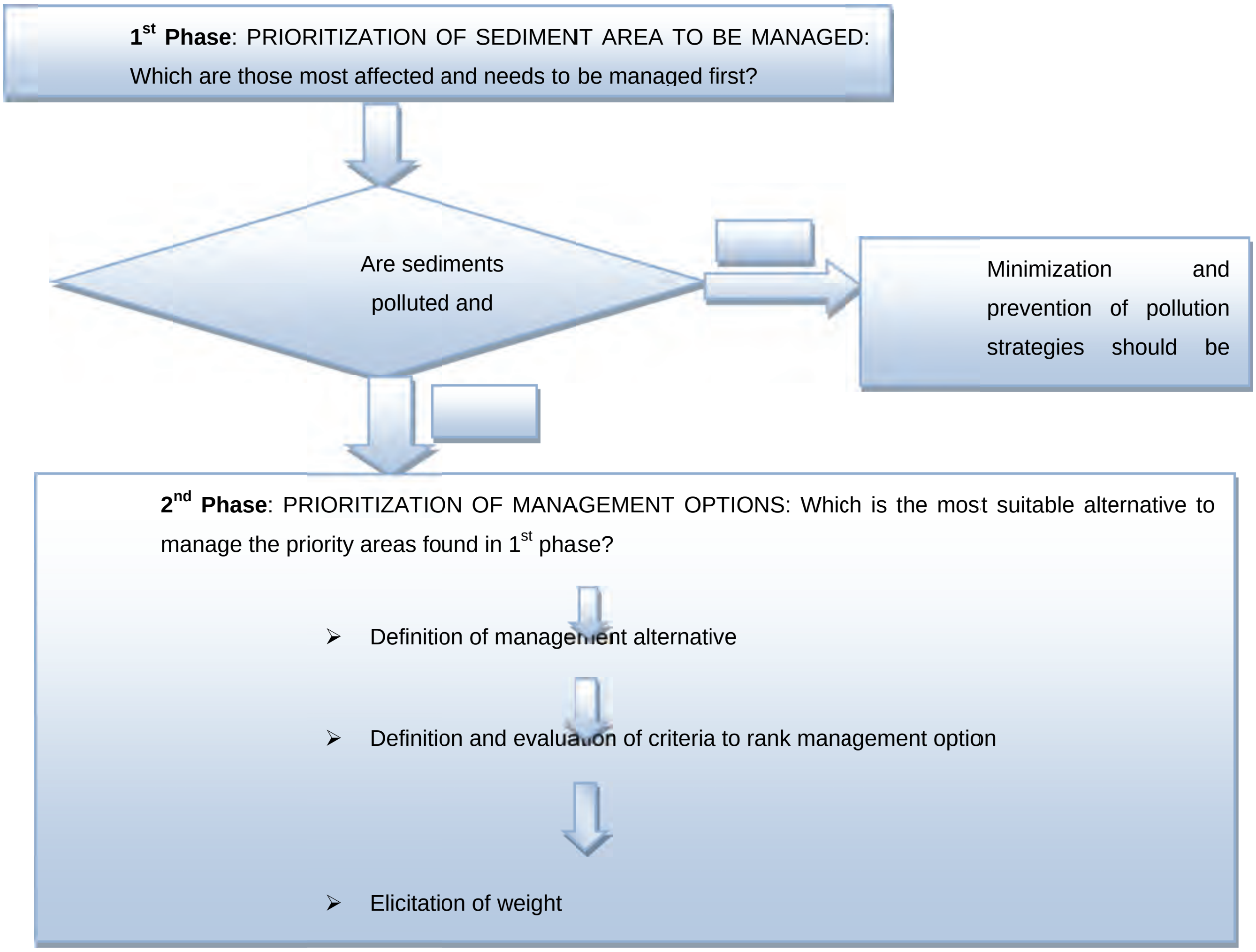

Figure 6: Proposed methodology for decision-making in sediment management (Alvarez-Guerra *et al.*, 2010)

4 SEDIMENT METHODS AND MODELS REVIEW

The generation, transport pathways, and fate of sediments in a catchment are driven by complex interactions of precipitation, land uses, urban and rural catchment runoff, groundwater transport, wastewater and storm water inputs, surface water transport, kinetic transformations and biological processes in the water column and sediment bed. Mathematical models designed to represent the generation, transport pathways, and fate of sediments can serve as powerful tools in understanding, and differentiating, the relative significance of natural processes and human activities on trends in water quantity, water quality and aquatic ecosystem resources. Models can be used to support the development of management plans with quantitative evaluations and comparisons of the effectiveness of alternative plans. Model frameworks can be applied to support evaluations of issues related to sediments such as:

- Understanding key “cause and effect” processes and interactions that have influenced historical distributions of sediments in the waterbody, sediment bed, and biota on a decadal time scale.
- Evaluating the effectiveness of alternative remediation scenarios, including “natural recovery”, in reducing sediments in the water column, sediment bed, and key target biota on a decadal time scale.
- Determining how many years will be required for “recovery” to achieve reduced sediments levels .

Suspended solids and sediment models can be broadly categorized into three groups as follows:

1. Firstly, Loading models: These models simulate field and catchment scale hydrological processes and determine the generation and transportation of sediment from source at the upper parts of the catchment to the receiving waters.
2. Secondly, receiving water models: these models can be divided into hydrodynamic and water quality models. The hydrodynamic they solve the hydraulics of water quality models including transport, deposition, etc. whereas water quality models simulate the movement of solids in the water column, determining the fate and transport of nutrients. These models vary depending also on the receiving water body, i.e. rivers and streams, lakes and reservoirs, and estuaries.
3. Thirdly are the ecological models which basically deal with eutrophication. For sediment yield modelling a loading model will be required to be developed.

This chapter gives an overview of models and/or methods for the evaluation and management of sediments, with a particular focus on South African perspective. The overview covers sediment yield, sediment transport, integrated modelling and impact assessment, and model selection.

4.1 SEDIMENT YIELD ASSESSMENT AND TECHNIQUES IN SOUTH AFRICA

Various studies have been conducted in South Africa, as shown in **Table 7** to estimate soil loss and sediment yield from different catchments. The existing literature estimates mean annual soil loss in South Africa with great disparity; as Midgley's (1952) gives a figure of 363 million tonnes (3 t $ha^{-1} yr^{-1}$), Schwartz and Pullen's (1966) value of 233 million tonnes (1,9 t ha^{-1} yr^{-1}) and Rooseboom's 1976 estimate of 100-150 million tonnes (0,82-1,22 t ha^{-1} yr^{-1}) of which are based on the sediment yield of main rivers. Other published values, are 500 million tonnes (4,1 t ha^{-1} yr^{-1}) annually suggested by Van Rensburg (1992) and the 400 million tonnes (3,3 t ha^{-1} yr^{-1}) by Huntley et al*.* (1989).

Midgley's (1952) , Schwartz and Pullen's (1966) and Rooseboom's (1976) all calculated their sediment yields from accumulation in main dams, but different mean annual loss values were obtained. Rooseboom *et al.* (1992) developed a statistical method that accounts for variations in regional conditions, which resulted in developing sediment yield maps for the whole of South Africa.

Table 7: Important studies that have been conducted in South Africa (Garland et al.)

Author/date	Description	Key findings
Bennet 1945	Review based on visits to several regions	South Africa is severely eroded
Midgley 1952	Calculation of sediment yield from accumulation in main dams	Mean annual soil loss for South Africa was 363 million tonnes per year
Schwartz & Pullen 1966	Calculation of sediment yield from accumulation in main dams	Mean annual soil loss for South Africa was 233 million tonnes per year
Rooseboom 1976	Calculation of sediment yield from accumulation in main dams	Mean annual soil loss for South Africa was 100-150 million tonnes per year
Smithen & Schulze 1982	Calculation of rainfall erosivity Parameters for Southern Africa	Maps of annual and seasonal rainfall erosivity based on EI30 index
Beinart 1984	Historical review of colonial/settler Government interventions to combat	Conservation schemes using scientific expert based approach are

Author/date	Description	Key findings
	soil erosion	unlikely to be successful in rural Africa. Erosion problems still persist
Braune & Looser 1989	Calculation and estimation of off-site Cost of erosion	Annual off-site costs of erosion are at least R80 million in 1989 Rands
Rooseboom *et al* 1992	Assessment of approaches/techniques for calculating sediment yield in South Africa	Previous techniques were unsuccessful due to large variations in regional conditions. New empirical model for sediment yield assessment developed
Cooper 1996	Review and analysis of South African soil conservation policy prior to 1992	Policy was technocratic, dualistic and only marginally successful: survey of experts showed that erosion was still a problem

Three main techniques have been widely applied in the prediction and estimation of sediment yield in South Africa. The methods include use of sediment yield maps, reservoir deposit data and sediment load-discharge rating curves which are discussed further in the following subsections.

4.1.1.1 Sediment yield maps

The most common method together with direct measurements that has been applied in South Africa for estimation of sediment yield has been the application of the sediment yield maps that were developed by Rooseboom *et al.* (1992). The sediment yield map and the accompanying probabilistic approach was developed by considering soil erodibility with respect to soil type, catchment slopes and land use, observed sediment yield values obtained from reservoir survey data and river sampling, boundaries of river catchments and rainfall characteristics , location and size of catchments and other information on relevant geographical and environmental factors that were deemed to have significant influence on erosion and sediment yield in a catchment.

In general the sediment yield map method developed by Rooseboom *et al.* (1992) followed a given procedure in which a standardized yield was determined for each region, and could be multiplied by a factor that accounts for the probability of exceedance for the region, as well as low, medium and high sediment catchment areas based on a soil erosivity index considering soil, rainfall, slope, land use, etc.

4.1.1.2 Reservoir sediment surveys

Reservoir surveys measure the reservoir area and capacity, and any changes in the storage capacity are attributed to sediment deposition or erosion. Typical results from a reservoir survey include; measured sediment deposition since previous surveys, sediment yield from the contributing drainage, future storage-depletion trends, location of deposited sediment (lateral and longitudinal distribution), sediment density, and reservoir trap efficiency. It is possible to calculate the sediment yield from reservoir deposit data. In semi-arid regions that have high rainfall intensity, the storage capacity of a reservoir is usually in the order of the mean annual runoff and the reservoirs therefore trap approximately 97% of the sediment yield (Basson, 2008). Therefore the loss in storage is taken as a true reflection of sediment accumulation.

Any reservoirs whose trap efficiencies fall below the required percentage of 97% cannot be used in the determination of the sediment yield because of the unreliable sediment deposit data. The data on sediment deposit in reservoirs can be obtained from the Department of Water Affairs or a re-survey can be done. Sediment volumes are calculated from the analysis of the observed decrease in the reservoir storage volume during re-surveys with respect to previous surveys or initial volume at commissioning.

An equation proposed by Rooseboom *et al.* (1992) below is used to compute the equivalent fifty (50) year sediment volume, based on the sediment volume after a known period, preferably after 10 or more years.

$$\frac{V_t}{V_{50}} = 0.376 \ln \frac{t}{3.5} \qquad (4\ 1)$$

Where

V_t = sediment volume after t years.

V_{50} = sediment volume after 50 years.

t = time (years).

The sediment yield *Sy* is then computed using the equation;

$$S_y = \frac{1.35 V_{50}}{50 A_e} \qquad (4\ 2)$$

Where

S_y = Sediment yield in tons per annum per square kilometre

A_e = Effective Catchment Area

The sediment density used in South Africa for 50 year old deposits is 1350 kg/m^3. Another study by Batuca and Jordaan (2000) showed the history of silting in four South African reservoirs; namely Windsor, Van Ryneveldspass, Floriskraal, and Welbedacht reservoirs. The resurvey data (DWAF 1996) of a large number of South African reservoirs made possible the development of the following relationship describing the time evolution of sediment volume deposited in these reservoirs:

$$V_s = coef * t^{\exp} \tag{4 3}$$

Where V_s is the sediment volume accumulated in the catchment and t is the time of operation in years. The '*coef*' and the *'exp'* values for the above mentioned reservoirs and the other data are given in the **Table 8**. The '*exp*' value decreases with time, toward the value of 0.5 which characterizes the quasi equilibrium conditions of the silting process, the '*coef*' value depends on the reservoir capacity and its location.

Table 8: Silting characteristics for four reservoirs in South Africa (Batuca and Jordaan, 2000)

Reservoir	River	Original capacity (hmc)	Silting ratio (%)	Silting duration (years)	Coef	Exp
Welbedacht	Caledon	113.80	86.1	23(1996)	20.90	0.50
Windsor	Klip	4.62	83.3	36(1988)	0.65	0.50
Van Ryneveldpass	Sondags	78.82	39.8	53(1978)	0.85	0.93
Floriskraal	Buffels	67.44	25.4	35(1992)	0.18	1.32

4.1.1.3 River sediment sampling

The double mass curve of cumulative sediment discharge against cumulative water discharge has been applied in South Africa not only to establish whether conditions are stationary but also to determine the long term average sediment concentration. The development of the double mass curve represents the influence of: availability (cumulative sediment load) and transporting capacity (cumulative water discharge). If conditions are stationary the average progression has to be in the form of a straight line, the slope of which is mathematically equal to the average sediment concentration (Rooseboom, 1981).

4.1.1.4 Capabilities and limitations of some identified Sediment yield models

Various models have different capabilities and limitations. **Table 9** gives a summary of capabilities and limitations by describing the model's simulation type, catchment size, spatial distribution, nature of overland flow, erosion processes modelled, land use, and the nature of their output.

In general, physical process simulation models have several disadvantages compared to the regression-type models such as the MUSLE. These disadvantages are related mostly to the increased complexity of the physical process models. Firstly, the models of large catchments are computationally extremely "heavy". Secondly, the data requirements are more extensive because of increased complexities and the need to evaluate many parameters at different spatial scales. However, in some ways data requirements are simplified for physical process models in that the necessary data are more easily measured and identified because of the physical process basis. Data requirements for regression models are often much more subjective and the parameters often harder to relate to observable and measurable quantities.

Table 9: A comparison of physically-based erosion and sediment yield models (Basson, 2008)

Model Feature	**SHETRAN**	**ANSWERS**	**WEPP**	**EUROSEM**	**LISEM**	**ACRU**
Simulation Type: continuous	Y	N	Y	N	N	Y
Single event	Y	Y	Y	Y	Y	Y
Catchment size	<2500 KM^2	<50 KM^2	<2.6KM^2	Small catchment	Small catchment	<10000 Km^2
Spatial distribution	Grid	Grid or GIS raster	Grid	Uniform Slope planes	GIS raster	GIS raster
Overland flow: Rainfall excess	Y	Y	Y	Y	Y	Y
Upward saturation	Y	N	N	N	Y	Y
Erosion process: Raindrop impact/ Overland flow	Y	Y	Y	Y	Y	Y
Rilling	N	N	Y	Y	Y	Y
Crusting	N	Y	N	Y	Y	Y
Channel banks	Y	N	N	Y	N	N
Gullying	Y	N	N	N	N	N
Landsliding	Y	N	N	N	N	N

Model Feature	SHETRAN	ANSWERS	WEPP	EUROSEM	LISEM	ACRU
Output: Time-varying Sedigraph	Y	Y	N	Y	Y	Y (daily)
Time-Integrated yield	Y	Y	Y	Y	Y	Y
Erosion map	Y	Y	Y	Y	N	Y
Land use	Most Vegetation covers	Mainly agricultural	Wide range of Land use	Mainly agricultural	Mainly agricultural	Mainly agricultural

4.2 SEDIMENT TRANSPORT MODELS

4.2.1 SEDIMENT TRANSPORT OF NON-COHESIVE SEDIMENT

Several sediment transport capacity equations are available to deal with non-cohesive sediments of sediment diameter > 0.03 mm. Most of these equations have a streampower basis and have been calibrated against laboratory and/or field data. Non-cohesive sediments consist of coarse material in the streambed which can be mobilized by flowing water, and may be transported either in suspension or as bed load. Equations describing the capacity of flowing water to transport bed material may be divided into two groups.

- Bed load equations which describe the amount of material transported as bed load.
- Total load equations which actually describe the total bed material load which includes bed material transported in suspension plus bed load.

Many bed material transport equations have been developed, the application of these different sediment equations to the same dataset can generate a wide range of magnitude estimates of transport rates. Therefore the results of an analysis are heavily influenced by the choice of the transport equation. Once sediment yields from sub-catchments have been determined, the sediment has to be routed downstream in the river system by mathematical modelling. A brief description of some of the sediment transport equations is given below:

a) **Ackers and White (1973)** – The initial underlying theoretical work was developed by considering the transport of coarse material and fine material separately. It was sought to account for the intermediate grains by establishing a transitional relationship. These equations have been calibrated to a wide range of data and good results have been claimed, for 50% or more of the results.

b) **Engelund and Hansen (1967)** – Engelund and Hansen (1967) applied Bagnold's stream power concept and the similarity principle to obtain the sediment concentration.

c) **Van Rijn (1984)** – Van Rijn (1984) developed an analytical relationship for sediment load transport in terms of the saltation height, particle velocity and bed load concentration. The transport equation can be expressed in a simplified form when only the mean velocity, flow depth and particle size are known.

d) **Yang' equation (1973)** – Yang (1973) proposed a sediment transport formula based on the concept of unit stream power, which can be utilized for the prediction of total bed material concentration transported in sand bed flumes and rivers.

e) **Rooseboom, 1974** – The basic principles of minimum applied stream power has also been used in South Africa in 1974 by Rooseboom and have since been used in the planning and design of various reservoir sedimentation studies. Rooseboom(1975) found that the suspension theory (Rouse, 1937) can be used to describe both bed and suspended load and the incipient motion criteria, and is therefore well suited to analysis of total carrying capacity. Sediment transport capacity per unit width in terms of flow parameters can be calculated if it is assumed that sediment particles are transported at the same velocity as the fluid. The equation is used to compute for total sediments in a stream.

4.2.2 SEDIMENT TRANSPORT OF COHESIVE SEDIMENT

Cohesive sediments are composed primarily of clay-sized material, which have strong interparticle forces due to their surface ionic charges. As a particle size decreases, its surface area per unit volume increases, and the interparticle forces dominate the behaviour of sediment. Thus in practice, silt and clay are both considered to be cohesive sediment. The transport of fine sediments can be achieved by using:

a) the diffusion equation proposed by Zhang (1980),
b) sediment transport equations which have been recalibrated with fine sediment transport data, and
c) numerical models.

4.2.3 HYDRODYNAMIC MATHEMATICAL MODELLING

Mathematical equations and their solutions have been developed to represent the sediment transport concepts in real life situations. All the mathematical models developed so far are based on the following five basic equations. These equations are written only in one dimension and can be extended for all three dimensions.

(1) Continuity equation for water flow

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0$$

(2) Momentum equation for water flow

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + gA\frac{\partial z}{\partial x} = 0$$

(3) Flow resistance equation

$$U = aS^b$$

(4) Continuity equation for sediment

$$\frac{\partial A}{\partial t} + \frac{1}{1-\lambda}\frac{\partial G}{\partial x} = 0$$

(5) Sediment transport capacity equation

$$G = cU^d$$

Where, Q = discharge, A = cross-section area, g = gravitational acceleration, z = flow depth, a, b = parameters, S = bed slope, λ = porosity of sediment mixture, G = Sediment transport rate, and c, d = parameters, U = Mean flow velocity.

Both analytical and numerical solutions have been developed to solve these equations. Analytical solutions of these equations are useful due to their simplicity and effectiveness but analytical solutions can be developed and applied only in very simplified and simple cases. Numerical solutions are very effective in solving the complex differential equations in complicated conditions. Accurate prediction of sediment transport should be based on reliable hydrodynamic modelling.

4.3 INTEGRATED SEDIMENT MODELLING AND IMPACT ASSESSMENT

4.3.1 INTEGRATED MODELLING METHODS

Modelling sediment transport over a wide range of spatial scales and hydrological events remains a fundamental challenge. Transport of sediments in a catchment, through channels to the point of destination in a consolidated manner requires integration of various components. In South Africa attempts for integrated sediment modelling have not been made, however major progress has been recorded in terms or estimating the sediment yields using simplified statistical analysis for the whole country. The sediment yield maps for SA that were developed by Rooseboom (1992) are vastly used in sediment yield estimation in SA.

Efforts on mathematical modelling at the catchment level were made in the same study by Rooseboom *et al.* (1992), where a deterministic model was developed and was found not to adequately describe the large variability in sediment yield especially from smaller catchments. The results from the model indicated that it was not possible to obtain meaningful relationships between yields and sediment carrying capacities even if the formulae have a coefficient representative of the sediment availability. Schulze (1995) developed the ACRU model in South Africa which gives event by event catchment sediment yield estimation by the application of Modified Universal Soil Loss Equation, MUSLE (Smithers, 2002; Williams, 1975).

In river sediment transport, Rooseboom (1974) developed a formula based on the stream power principles that solves for total load in a one dimensional open channels. Other mathematical methods exist that solve for sediment transport in rivers; however they have not been used in South Africa. Most studies in SA on river sediment transport have used physical models in laboratories and measured sediment surveys in rivers and reservoirs.

Mathematical modelling of reservoirs has been carried by De Villiers and Basson (2007) who studied a two-dimensional mathematical modelling of reservoir hydrodynamics and cohesive sediment transport processes, using advection-dispersion theory. The study used Mike21C software from DHI Water and Environment, to model the transport of fine cohesive sediment for Welbedacht Reservoir. Integrated modelling of sediment transport requires; establishing catchment or sub-catchment sediment yields, transporting the sediment through the river channel and transporting/depositing in the reservoir. This kind of study has not been carried out in South Africa, and therefore the need to carry out this study.

4.3.2 SEDIMENT IMPACT ASSESSMENT METHODS

The first step in understanding and implementing a sediment impact assessment is to define the anticipated channel bed response. This is an assessment of bed stability to determine if the channel bed is aggrading, degrading, or is relatively stable. A channel is considered to be aggrading when long term sediment deposition occurs on the bed, degrading when long-term sediment removal occurs from the channel bed and stable (or in dynamic equilibrium) when the prevailing flow and sediment regimes do not lead to long-term aggradation or degradation. Other aspects of a stability assessment may include bank stability or planform stability. The sediment impact assessment is primarily concerned with the stability of the channel bed (USDA, 2007).

In selecting the appropriate type of sediment impact assessment to implement, it is also important to determine whether the channel of interest is an **alluvial channel** or a **threshold channel**. A variety of techniques are used to assess the impact of sediment. The approaches described in this document are not exhaustive, nor are they applicable in all situations. However, a final sediment impact assessment should be viewed as a closure loop at the end of the design process to:

- validate the efficacy of the design channel geometry
- identify flows which may cause aggradation or degradation over the short term (these changes are inevitable and acceptable in a dynamic channel)
- recommend minor adjustments to the channel design to ensure dynamic stability over the medium to long term

The type of sediment impact assessment used will determine the certainty of the result, as well as the precision of a conclusion that the channel will aggrade, degrade, or remain stable. The selection of the appropriate methodology should be done with a firm understanding of the assumptions, accuracy, data requirements, and limitations of the approach. A few of the most common techniques are outlined in the following subsections.

4.3.2.1 Visual Geomorphic Assessment

A visual geomorphic assessment is primarily a qualitative check done for both threshold and alluvial streams. This may be the only assessment needed at feasibility stage or it may be the first step of a more detailed sediment impact assessment, if required. Visual geomorphic assessments of sediment impacts are generally sufficient where:

1. project failure will have minimal adverse effects
2. minimal change to the channel shape is proposed
3. the river catchment land use and cover and erosion processes are relatively stable

The visual geomorphic assessment includes judgment of current conditions, expected future conditions, and the river's anticipated response to the designed project. It includes the identification of potentially destabilizing processes of erosion, sediment storage, and deposition. A visual assessment can involve the use of channel evolution stage, the use of Lane's stream balance relationship and assessments of dominant channel processes.

4.3.2.2 Equilibrium slope calculations

Equilibrium or stable slope calculations are often used to support or refine visual assessments. The calculation of a stable or equilibrium slope may also serve as a form of sediment impact assessment, as well as being an integral part of the restoration design. The equilibrium slope of a channel is defined as the slope at which the sediment transport capacity of the reach is in balance with the sediment transported into it. If the sediment transport capacity were to exceed the sediment supply, channel bed degradation will occur until the channel bed slope is reduced to the extent that the boundary shear stress is less than what is needed to mobilize the bed material. This new, lower slope is the equilibrium slope, S_{eq}. Possible causes of the sediment transport capacity exceeding sediment supply could include an upstream reduction in sediment yield (such as in a stream reach below a dam), an increase in sediment transport capacity during high discharges, or construction of a straight channel, resulting in increased stream gradient. This lowered, degraded bed may result in undermining or collapse of riparian structures or bank instability.

Equilibrium slope calculations are typically used for threshold streams. In the context of a sediment impact assessment, they are applied to a range of design flows. A variety of techniques can be used to calculate the limiting or equilibrium slope. One approach that is suitable for gravel-bed streams is the Meyer-Peter and Müller bed load transport equation.

4.3.2.3 Sediment rating curve analysis

The sediment rating curve analysis is a relatively simple technique that can be used to assess the sediment transport characteristics of an existing or proposed stream channel. For this approach, use is made of sediment rating curves to compare the sediment transport capacity of the supply reach to the existing and proposed channel reach conditions. This approach relies on the technique of analogy. If the existing channel is stable, then sediment transport capacity in the proposed channel may be compared to that in the existing channel. If the supply reach is not fully alluvial, a carefully chosen reference reach may be used as a surrogate for the supply reach. This analysis is suitable for streams where the sediment supply is not limited in either the upstream (supply) or project reaches; that is, where the stream is certainly alluvial in nature. It is generally not suitable for threshold streams.

This qualitative technique does not require stream gauge data or sediment gauge data. It does require an estimate of the sediment grain size distribution from the supply reach, an estimated range of peak flows, and a description of hydraulic characteristics of both the study and supply reaches. By comparing the sediment rating curves of the two reaches, an estimate can be made of the sediment transport capacity of the study reach, relative to the capacity of the sediment supply reach.

4.3.2.4 Sediment budget analysis

A sediment budget analysis is a quantitative assessment of channel stability using the magnitude and frequency of all sediment-transporting flows. A sediment budget analysis should be conducted for all realigned and constructed alluvial channels, after preliminary dimensions are determined, using the channel-forming discharge. Slight adjustments to the design may be required, after which another sediment budget analysis is conducted.

The stream's sediment budget is estimated by comparing the mean annual sediment load for the project channel with that of the supply reach(es). The mean annual sediment load from each reach is calculated by numerically integrating the annual flow-duration curve with a bed-material sediment rating curve. While the sediment load is typically calculated for annual conditions, it may also be assessed for a flow event of interest, depending on specific conditions and purposes. If more sediment comes into the system than can be passed, the excess will likely be deposited in the reach. If more sediment can be transported than what is coming into the reach, then erosion or degradation can be anticipated.

4.3.2.5 Non-equilibrium sediment transport

A sediment impact assessment should include a non-equilibrium sediment transport model for high risk or high cost projects. River systems are governed by complicated dependency relationships, where changing one significant geometric feature or boundary condition affects other geometric features and flow characteristics, both temporally and spatially. Changes at any given location in a stream system are directly related to the inflow of sediment from upstream. This is typically done by application of computer models such a HEC-6 and USACE SAM.

4.3.3 SEDIMENT IMPACT ASSESSMENT MODELS

In practice, the water resource systems for which sediment impact assessments are done are usually complex and have high risks associated with failure. It is for this reason that often non-equilibrium sediment impact assessment is essential and a number of computer models have been designed to undertake this assessment. In this section, the most commonly used sediment impact assessment models are described. Once again, it is critical to note that the number of models described here is not exhaustive.

4.3.3.1 Sediment Impact Assessment Model (SIAM)

The Sediment Impact Assessment Model (SIAM) can be viewed as a screening tool for the assessment of multiple rehabilitation alternatives, particularly in the reconnaissance and feasibility phases of a project. It provides a framework to combine sediment sources and computed sediment transport capacities into a model that can evaluate sediment imbalances and downstream sediment yields for different alternatives.

SIAM is not an event-based sediment routing model, which limits its applicability to investigations where average annual sediment budget calculations are sufficient. SIAM computations are based on annual flow duration, which makes modelling of individual events difficult. Channel geometry is not updated based on erosion or deposition, so the results are only indicative of a single channel configuration for the entire period of record being analysed. Since SIAM is a reach-based model that uses reach-averaged parameters and produces reach-averaged results, information on specific locations of erosion/deposition cannot be determined.

4.3.3.2 iSIS-Sediment Impact Assessment MODEL

iSIS was developed and is jointly owned, developed and supported by Wallingford Software Ltd and Halcrow Group Ltd is an ‘industry standard’ 1-dimensional, fixed-boundary, hydrodynamic simulator that models flows and water levels in open channels and estuaries (http://www.wallingfordsoftware.com/products/isis/). It is able to model complex and branched channel networks, and includes methods for simulating floodplain as well as in-channel flows.

iSIS-sediment uses equations for sediment transport and sediment continuity to calculate sediment transport rates, erosion/deposition and bed elevation changes within a modelled reach. Cross-sections are updated according to predicted quantities of erosion/deposition and the hydraulic model is updated accordingly at the end of each timestep. Sediments can be divided into as many as 10 particle size classes. Transport rates for each size fraction are predicted using one of four sediment transport equations. Fractions can be specified as either cohesive or non-cohesive. In this study, the Westrich-Jurashek sediment transport equation. Once calibrated for observed conditions, an iSIS model is often used to estimate inundation levels associated with extreme events. iSIS may also be used to investigate the hydrodynamic impacts of proposed engineering works, in-channel and/or floodplain activities or changes to catchment hydrology.

In the context of Impact Assessment, iSIS is used to predict the hydrodynamic effects of any proposed works or activities in the channel or on the floodplain at reach and system scales. However, as it represents the river in one dimension only, iSIS is not suitable to predict local hydrodynamic impacts. As iSIS Flow is a fixed-boundary model it is not able to predict morphological adjustments, although these may be inferred through consideration of the longstream distributions of key variables such as mean velocity, bed shear stress and specific stream power. To predict morphological changes involving bed scour (incision) or deposition (aggradation) the sediment module – iSIS Sediment – in iSIS is used. iSIS Sediment accounts for sediment transport and bed level changes through aggradation or degradation. Prediction of sediment transport rates, changes in bed elevation and amounts of erosion and deposition throughout the channel system are made by inputting the channel flow hydraulics calculated in iSIS Flow together with information on the bed material of the channel to a range of sediment transport prediction equations included within the sediment transport module. Available sediment transport functions include the Engelund-Hansen, Ackers-White and Westrich-Jurashek transport equations.

4.3.3.3 River Energy Audit Scheme (REAS)

The River Energy Audit Scheme (REAS), predicts sediment Sources (Scour), Pathways (Transfers) and Sinks (Deposition) over a period of years by estimating the difference in time-integrated specific stream power between consecutive reaches to indicate potential continuity or imbalance in the sediment transfer system. REAS calculates the balance or imbalance between the specific stream power available in a reach in a year (that is the annual stream energy in KJ/year) with that in the next reach downstream. The following input variables are required to run REAS for each study reach in the river system

- Representative bed material particle size(s);
- Representative flow duration curve;
- Representative channel cross-section;
- Representative bed slope; and
- Representative roughness values for the channel and floodplain.

The annual energy budget for a reach must take into account the full range of discharges acting on the channel over a period of years. This is performed by taking the entire flow record available for the reach in question (15 minute or mean daily values), ranking the values from lowest to highest and producing a cumulative probability curve . The discharges are then split into ranges (usually 25-35 classes) and their frequency determined. If gauged data are not available for the reach in question, or the discharge record is short, surrogate methods have to be used. These include:

1. Scaling discharge from a gauge elsewhere in catchment. This can be achieved through simply scaling by the ratio of drainage areas;
2. Scaling discharge from a donor catchment with similar hydrological and morphological characteristics; or
3. Calculation using hydrological modelling.

Because REAS uses a range of discharges a flow depth and channel top width must be defined for each flow. Manning’s flow resistance equation is used for this purpose (Chow, 1959). It is acknowledged that in a simple model such as this, obtaining the energy gradient may prove to be impossible due to the wide spacing of cross sections which would prevent generation of a gradually varied flow profile. This source of uncertainty will be small in channels with low bedslopes due to the fact that the energy slope will approach that of the bedslope. In higher gradient streams or channels with very variable bedslopes the source of error caused by the approximation of energy slope through the use of bedslope is acknowledged as potentially a significant source of uncertainty.

To solve Manning's equation a cross-sectional representation of the channel for the reach in question must be defined. This requires a survey of what is considered to be the geomorphologically active channel and, if out of bank flows are thought to be significant, the floodplain as well. It is recognised that field survey data will probably be the most costly input to obtain when using the REAS and the longstream spacing of cross-sections may have to be significant. This will inevitably reduce the resolution of the model in terms of the number of reaches that can be defined.

4.4 SELECTION OF SEDIMENT MANAGEMENT MODEL

4.4.1 OVERVIEW

Modelling sediment transport over a wide range of spatial scales and hydrological events remains a fundamental challenge. This is because transport of sediments in a catchment, through channels to the point of destination in a consolidated manner requires integration of various components. Methods that can be used for sediment studies include field studies, laboratory experiments and mathematical modelling. Accurate analysis of transport processes can be carried out by combining these various methods of evaluation (Ed. Tsanis). Field studies are used for delineation of the physical processes of transport. Laboratory experiments may be used for understanding important mechanisms, e.g. hydraulically induced flows, wind induced flows, and sediment transport in general. The laboratory experiments are less costly and more easily controlled than field measurements. However, field measurements are most desirable for monitoring climatological features. Sediment transport mathematical models therefore take up the conceptualized processes using available data to simulate the processes to obtain sediment yield from a given catchment, to evaluate sediment impacts in the catchment, to evaluate sediment management options, etc. Therefore it is crucial that while mathematical modelling is sought for, field and laboratory experiments results be used to enhance the model capability. A short description of each method is given below.

a) **Field studies**

Field studies are necessary to provide climatological features of physical, chemical, and biological processes, and to provide data sets for model verification and calibration. The related field measurements include water level, water currents, transparency, sediment concentration and water chemical concentrations, among others.

b) **Laboratory experiments**

Experiments in laboratories can provide databases for model calibration. A physical model is a scaled down version of the prototype. Physical models have a long tradition and are appealing because the results may be easily visualized. The models may be expensive to build but once constructed may be used for a variety of studies.

c) **Numerical modelling**

A numerical model is a set of equations which are thought to represent the characteristics of the process being studied. In the last few decades, with the development of powerful computers and computational methods, numerical modelling has become a powerful tool for engineers working to solve complex environmental problems like sediment transport and its impacts. Before applying model results, evaluation of model performance is very important and necessary in enhancing the product's quality and credibility. Consequently, laboratory and field data are required for model calibration and verification.

4.4.2 DATA AVAILABILITY IN SOUTH AFRICA

To conduct a sediment transport study using mathematical modelling various data is crucial so that the processes can be replicated using the correct parameters. The data that will be required in any sediment study includes sediment flow, rainfall and climatic data, river discharges, topography, land use and soil type, and abstraction data. These data can be obtained from the department of Water Affairs in South Africa as well as the Weather Service of SA. A brief explanation of available sediment flow data is provided;

Sediment flow data

Sediment flow data is very important as it is the calibration and verification data for the model developed. In South Africa observed sediment data exists as yield, and can be obtained from two types of data sources. These sources are;

a) Reservoir survey data

Reservoir survey data can provide information on reservoir deposit sediment volumes. The sediment yield calculation method that makes use of reservoir deposit data is based on the general concept that any reduction in storage volume of a reservoir that is observed through reservoir surveys is directly related to the amount of sediment being accumulated in the reservoir.

The reservoir survey data will be obtained from the Department of Water Affairs (DWA). The DWA dam list will provide historical information on surveyed and re-surveyed reservoirs and dams, with information such as: the name of the dam, height at full supply level, survey dates and the period (in years) between the surveys and re-surveys with their corresponding storage volumes at the time of surveying.

b) River suspended sediment sampling data.

Sediment load at a gauging station will be determined from river suspended solids data. The Department of Water Affairs historical flow records for gauging stations in the case study area will be obtained. The major problem will be sediment data sets may be available for short periods and not representative enough to be considered as reliable. The sediment load will be computed from the relationship between the suspended solid concentration and the discharge.

4.4.3 CRITERIA FOR MODEL SELECTION

The identification and choice of the best possible model to utilize in sediment yield modelling depends on a number of factors. A multitude of models have been developed to simulate erosion and sediment yield from a catchment, the choice of a suitable model to utilize is a challenging task. Some models are easy to apply, others are complex and often require extensive hydrological modelling skills.

The important aspects that need to be taken into consideration when choosing a numerical model to utilize have been discussed below.

i.) Purpose of study

To select a model, we must ensure that the purpose of the study is clear and understood. This study seeks to develop an integrated framework for assessment and management of sediment impacts on water resources in South Africa using various case studies. This means that sediment transport through the catchment has to be modelled so as to be able to establish sediment yield. A decision has to be made whether to build a distributed model or a lumped model. As sediment sources vary considerably through the catchment it might be necessary to develop a distributed model that will give a better representation. Once the sediment yield is established then sediment impacts can be assessed and various methods or ways to manage these impacts can be evaluated on their suitability.

ii.) Quantity and quality of data available

To build a distributed parameter model requires many parameters for example soil types, land use, and so forth. The acquision of these depends on field observation and parameter identification. If there is a small amount of reliable information it will not be worthwhile to establish a complex model because there is no sufficient data for model calibration. A complex model will not be accurate without reliable data.

iii.) Catchment size

Some of the models that can be used in modelling catchment sediment transport are given below. It is very clear that the size of the catchment is very crucial in the choice of model as some models can be used in big catchment as compared to others.

Model Feature	**SHETRAN**	**ANSWERS**	**WEPP**	**EUROSEM**	**ACRU**	**SWAT**
Catchment size(km^2)	<2500	<50	<2.6	Small catchment	<10 000	Large rural catchments

iv.) Accepted models

Currently due to technological advancement, mathematical models have been developed overwhelmingly. A model to be accepted must have been tested and validated. The model has to have a proven record of application with sufficient history.

v.) Linkage to other models

In integrated modelling it is crucial to ensure that the suggested models to be used in the study are compatible and they can be easily linked. This can save time and resources.

vi.) Good representation of the catchment and the processes therein

As pointed out earlier it is crucial to ensure that the physical catchment I is properly represented and the processes are captured well. This is the backbone of the model.

vii.) Appropriate processes for simulation

Correct representation of the physical processes in mathematical form will allow for correct simulation. Adequate knowledge of specific intrinsic physical processes that the model can simulate is very necessary.

viii.) Cost of the models, what time frame the project has and how long it will take to complete models.

Models can be very expensive considering the amount of time and resources that have been used to develop them. However there exist some models that are free over the internet and can be freely downloaded. It will depend therefore the amount of money available to buy software, and if the freeware will not be sufficient to conduct the study. Another important aspect is the time available to model. The art of modelling requires prior knowledge especially of the underlying processes so as to provide expert knowledge during the process. Some models are quite complex and require that the modeller has to be expert whereas some models can be learnt quite easily. Models therefore should be decided on depending on the amount of time available for the project.

ix.) Good model documentation and support

Essential documentation and support is crucial for non-expert users. Choosing a complex model that is not well understood can result in erroneous representation of the system, causing wastage of resources. For non-expert users it will be important to choose a model with support and proper documentation.

x.) Spatial and temporal scale

It is important as well to be able to assess the scale that the model can be employed. In terms of temporal, some models can simulate continuously whereas other models can be event based. Spatial scales will determine the type of parameters to use either lumped or distributed.

xi.) Other issues

In sediment studies, one other major issue to be able to know is whether the focus is on sediment transport to the reservoir or on the upstream conditions within the channels and bank processes? This will allow for a decision to be made on how far the study will go in understanding of upland and other sediment source processes.

Considering the above criteria loading models shown in **Table 10** and hydrodynamic models in **Table 11** can be evaluated, on their suitability for a particular study/purpose.

	Field-F Agricultural catchment-A Urban catchment-u	Level of Analysis Screening-S Detailed-D	Rigor Empirical-E Semi-Empr-S Phys-Based-P	Spatial Scale Lumped-L Distributed -D	Temporal scale Event-E Continuous -C	Level of Effort Low-L Medium-M High-H	Platform[x]	Availability
AGNPS/AnnAGNPS	A	S,D	E	D	E,C	M-H	WIN/SC,AV	Public
AGWA (KINEROS-2)	A,U	S,D	P	D	E	M-H	WIN,AV	Public
AGWA (SWAT)	A	S,D	S	D	C	M	WIN,AV	Public
ANSWERS	A	S,D	P	D	E	M,H	DOS/SC	Public
ANSWERS-2000*	A	S,D	P	D	C	M,H	WIN,AV	Public
BASINS (HSPF)	A,U	S,D	P	D	C	M,H	WIN,AV	Public
BASINS (SWAT)	A	S,D	S	D	C	M,H	WIN,AV	Public
DWSM	A	S,D	P	D	E	M	SC	Public
EPIC	F	S,D	E	L	C	M	DOS/UNIX	Public
GLEAMS	F	S,D	E	L	C	M	DOS/SC	Public
GSSHA**	A,U	D	P	D	E,C	H	DOS	Proprietary
GWLF	A	S	E	L	C	M	WIN,AV	Public
HSPF	A,U	S,D	P	D	C	M-H	DOS	Public
KINEROS	A,U	S,D	P	D	E	M-H	DOS/WIN/SC	Public
MIKE-11	A	S	P	L	E,C	H	WIN,AV	Proprietary
MIKE-SHE	A	D	P	D	E,C	H	WIN,AV	Proprietary
OPUS	F	D	P	D	C	M	DOS	Public
PRMS	A	S,D	P	D	E,C	M-H	DOS/UNIX/SC	Public
REMM*	F	S,D	S	L	C	M	WIN	Public
SWAT	A	S,D	S	D	C	M	WIN,AV	Public
SWMM	U	S,D	P	D	E,C	H	DOS/SC	Public
VFSMOD*	F	D	P	D	E	M	DOS/WIN/SC	Public
WEPP	A	S,D	P	D	E,C	M	WIN/DOS	Public
WMS (HSPF)	A,U	S,D	P	D	C	M,H	WIN	Proprietary
WMS (GSSHA)	A,U	D	S	D	E,C	M,H	WIN	Proprietary

Table 10: Loading models (Source: Latif & Hantush, EPA)

*Models having insufficient application history but are very promising.

**Flows is physically based, sediment transport is semi empirical.

x SC= Source Code. AV= ArcView. AI= ArcInfo. WIN= WINDOWS.

Table 11: Hydrodynamic models (Source: Latif & Hantush, EPA)

	Dimension	Waterbody Stream-S River-R Lake/Res.-LR Estuary-E Coastal-C	Level of Analysis Screening-S Detailed-D	Rigor Empirical-E Phys. Based-P	Steady-S Unsteady-U	Level of Effort Low-L Medium-M High-H	Platform (SC=Source Code available) & GIS	Availability	Water Quality Model Linkage
CE-QUAL-RIV1	1-D	S, R	S, D	P	U	M-H	SC	Public	
CE-QUAL-W2	2-D	S, R, LR, E	S, D	P	U	H	SC	Public	
CH3D-WES	3-D	S, R, E, C	S, D	P	U	H	UNIX	Public	CE-QUAL-ICM, WASP5
DELFT3D	3-D	S, R, LR, E, C	S, D	P	U	M-H	WIN	Proprietary	
DYNHYD5	1-D	S, R, E	S, D	P	U	M	DOS/WIN	Public	WASP6
EFDC	3-D	S, R, LR, E, C	S, D	P	U	M-H	SC	Public	WASP6, CE-QUAL-ICM
MIKE-11	1-D	S, R, E	S, D	P	U	M-H	WIN, AV	Proprietary	
MIKE-21	2-D	R, LR, E, C	S, D	P	U	M-H	WIN	Proprietary	
MIKE-3	3-D	R, LR, E, C	S, D	P	U	M-H	WIN	Proprietary	

4.4.4 CHECKLIST FOR ASSESSMENT OF CONCERNS IN SEDIMENT TRANSPORT

Table 12 shows the concerns that need to be addressed in sediment transport and the required type of model to address the concern as well as the various possible models.

Table 12: Sediment concerns

Concern	Required	Possible models
Hydrologic: What is the hydrological regime of the river in study? What are the land use effects or influence on the hydrological flows?	• Catchment loading model	SWAT/ HSPF /GSSHA/ ACRU/HEC-HMS
Sediment mobilization and transport: How much sediment is delivered through the river? What are the sources of sediment? What are the rates of sediment loading from the tributaries? How do the hydrologic regime and ongoing geomorphic processes affect the morphology of tributaries and the main river?	• Catchment loading model • Routing model	SWAT/HSPF/GSSHA/ACRU/HEC-HMS CONCEPTS/HEC-RAS/ GSSHA/ MIKE 11/HEC-6
Water quality What is current water quality in the river system? What can be done to improve water quality sediment transport and nutrient loading in the river?	• Catchment loading model • Routing model • Water Quality model	SWAT/HSPF/GSSHA/ACRU/HEC-HMS CONCEPTS/HEC-RAS/ GSSHA/ MIKE 11/HEC-6 CE-QUAL-W2/CE-QUAL 2E/ HEC-RAS+NSM/ ADH+NSM

4.4.5 CRITERIA FOR SEDIMENT IMPACT ASSESSMENT MODELS

The choice of the appropriate technique to estimate the sediment impact of a water resource system includes not only an assessment, but also the potential impacts of system failure. As the risk and uncertainty increase, the use of more detailed models is recommended. However, the use of increasingly complicated models is not necessarily recommended. On its own, a more complicated analysis will not necessarily be sufficient or more accurate. The reliability of any model is dependent on the skill and experience of the assessor, as well as the input data. Since each river system is unique, assessors should review the assumptions and data requirements and consider their own experiences when determining the appropriate technique to use.

To be able to conduct a sediment impact assessment existing models have to be evaluated to indicate their requirements in terms of data input, expected output, capabilities and limitations. **Table 13** shows an evaluation of models on the various assessment aspects.

Table 13: Factors to be considered for sediment assessment models

MODEL	**Sediment impact assessment model (SIAM)**	**SWAT-Soil Water Assessment Tool**	**River Energy Audit Scheme (REAS)**
Data	Sediment reach ✓ Bed material composition ✓ Sediment properties ✓ Hydrology(discharges) ✓ Hydraulics (depth, area, velocity, hydraulic radius, wetted perimeter, top width, friction slope, and roughness for each flow profile) ✓ -Sediment loading from local sources (eroding channel banks, gullies, upland surface erosion, and point sources such as sand and gravel mining operations)	✓ Sediment flow ✓ Rainfall ✓ River discharges ✓ Climate ✓ Topography ✓ Land use ✓ Soil type ✓ Abstraction data	✓ bed material particle size ✓ flow duration curve ✓ channel cross-section ✓ bed slope ✓ roughness values for the channel and floodplain
Output	✓ local bed material balance average annual transport capacities bed ✓ material and wash material supplies ✓ Local sediment supply totals for each sediment reach.	✓ Hydrologic Response ✓ Units (HRU) output file (.sbs), the sub-catchment output file ✓ the main channel or reach output file (.rch). ✓ pesticide summary file ✓ Stream Water Quality Summary ✓ Reservoir Summary	✓ Stream power
Capabilities	✓ the data input structure of SIAM allows individual sediment sources to be easily entered and/or modified, allowing the user to quickly alter sediment loadings to reflect various sediment ✓ management techniques	✓ Sediment settling and resuspension of sediment in channels and reservoirs.	✓ Determines stream power

MODEL	Sediment impact assessment model (SIAM)	SWAT-Soil Water Assessment Tool	River Energy Audit Scheme (REAS)
Limitations	✓ SIAM is a reach-based model that uses reach-averaged parameters and produces reach-averaged results, information on Specific locations of erosion/deposition cannot be determined.	✓ Cannot model diversions	✓ the input of sediment from the catchment surface itself cannot be accounted for. ✓ REAS is not a sediment routing model. ✓ Data Availability-sediment grainsize Distributions

4.4.6 CHOOSING THE APPROPRIATE SEDIMENT IMPACT ASSESSMENT TECHNIQUE

The choice of the appropriate technique to estimate the sediment impact of a water resource system includes not only an assessment of the investigation aims and catchment condition, but also the potential impacts of system failure. Visual and qualitative assessments are appropriate for sites where there is low risk and minimal change to an otherwise stable system. These can be accomplished with the aid of primarily judgment based tools. As the system of interest becomes more complex, and where there is a higher risk to life and property, more analytical approaches are used. Many analytical techniques are available that typically require the calculation of hydraulic parameters for the range of natural discharges, such as velocity and shear stress. All of these techniques require data determined from field observations and measurements, as well as calculations. **Table 14** illustrates typical assessment techniques for estimating the impacts of sediment on different project types and catchment conditions.

As the risk and uncertainty increase, the use of more detailed models is recommended. Table 9 shows increasing complexity, from Lane's stream balance approach, to the more elaborate computer models. However, the use of increasingly complicated models is not necessarily recommended. On its own, a more complicated analysis will not necessarily be sufficient or more accurate. The reliability of any model is dependent on the skill and experience of the assessor, as well as the input data. Engineering judgment becomes more critical with increasing risk, and the required field work and data collection become more labour intensive. Therefore, the suitable assessment column should be regarded as a cumulative recommendation that increases with increasing risk.

Since each stream system is unique, assessors should review the assumptions and data requirements and consider their own experiences when determining the appropriate technique to use.

Table 14: Selection guidance for sediment impact assessment technique (USDA, 2007)

Study Type	Site/ catchment Assessment	Risk to life, property	Suitable sediment impact Assessment
Bank Stabilization No significant change to cross section, slope, or planform	Relatively stable catchment and site	Low	Confirm that there is no significant change in the local hydraulic conditions from pre- to post project and note catchment stability
Bank Stabilization No significant change to cross section, slope, or planform	Moderately active catchment and site	Moderate	Assess stable channel grade at design flows. Field check indications of future channel evolutionary change
Bank Stabilization No significant change to cross section, slope, or planform	Moderately active catchment and site	High	Rating curve comparison of above and through site
Channel Stabilization Small change to cross section, slope, or planform	Moderately active catchment and site	Low	Rating curve comparison of above and through site, as well as pre- and post-project
Channel Stabilization Small change to cross section, slope, or planform	Moderately active catchment and site	Moderate	Sediment budget analysis
Channel Stabilization Small change to cross section, slope, or planform	Active catchment and site	High	Long-term numerical modelling

5 FRAMEWORKS REVIEW

5.1 APPROPRIATE SCALE FOR DEVELOPING SEDIMENT MANAGEMENT FRAMEWORKS

Although local and site-specific sediment scales are still likely to be the main scales at which interventions are made, they need to be placed within a broader context and with full appreciation and consideration of their impacts within the river catchment (Owens, 2005). For sediment management to be effective the river catchment represents the most appropriate scale for consideration. This is the scale over which sediment supply, transfer and deposition occur (Apitz and White, 2003). Sediment is part of the hydrodynamic continuum, actions on a sediment unit can affect other parcels resulting in conflicting, counterproductive or inefficient management actions if not coordinated (Apitz *et al.*, 2006).

Owens (2005) gave several reasons why the river catchment scale approach is required for effective sediment management. These include the fact that local interventions will in most cases impact on other parts of the river catchment, most large river catchments throughout the world are highly populated and/or modified by human activities (such as deforestation) and, in many cases source control will be the optimal long-term solution (environmentally, socially and economically). Thus, sediment management in a river catchment scale integrates the management of all activities that influence sediment generation and transport. Apitz and White (2003) noted that river catchment approach to sediment management ensures that the sediment balance is achieved throughout the river system meaning that ranges of spatially varying environmental benefits are achieved.

Owens (2005) further presented a schematic presentation of some of the main influences and impacts of sediment within a river catchment (**Figure 7**).

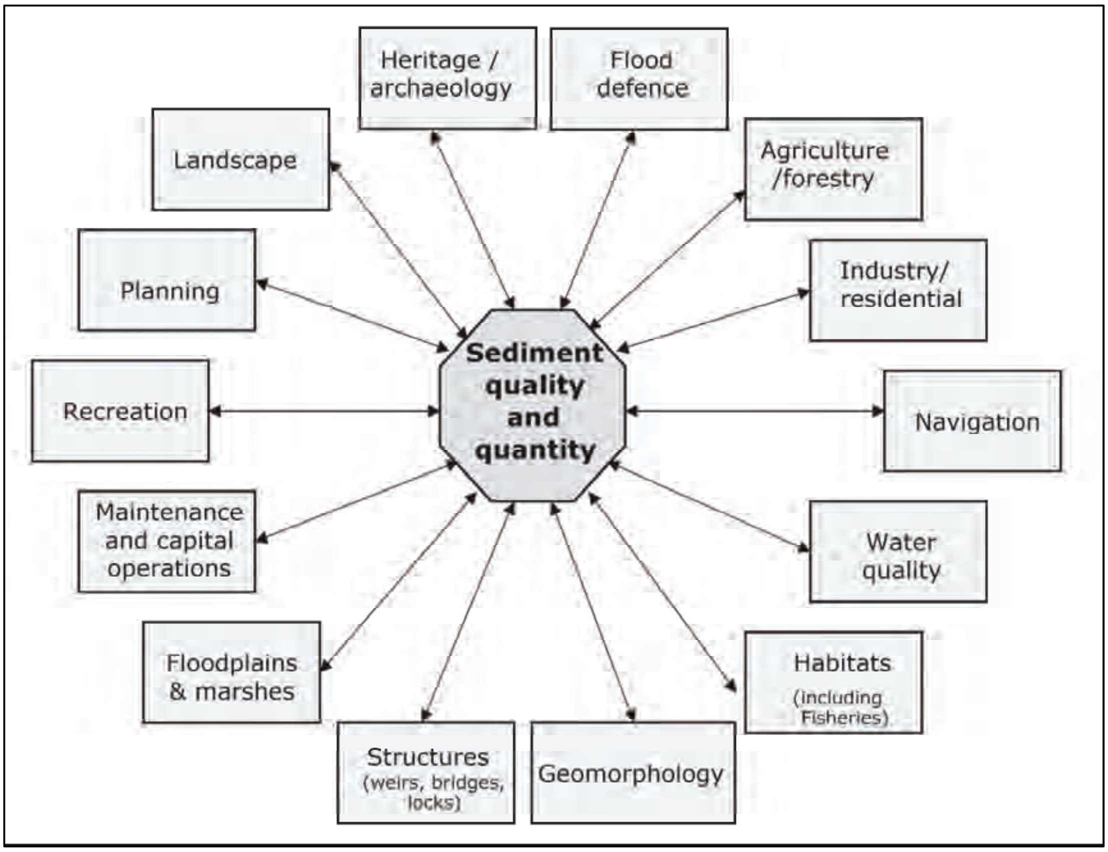

Figure 7: Schematic representation of some of the main influences and impacts on sediment within a river catchment (from Owens *et al.*, 2004)

5.2 SEDIMENT MANAGEMENT FRAMEWORKS

Although there is need to develop sediment management frameworks that can be used in any catchment, it is important to remember that each catchment is different and the complex role that sediment plays means that different objectives, pressures, impacts and mitigation measures will need to be considered in different catchments and even in different sites within a given catchment (Apitz *et al.*, 2009). Thus, a conceptual model may assist in identifying the need for site-specific assessment or catchment-scale assessment. In order for river catchments to be used as sediment management units, it is vital to have a conceptual model of river catchment functioning that links different areas in space and time, and allows potential consequences (impacts) of drivers to be evaluated (White and Apitz, 2008). **Figure 8** shows an example of such a model which has been described in Apitz *et al.* (2007).

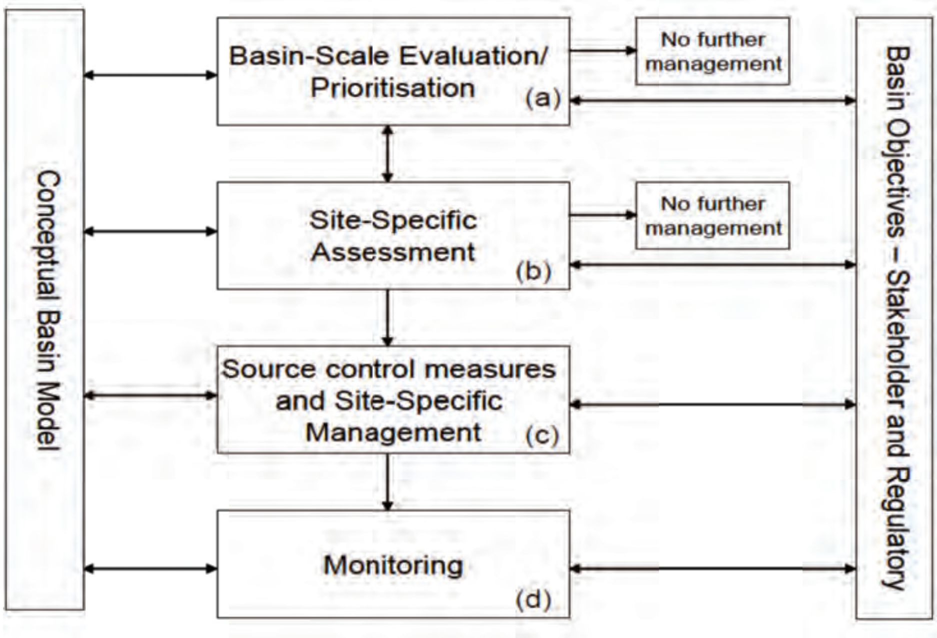

Figure 8: Conceptual diagram on the relationship between catchment-scale and site-specific assessment and management in a river catchment (SedNet, 2004)

Apitz and White (2003) proposed a conceptual framework (**Figure 9**) for river-catchment-scale sediment management. The framework gives an expanded and more detailed description of **Figure 8**. It is comprised of two principal levels of decision making for catchment-scale evaluation (site prioritization) and site-specific assessment (risk ranking), respectively. High priority (high risk) sites and sites prioritized for management for socio-economic purposes are evaluated for management options.

A catchment-scale assessment involves the balancing of a Conceptual Catchment Model, which considers the mass flows of particles and contaminants, screening level assessment of sediment quality and archived data, and catchment-scale objectives to generate a Catchment Use Plan (Apitz and White, 2003). Site-specific management options are driven by site-specific impact on catchment-scale objectives, site-specific risk, technical feasibility and regulations (Apitz and White, 2003). The framework addresses the complexities inherent in managing sediments at both catchment-wide and site-specific scales.

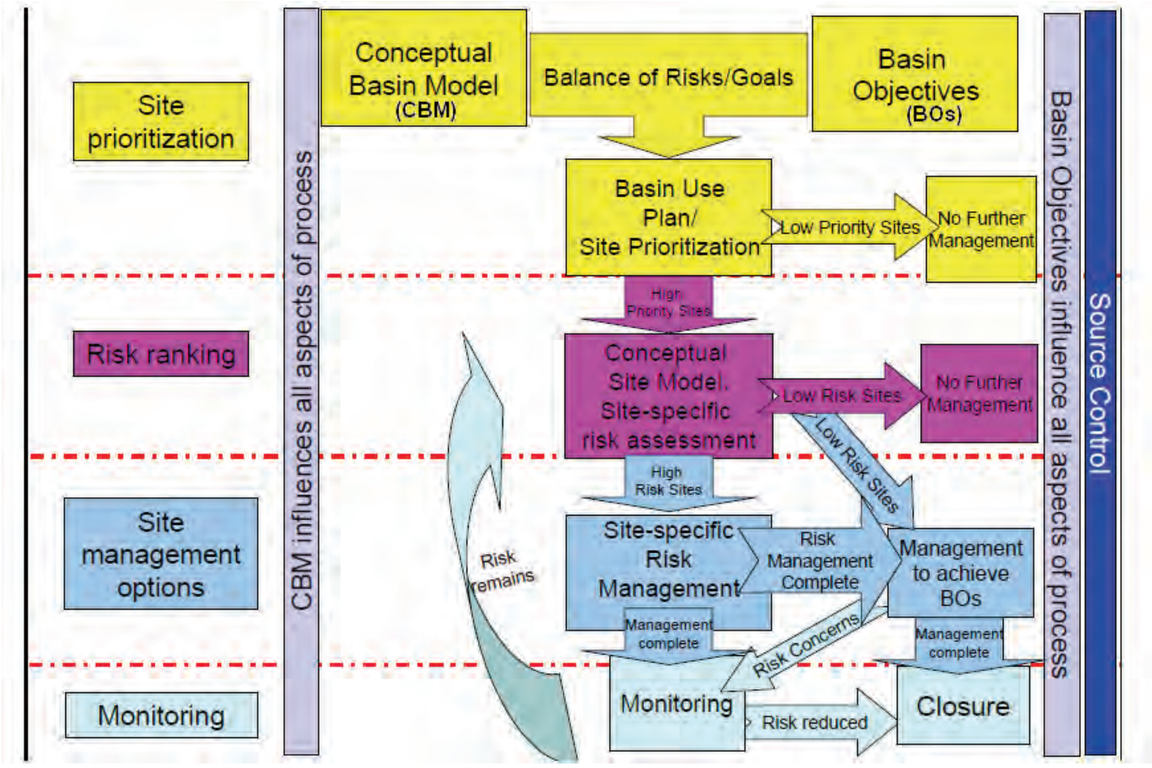

Figure 9: Proposed conceptual approach to catchment-scale sediment management (Apitz and White, 2003)

Sediment budget is one of the conceptual frameworks that can be used in sediment management. It is a useful and powerful conceptual framework for examining the relationships between sources, sinks, river transport, catchment yield, land use, climate variability/change, seismicity and isostatic adjustment (Wasson, 2002). Sediment budget concept represents a basic framework for assessing erosion and sediment delivery in reservoir catchments (Chen and Lai, 2005). As conceptual framework, the sediment budget links hydrology, geomorphology, geochemistry and biogeochemistry through its accounting of sources, sinks and processes of mass exchange between water, sediment, solutes and nutrients at a range of temporal and spatial scales (Slaymaker, 1997) and poses questions about sediment storage and virtual velocities and generates sediment budget models incorporating sediment source-to-sink fluxes that inspire research agendas (Slaymaker, 2003).

The sediment budgets could provide a basis for designing sediment control and management strategies for reducing the efficiency of sediment delivery from the individual areas to the river systems, and increasing storage elsewhere in the catchment (Chen and Lai, 2005). A sediment budget is an account of the sources and deposition of sediment as it travels from its point of origin to its eventual exit from a drainage catchment (Reid and Dunne, 1996). The difference between the sediment sources and the sinks in each cell, hence for the entire sediment budget, must equal the rate of change in sediment volume occurring within that region, accounting for pertinent engineering activities (Rosati and Kraus, 1999). The sediment budget equation can be expressed as:

$$\sum Q_{source} - \sum Q_{\sin k} = \Delta V + P - R = \mathrm{Re}\,sidual \tag{5.1}$$

where *Qsource* and *Qsink* are the sources and sinks to the control volume, ΔV is the net change in volume within the cell, *P* and *R* are the amounts of material placed in and removed from the cell, respectively; and *Residual* represents the degree to which the cell is balanced. **Figure 10** illustrates the parameters appearing in Equation 5.1.

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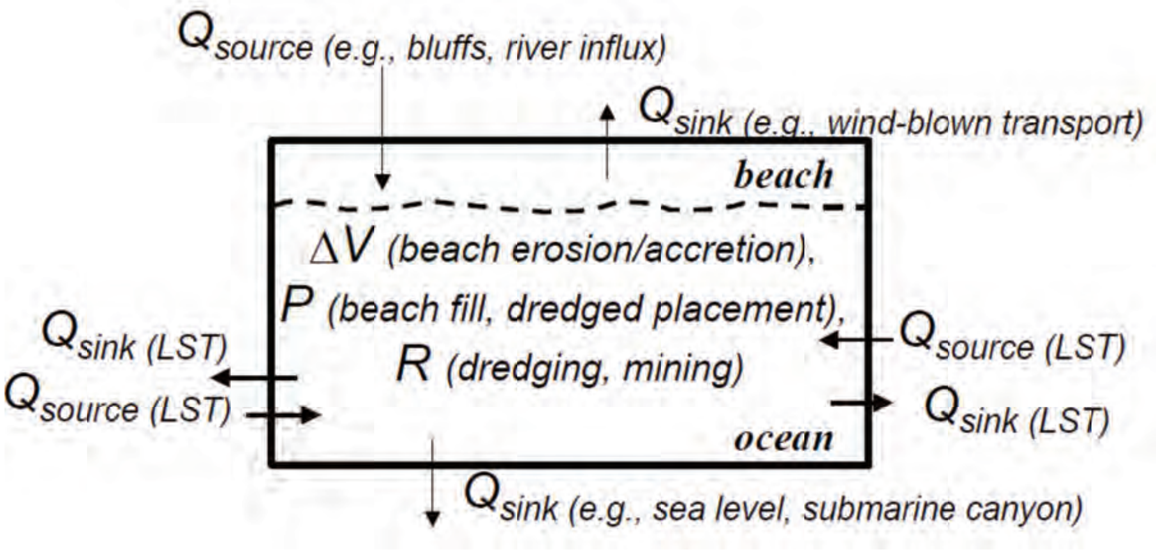

Figure 10: Sediment budget parameters (Rosati and Kraus, 1999)

Rosati (2005) reviewed commonly applied sediment budget concepts and introduced new considerations intended to make the sediment budget process more reliable, streamlined, and understandable. The conceptual model may be put together in part by adopting sediment budgets developed for other sites in similar settings, and incorporates all sediment sinks, sources, and pathways (Rosati and Kraus, 1999). The conceptual model is developed initially, perhaps based upon a reconnaissance study at the site as part of the initial data set (Rosati, 2005). Once the conceptual sediment budget has been completed, data are assimilated to validate the conceptual model rather than to develop the model (Rosati, 2005).

Apitz *et al.* (2009) modified Landis Regional Risk model to support the risk assessment of sediments at the river catchment scale leading to the development of a sediment risk ranking conceptual model (**Figure 11**). The model provides a framework to link catchment objectives to sediment sources and enables assessment of relative risk including impacts and benefits, and generates testable hypothesis about sources and potential impacts (Apitz *et al.*, 2009).

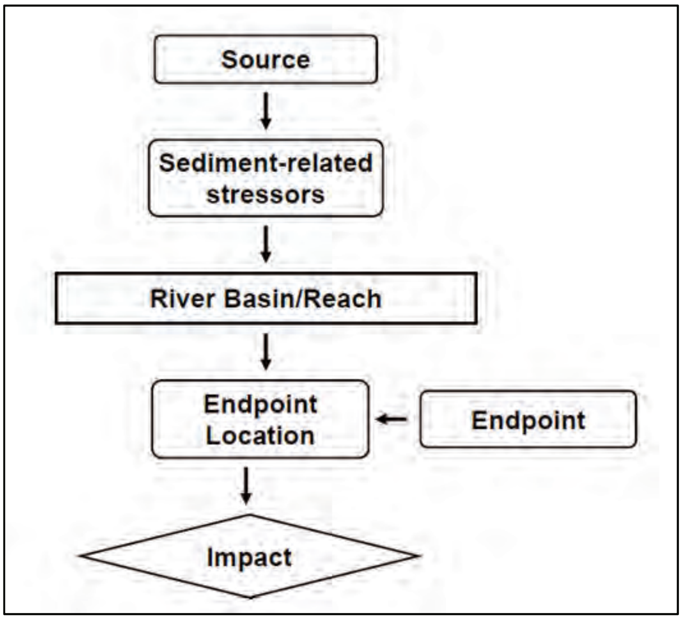

Figure 11: Sediment risk ranking conceptual model (Apitz *et al.*, 2009)

Apitz *et al.* (2005) focused on the development of contaminated sediment management approaches within a risk-based framework (the assessment and management of sediments based on their potential risk to human health and the environment). The study reviewed key elements of an effective sediment investigation and risk evaluation strategy including the development of a Conceptual Site Model (CSM), a discussion of some of the key factors influencing sediment investigations and ecological risk assessment of sediment-bound chemicals on aquatic biota.

A CSM is a basic description of how contaminants behave in a system and it provides an essential framework for determining source control requirements and addressing unacceptable risks (AWTA, 2009). The CSM identifies key site-specific or chemical specific factors affecting risk and potential remedy performance, and how these factors will change with time. By presenting this information in an organized framework, the CSM clarifies the development of risk reduction strategies, promotes identification of key data gaps and uncertainties, and comprises a framework for quantitative evaluation of remedy performance, effectiveness, and permanence (including, in some cases, numerical modelling) (Magar *et al.*, 2009).

CSM also serves as an important communication tool between scientists, regulators, and stakeholders across several technical disciplines and through several phases of an investigation (Apitz *et al*., 2005). An example of a more detailed, process-based CSM developed for specific areas of a site is provided in Magar *et al.* (2009).

Chapman and Anderson (2005) proposed a decision-making framework (Fig. 5.9) for contaminated sediments which emphasizes four guidance ‘‘rules’’. These can be simplified as:

- Sediment chemistry data are only to be used alone for remediation decisions when the costs of further investigation outweigh the costs of remediation and there is agreement among all stakeholders to act,
- Remediation decisions are based primarily on biology,
- Lines of evidence, such as laboratory toxicity tests and models that contradict the results of properly conducted field surveys, are assumed incorrect, and
- If the impacts of a remedial alternative will cause more environmental harm than good, then it should not be implemented.

The framework is explicitly based on ecological risk assessment principles (CCME, 1996) which have been described in detail in Chapman (2005). Application of this framework will allow for informed decision-making regarding the need to remediate contaminated sediments by using a consistent overall approach applicable to different sites so that findings can be readily compared and understood, and comparative risks can be more readily evaluated (Chapman and Anderson, 2005).

The framework in **Figure 12** was adopted by Chapman (2008) as the Canada-Ontario decision-making framework for managing contaminated sediments. The framework uses an ecosystem approach to sediment assessment and considers potential effects on sediment-dwelling and aquatic organisms, as well as potential for contamination by accumulating in the food chain. It is intended to standardize the decision-making process while also being flexible enough to account for site-specific considerations (Chapman, 2008). It is also based on four guidance rules used in the decision-making framework by Chapman and Anderson (2005). Detailed description of the decision-making framework is provided in Chapman. (2008).

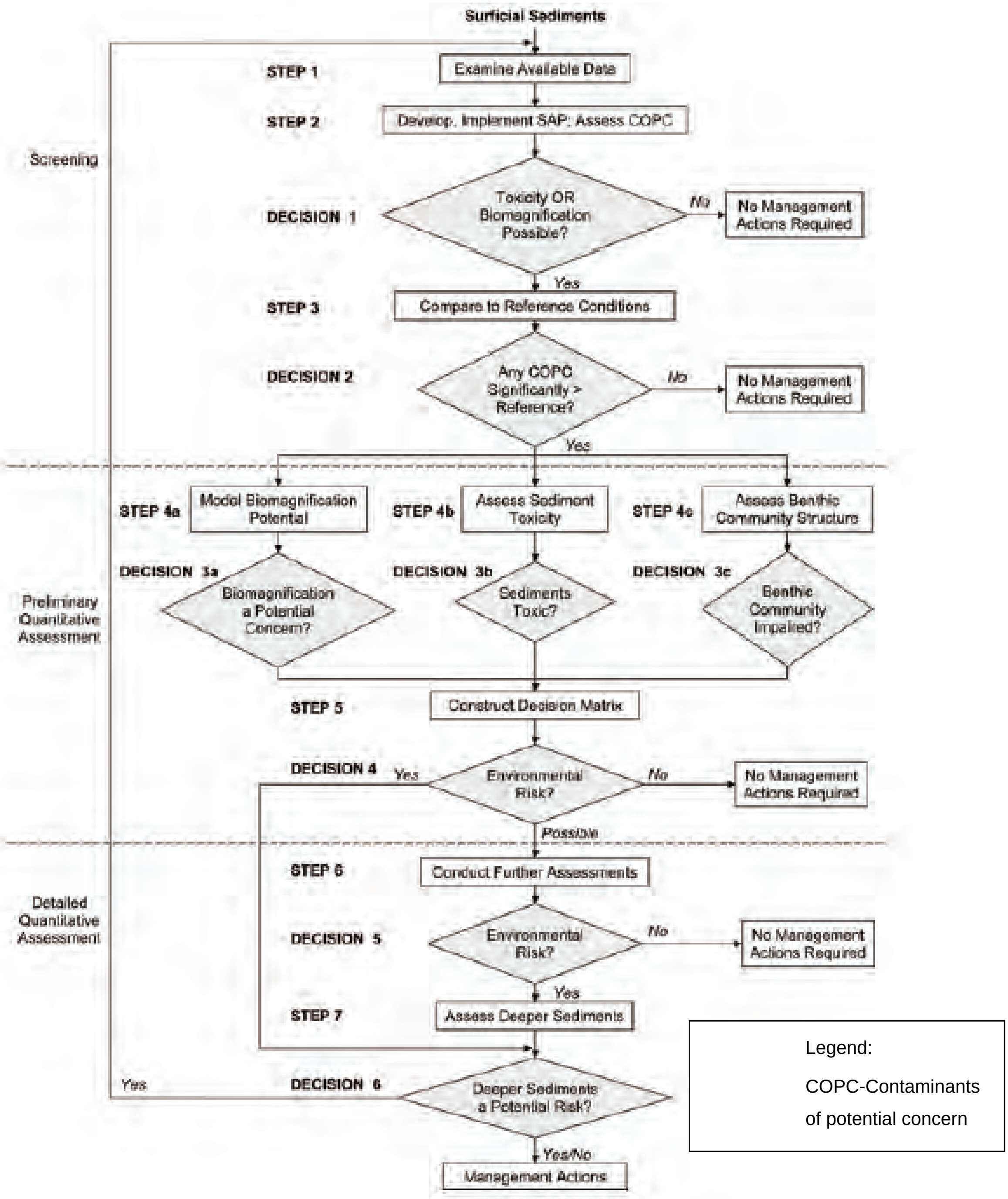

Figure 12: Canada-Ontario decision-making framework (Chapmand and Anderson, 2005; Chapman, 2008)

Peterson *et al.* (1999) described a decision tree/framework (**Figure 13**) which provides for early actions, where appropriate, to address more imminent adverse effects of contaminated sediments or to undertake actions that can be readily conceived and implemented without significant site evaluation. It also provides for early recognition and/or elimination of important ongoing external sources of contamination. Peterson *et al.* (1999) recommended that the decision tree be used in an iterative manner to arrive at a long-term sediment management strategy. The n processes in the decision tree include:

- Initial evaluation and early decision which identifies new sites and determines whether immediate action is appropriate, no action is appropriate, or no early decision can be made.
- Source control which is desirable if on-going external sources significantly contribute contaminants of concern to sediments or the water column.
- Site evaluation and risk assessment which is an iterative process aimed at determining existing and future risks to human health and the environment and prioritizing areas and issues of concern based on the developed models.
- Feasibility study/remedy selection which involves developing remedial objectives; identifying, screening, and developing technologies and alternatives; and conducting detailed and comparative analyses of alternatives

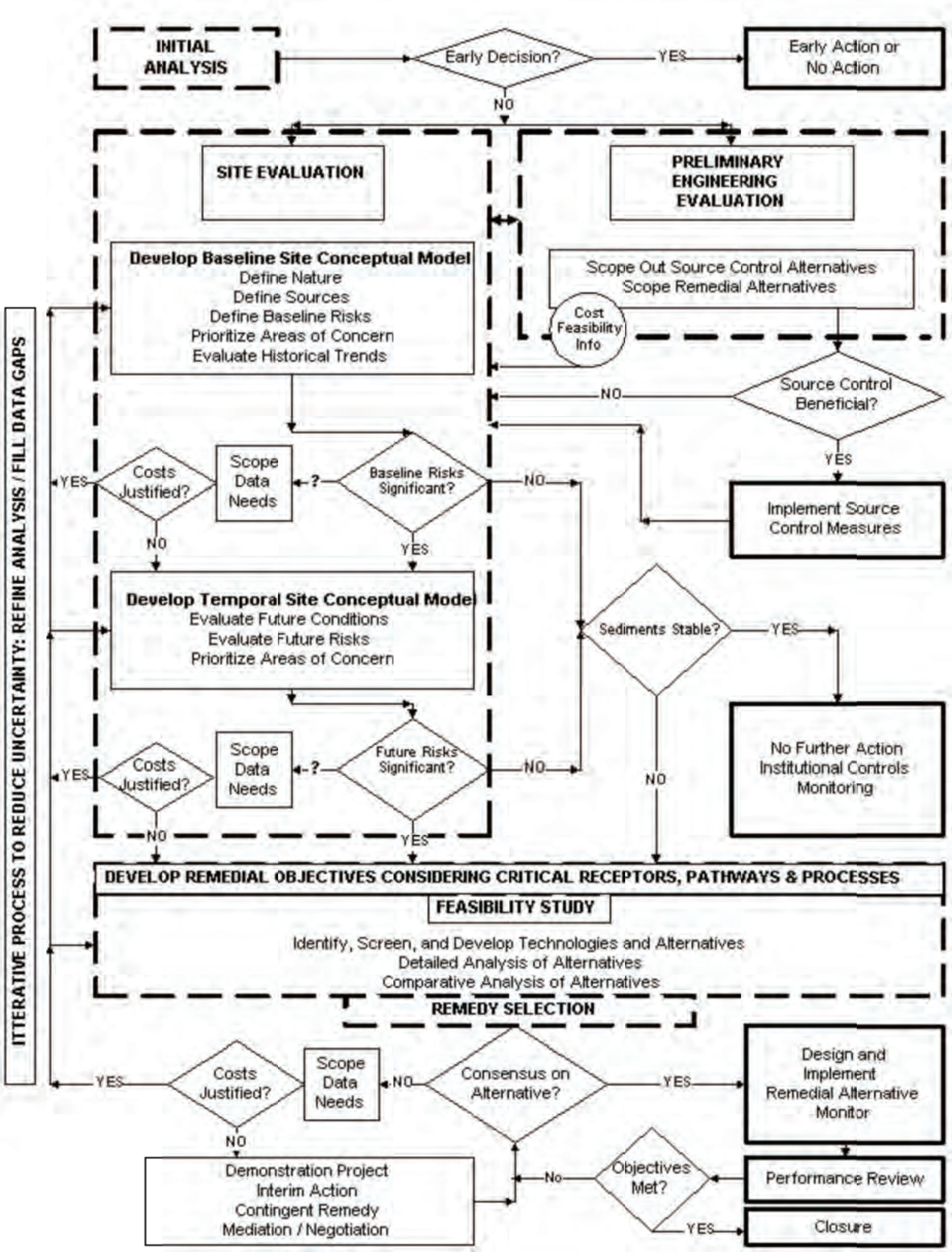

Figure 13: Contaminated sediment remedial action decision framework (Peterson *et al.*, 1999)

The decision making tree was used to characterize samples from the port of Piraeu, Greece in a study by Katsiri *et al.* (2008). The analysis showed that disposal to confined facilities is a feasible option for contaminated sediment management while non-hazardous sediments can be disposed in ordinary landfill.

Broads Authority applied the Driving Force-Pressure-State-Impact-Response (DPSIR) framework (**Figure 14**) in order to tackle the issues surrounding sediment management in a holistic way. Responses derived from the DPSIR model can be taken as options for local action to reduce sediment loading and can be considered under the do nothing, source control dredging, and in-channel management techniques. The DPSIR framework provides an overall mechanism for analyzing environmental problems and defines the interactions between various parameters and how they inform decisions. It incorporates the connectivity between human and ecological issues and would permit available performance indicators to be identified and organized in a manner that facilitates different regulatory needs (Cranford et al., 2012). The approach defines the interactions between various parameters defining drivers, pressures, state, impact and responses.

White and Apitz (2008) gave an example on how DPSIR framework can be used in contaminated sediment management wherein a direct comparison between sediment contaminant levels and target values is used to infer toxicity (or a much more extensive, site-specific ecological risk assessment) using tiered approaches. From such an assessment, the selection of appropriate remedial responses may include a complex comparative risk assessment, considering the financial regulatory, scientific and technical aspects of the site.

White and Apitz (2008) further gave an example of a catchment wide sediment management strategy for the Northfolk Broads, England. This involved development of conceptual model of the Broads sediment sources, sediment budget and DPSIR analysis. This was then used to identify priority options for sediment management for the Broads Authority. These included priority areas of research and/or monitoring and influencing policy and activities in areas outside the direct control of Broads Authority (White and Apitz, 2008).

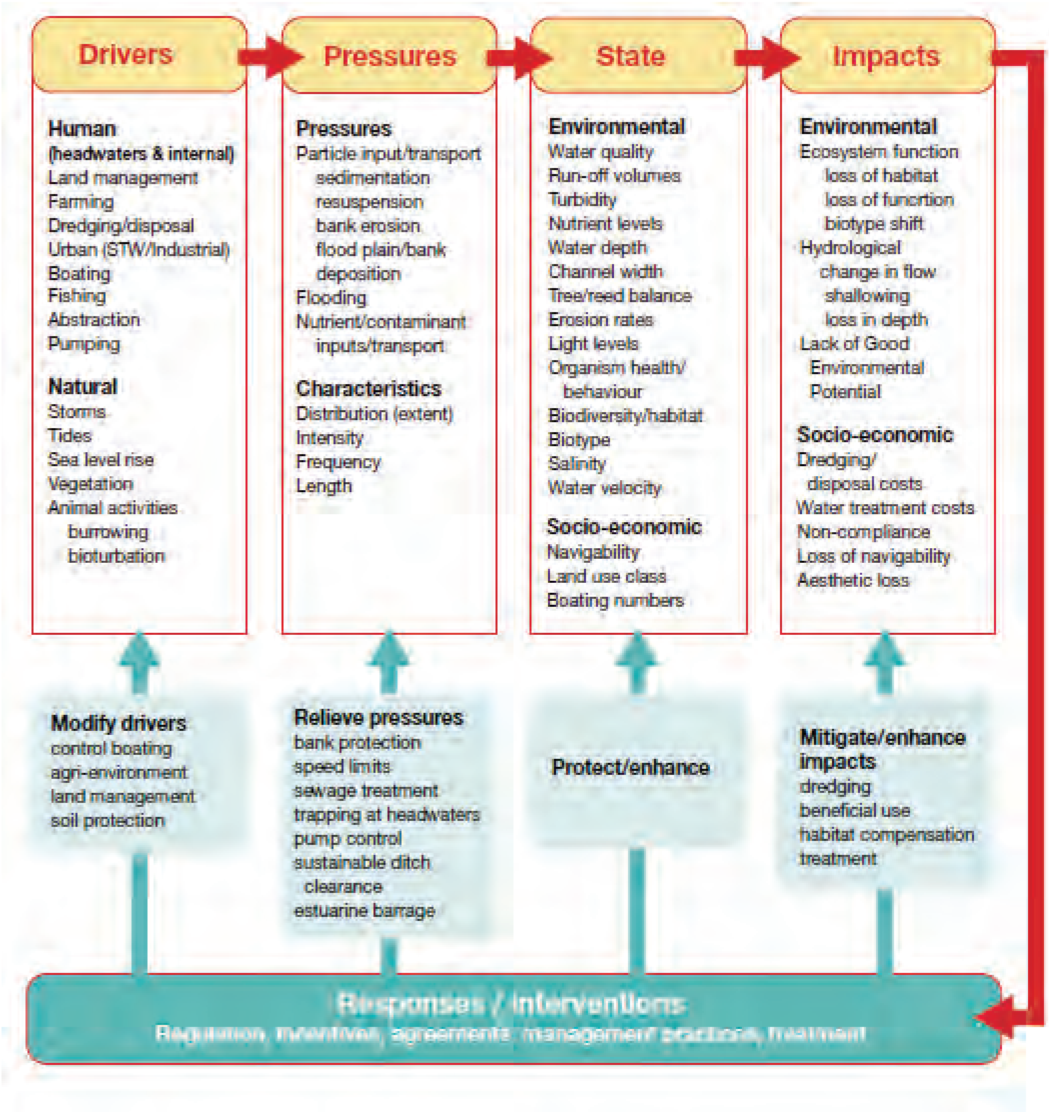

Figure 14: DPSIR framework

Owens (2009) reviewed the Adaptive Management (AM) approach for sediment management, including its characteristics, steps, and barriers to implementation. The study also gave some recent examples where the AM approach has been used for sediment quantity and quality issues. Adaptive management has been utilized for the management of water and river catchment resources, particularly in North America though its use for sediment resources is less developed (Owens, 2009). The suggested steps in the AM approach are shown in **Figure 15** as documented in Owens (2009).

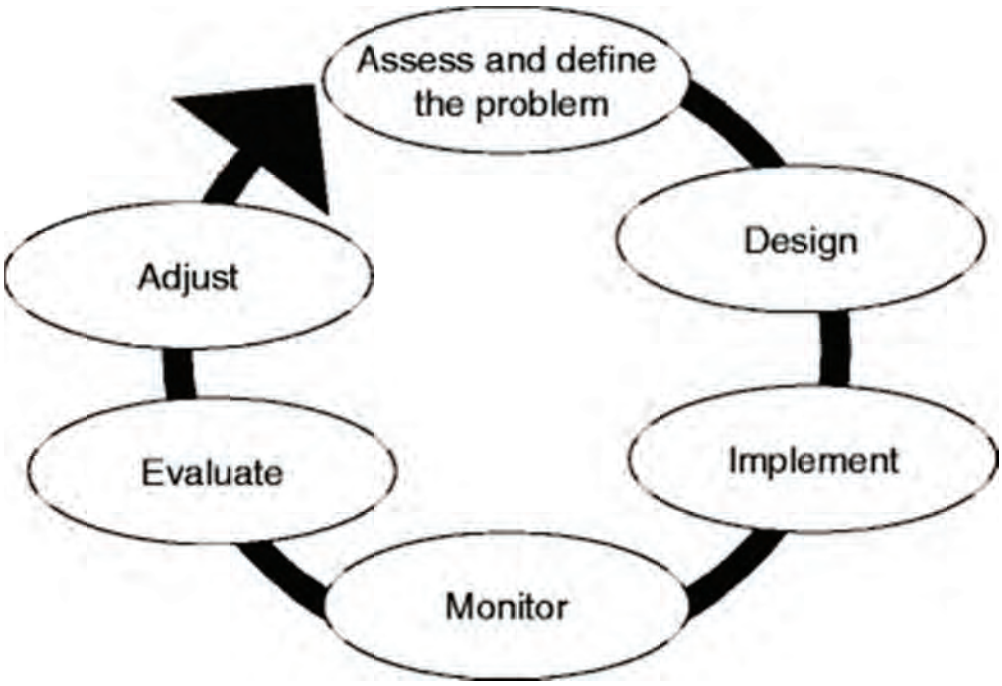

Figure 15: Suggested steps in the AM process (Williams *et al.*, 2007; BCMFR, 2008; Smith, 2008)

The AM approach can be expanded to take uncertainty into account. Owens (2009) noted that, in terms of sediment management, much of the present uncertainty (**Figure 16**) is of "structural or process uncertainty" due to an incomplete understanding of how environmental systems function, such as the understanding of relations between sediment and biological components of the system. The AM framework for sediment management at a river catchment scale is shown in **Figure 17** The concept of AM should be considered as a viable option early in the decision-making process.

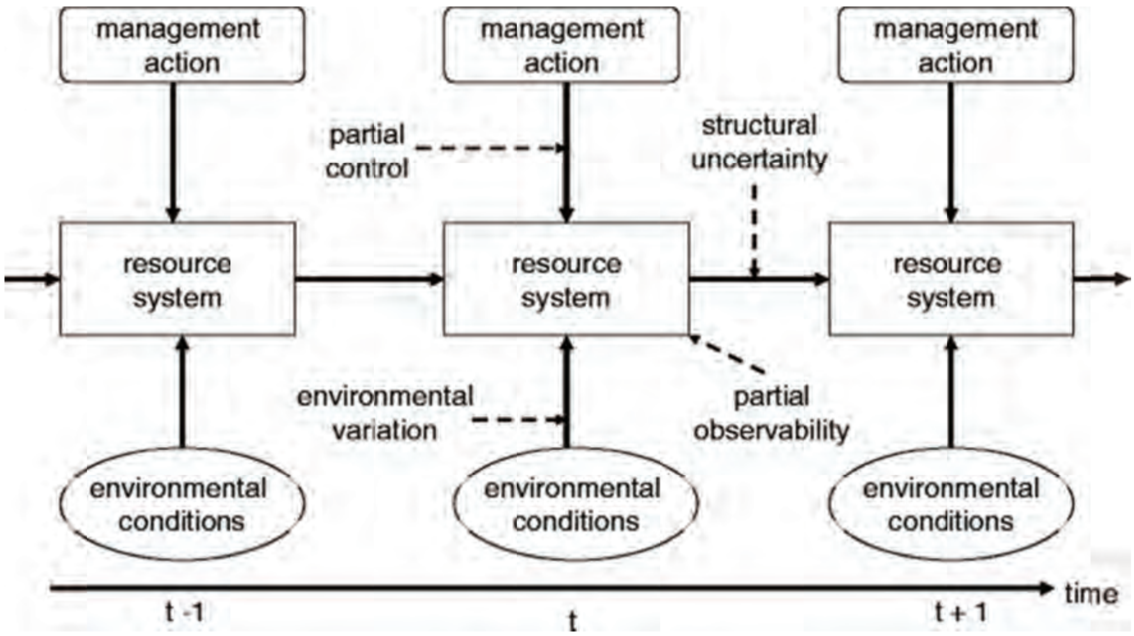

Figure 16: Uncertainty sources in natural resource management (Williams *et al.*, 2007)

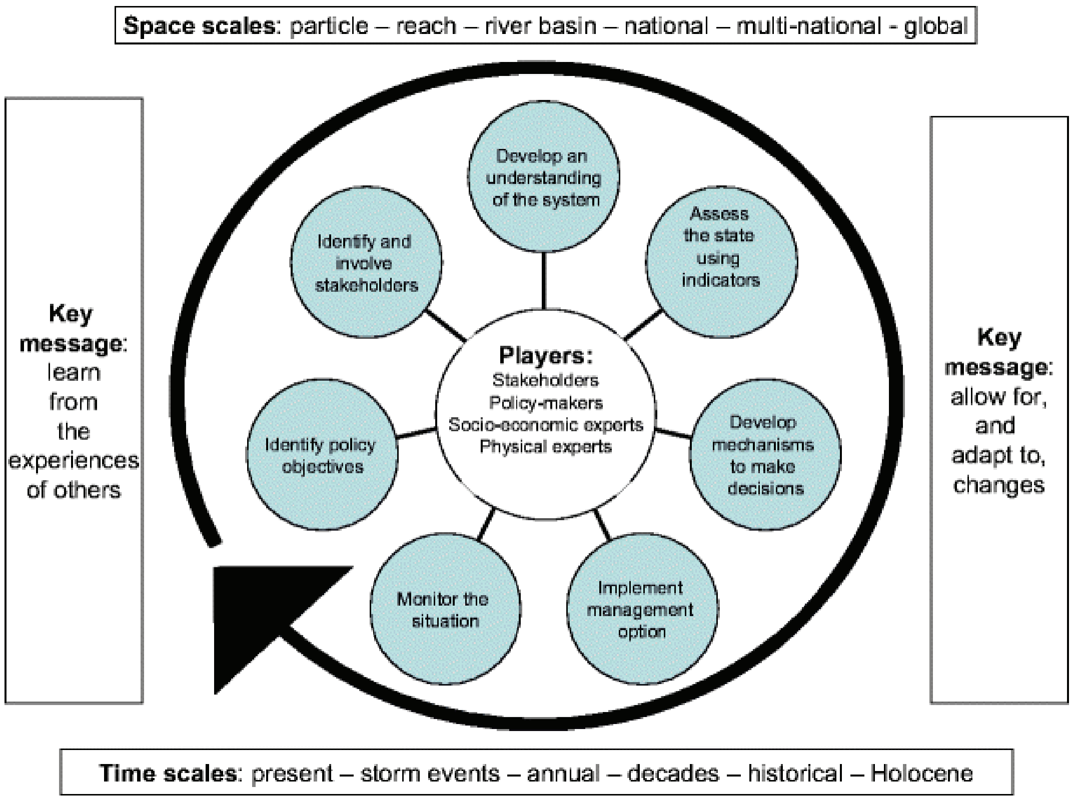

Figure 17: Adaptive framework showing the stages (*outside circles*) and players (*inner circle*) required for sediment management at the river catchment scale (Owens, 2009)

The AM was applied in development of the regional sediment management strategy of Perdido Pass, Alabama aimed at reducing erosion downdrift, rehandling of material that returns to the pass and optimize sand bypassing (see Lillycrop et al., 2011). The implementation of the framework resulted in substantial dredging cost savings. Other benefits included more efficient sand bypassing, reduction of material which returns to the pass and wider downdrift beaches.

U.S. Army Corps of Engineers *et al.* (2006, 2009) developed a sediment evaluation framework (SEF) (**Figure 18**) for the Pacific Northwest (the states of Washington, Oregon, and Idaho). The SEF provides a regional framework for the assessment, characterization, and management (disposal) of sediments in order to determine suitability for unconfined in-water disposal (U.S. Army Corps of Engineers *et al.*, 2009). The SEF is relevant to maintenance dredging and contaminated sediment (CS) cleanup related activities and it presents an evaluation framework for sampling, sediment testing, and test interpretation (U.S. Army Corps of Engineers *et al.*, 2006). The study noted that the framework provides the basis for evaluating the suitability for unconfined open water or other disposal options and supports the evaluation of the potential risk of in-place sediments and tools to evaluate the sediments based on potential cleanup options for dredging projects and sediment cleanup projects, respectively.

According to U.S. Army Corps of Engineers *et al.* (2006), the SEF was prepared to establish:

- An appropriate marine and freshwater sediment characterization framework agreeable to the public, stakeholders, and regulatory resource agencies.
- A uniform framework under which the Corps will carry out federal requirements in conducting the dredging and disposal program.
- A uniform framework for evaluating the effects of sediment management activities on water quality.
- Appropriate databases to track the long-term trends in sediment quality of specific dredging projects/locations and the river in general.
- Procedures or references for other regional/national guidance to assist in the identification and evaluation of alternative sediment management options.

The SEF is not intended to identify management practices for materials unsuitable for unconfined in water disposal or leave surfaces, but can be used to identify when additional management is appropriate in order for a dredging project to proceed (Braun, 2009).

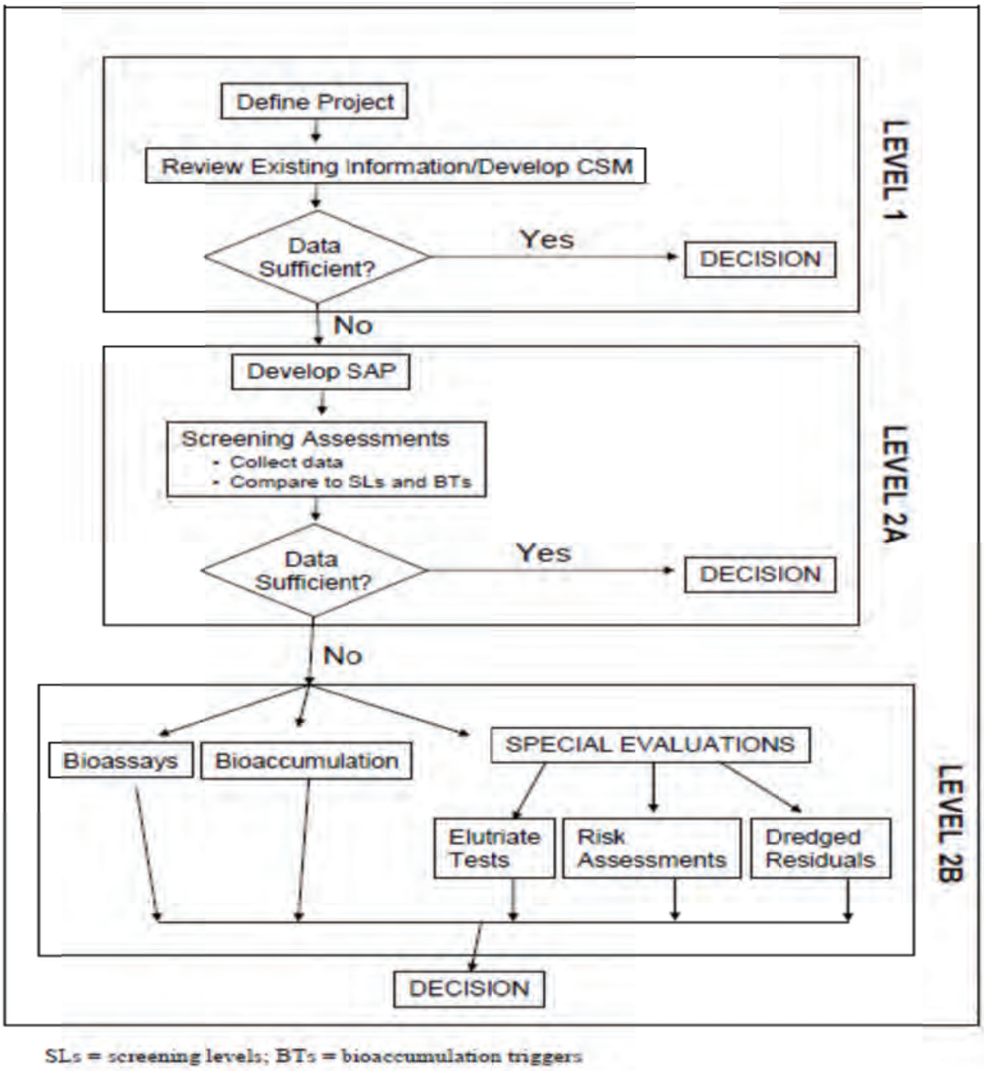

Figure 18: Generalized sediment evaluation framework (U.S. Army Corps of Engineers *et al.*, 2009)

The Corps and USEPA developed a technical management framework (**Figure 19**) for determining the environmental acceptability of dredged material disposal alternatives (USACE/USEPA, 1992). The Corps/USEPA management framework is a tiered decision-making process. Information about the sediments to be dredged is evaluated to determine the suitability of disposal alternatives in order of increasing complexity. Sediments that are determined to be uncontaminated are suitable for a wider variety of disposal options, and decisions can be made early in the evaluation process. Sediments that are contaminated require a more extensive evaluation within the decision-making framework, have additional testing requirements, and usually have fewer disposal options (USEPA, 1994). Further details of this framework are provided in United States Army Corps of Engineers and USEPA (2004).

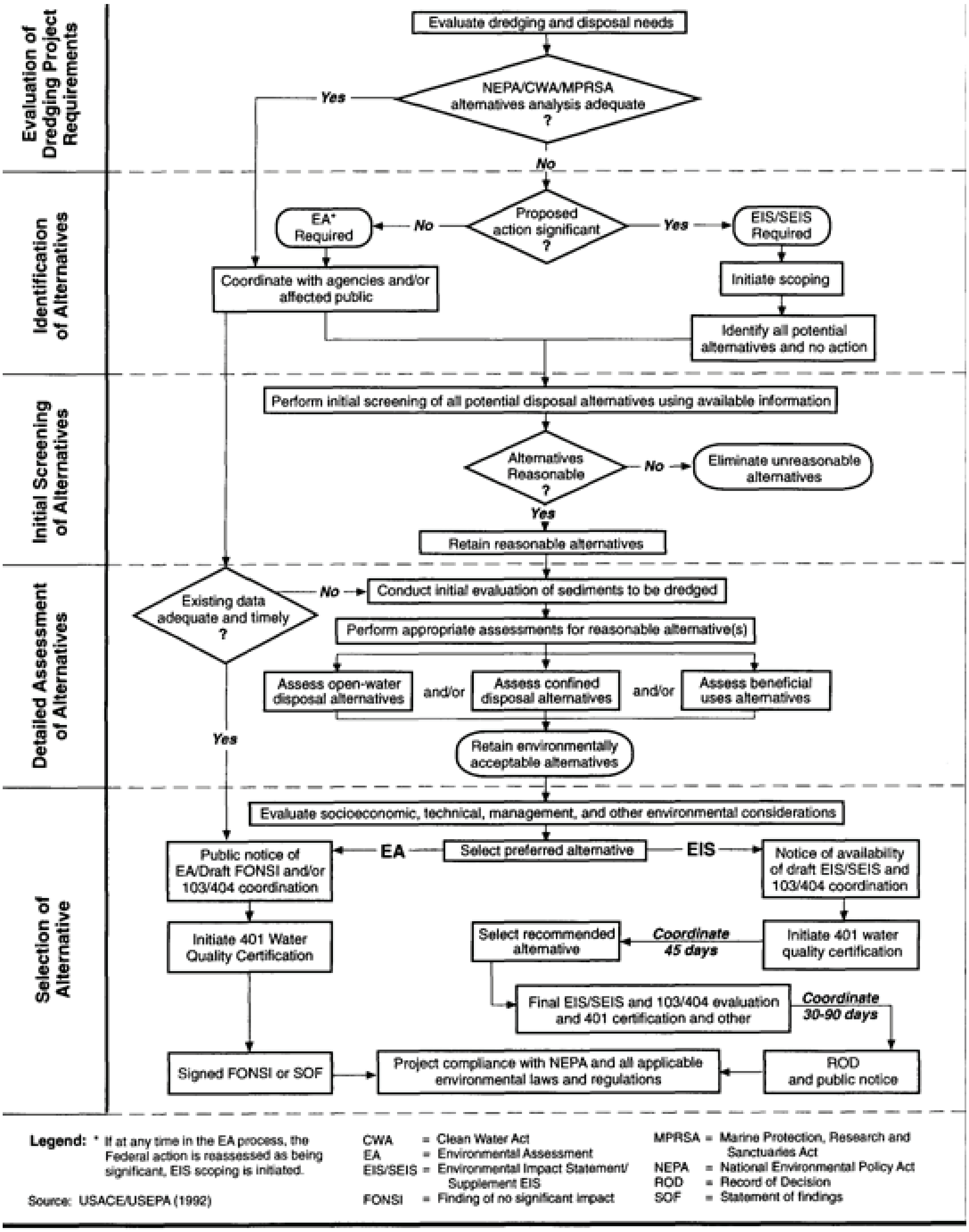

Figure 19: Corps/USEPA framework (U.S. Army Corps of Engineers and USEPA, 2004)

5.3 SUMMARY OF THE CHARACTERISTICS OF SEDIMENT MANAGEMENT FRAMEWORKS

Table 15 gives a summary of the characteristics of the reviewed sediment management frameworks. This will aid in selecting the appropriate frameworks for application in South Africa. Most of the frameworks can be applied on site-specific and river catchment scales. All frameworks except for the conceptual framework for river-catchment-scale sediment management do not show the level at which stakeholder participation should be undertaken within their structures.

Heise *et al.* (2004) noted that for effective and successful sediment management it is essential that the relevant stakeholders participate in the entire process, on both the local and catchment scales, during assessment, development and implementation, of sediment management plans. Stakeholder participation in water resources management has been emphasized in the National Water Act (NWA) of 1998 and National Water Resources Strategy (DWAF, 2004b). DWAF (2004a) further provides guidelines for stakeholder participation in integrated water resources management (IWRM) in South Africa. Stakeholder participation in IWRM should, therefore, be based on a well-defined process leading to clear benefits to participation. As such, stakeholders need to be able to express their needs, but also to see how these needs are going to be progressively realized by ongoing participation. The guidelines include a detailed procedure for stakeholder participation in IWRM.

Table 15: Characteristics of the reviewed sediment management frameworks

Framework	**Scale of application**	**Addresses management of**	**Stakeholder participation**	**Case study example**	**Reference (s)**
Conceptual framework for river-catchment-scale sediment management	Site-specific and river catchment	Quantity and quality	Yes	Not specified	White and Apitz (2003)
Sediment budget conceptual framework	Site-specific and river catchment	Quantity	No	Long Island, New York, and Ocean City Inlet, Maryland	Rosati (2005)
Sediment risk ranking conceptual model	Site-specific and river catchment	Quantity and quality	No	WFD River Basin, UK	Apitz *et al.* (2009)
A risk-based framework for contaminated sediment	Site-specific and river catchment	Quality	Yes	Canada and Ontario*	Chapman and Anderson 2005
Contaminated sediment decision tree/framework	Site-specific	Quality	No	Piraeu, Greece	Katsiri *et al.* (2008)
Driving Force-Pressure-State-Impact-Response (DPSIR) framework	Site-specific and river catchment	Quantity and quality	Yes	Northfolk Broads, England	White and Apitz (2008), Cranford et al., 2012)
Adaptive Management framework	Regional and river catchment	Quantity and quality	Yes	Perdido Pass, Alabama, US	Lillycrop *et al.* (2011)

Framework	Scale of application	Addresses management of	Stakeholder participation	Case study example	Reference (s)
Sediment evaluation framework	Regional	Quantity and quality	Yes	Pacific Northwest (the states of Washington, Oregon, and Idaho	U.S. Army Corps of Engineers *et al.* (2006)
Technical management framework	Regional	Quality	Not specified	US Corps navigation dredging	U.S. Army Corps of Engineers and USEPA (2004)

5.4 SEDIMENT MANAGEMENT FRAMEWORKS IN THE SOUTH AFRICAN CONTEXT

As stated earlier there are no documented sediment management frameworks in South Africa. However, there are various legislations concerned with water and environmental protection that may indirectly include sediment management. These include the NWA No. 36 of 1998 and National Environmental Management Act (NEMA) No. 107 of 1998. Section 21(g) of the NWA stipulates that the disposal of waste in a manner which may detrimentally impact on a water resource is a water use. According to DWAF (2008) the waste includes any solid material or material that is suspended, dissolved or transported in water (including sediment) and which is spilled or deposited on land or into a water resource in such a volume, composition or manner as to cause, or to be reasonably likely to cause, the water resource to be polluted.

The NWA also states that water use must be licensed unless it is listed in Schedule I, as an existing lawful use, and is permissible under general authorization, or if a responsible authority waives the need for a license. Thus, the NWA may aid in minimization and/or control of disposal of sediments in water bodies through licensing of sediment disposal activities. The NWA therefore contributes to sediment management through protection and management of water resources.

The principles of national environmental management stated in the NEMA serve as the general framework within which environmental management and implementation plans must be formulated. Section 4 (a) of Chapter 2 states that waste should be avoided or where it cannot be altogether avoided, minimized and re-used or recycled where possible and otherwise disposed of in a responsible manner. Section 4(b) states that environmental management must be integrated acknowledging that all elements of the environment are linked and inter-related, and it must take into account the effects of decisions on all aspects of the environment and all people in the environment by pursuing the selection of the best practicable environmental option. Thus, the NEMA also indirectly addresses sediment management through provision of principles of national environmental management.

6 FRAMEWORK DEVELOPMENT APPROACH

6.1 OVERVIEW

The literature review showed the need for integrated sediment management frameworks which is essential for sustainable sediment management in a catchment. The review also showed that sediment management frameworks for most river catchments in the world, including South Africa, have not yet been developed or are not yet well established. This creates the need to develop integrated sediment management framework. The appropriate scale for developing sediment management frameworks is a river catchment scale which integrates the management of all activities that influence sediment generation and transport. This study further reviewed existing sediment management frameworks in order to recommend how framework(s) suitable for South African river catchments can be developed.

6.2 INTEGRATED MANAGEMENT AND ITS IMPORTANCE

The imperative of integration stems from recognition of the interdependence of human and natural systems expressed in the research and policy agendas of sustainability. Integrated Resource Management is about integrated and "joined-up" management, and promoting of integration across sectors, applications, groups in society and time, based upon an agreed set of principles. Integrated Resource management seeks to tackle some of the root causes of the management crisis, namely the inefficiencies and conflicts that arise from un-coordinated development and use of resources, and in this case Sediments (Jeleni *et al.*, 2010).

Social equity, economic efficiency, and environmental sustainability constitute the three pillars of Integrated Resources Management, while quantity and quality are the two pillars of the resource's existence and value. The strategic path to achieving efficiency, equity and sustainability lies not in one sub-strategy alone but in the expression of these as cross-cutting and interrelated themes. This is consistent with managing complex systems where outcomes reflect the consequences of multiple factors, and moreover, because they are not entirely independent of each other or predictable, there is a need to adapt while learning. Both of these principles rely on the whole – the collective effort of all the different sub-strategies – rather than simply on a single strategy, (Jeleni *et al*., 2010).

What is therefore required is the vision, to address both principles through the creation of a desired long-term view for the resources in question that captures the idea of sustainable development, efficiency and equity. Hence the assessment of the current and future situation must take into consideration the Drivers Pressures States Impacts Response (DPSIR) indicators of the space in question in light of sustainability, efficiency and equity, by asking – “is this an optimal representative situation?” – then plan accordingly. The assessment clearly calls for a holistic approach, while striking a balance between the goals of equity, sustainability and efficiency. The basis for equity is, in essence, provided by the situation assessment and visioning. The former requires an assessment based on criteria pertaining to equity; the latter requires a vision that talks to equity, redress and transformation, (Jeleni *et al*., 2010).

Given, the above, a sediment balance sheet can be said to be achievable by allowing for trade-offs between quantity, quality, efficiency, equity and sustainability of the sediments. Within the context of a country, this balance sheet will have to be integrated in space (Site, Catchment and Regional) and Time to achieve sustainable, efficient and equitable distribution and management of sediments. This integration has to be achieved in both a bottom up, and a top down approach, and this requires a great deal of coordination between the various spaces, **Figure 20**, depicts this integration.

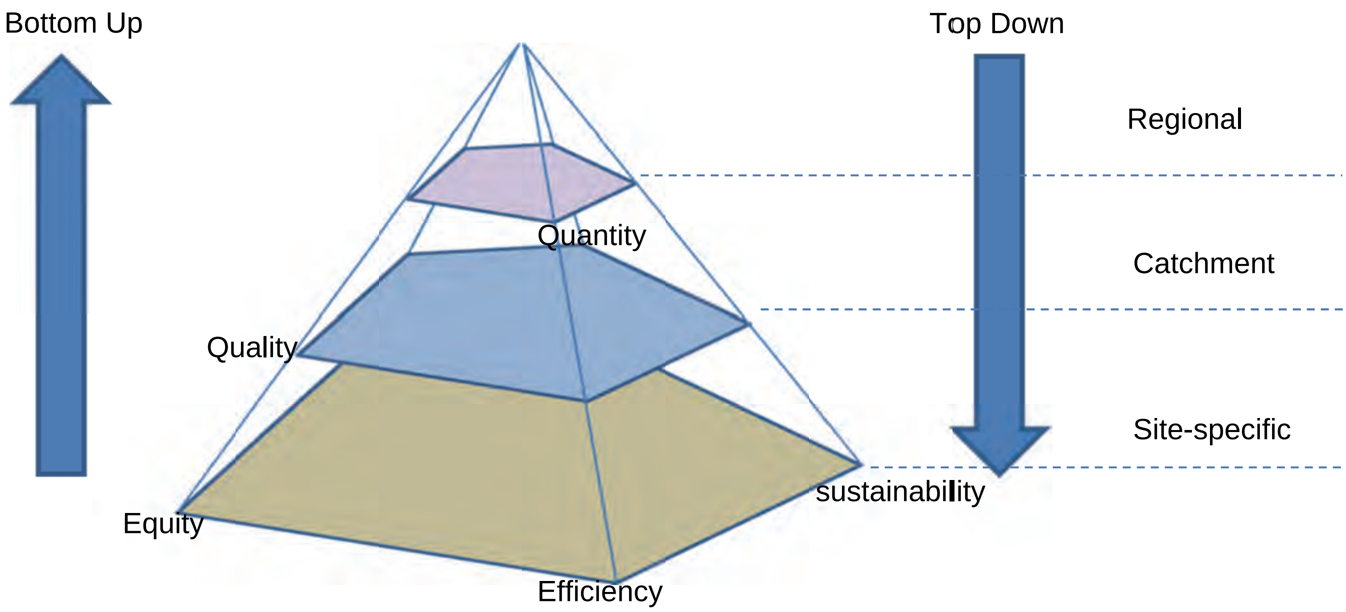

Figure 20: Integration hierarchy

According to Jeleni *et al*. (2010), integration can be defined as a “continual process, rather than a goal, of logically quantifying both the short term and long term effects of the decision process (governance and the tools) in a single platform". There are three levels of framework forming the integration hierarchy on a water sector level, and this are:

1. Level-I-Frameworks – this type of integration frameworks refers to a collection of tools that have been combined in order to represent a specific system/issue or a domain. These can be referred to as just "Frameworks" or "Integrated Tools".
2. Level-II-Frameworks – these integration frameworks refers to a collection of tools which have traditionally been used within their own separate systems, each consisting of similar tools to prepare input data, write input files and analyse model output. These can be referred to as "Integrated Frameworks".
3. Level-III-Frameworks – the level III integration frameworks refers to open frameworks for linking integrated tools and/or frameworks focusing on generic linkages and functional modularity. These can be referred to as "Generic Integrated Frameworks".

Jeleni *et al*. (2010) Identified Ten Level-II-Frameworks which can be represented as building blocks grouped into the "pillarly" and "foundational" blocks. The foundational blocks are those Level-II-Frameworks that are a necessity to the existence of the Generic Integrated Conceptual Framework (GICF), while the pillarly blocks do not need to be all in existence at once, but a sufficient number of them must be in place. The Level-II-Frameworks are as follows in their groups:

- Foundational – this consists of the:
    - Coordination and conflict resolution integrated framework – IWRM requires the participation of all units of government and stakeholders in decision-making through a process of coordination and conflict resolution.
    - Monitoring and compliance integrated framework – IWRM is not a goal but a process which requires continual monitoring and ensuring compliance to agreed objectives.
    - Data and information management integrated framework – data/information is the medium through which integration takes place, and before any discussion/decision can take place, some form of data/information must first be presented. This is true for IWRM, and a structure for data management is a prerequisite for a successful integration.
- Pillarly – this consist of :
    - Water resources assessment and development integrated framework – this is to enable interdisciplinary understanding of the dynamic linkages between the ecological, social and economic components of human-

environment systems associated with water resource management, over time. This can be used to inform the CMS.

- Regulatory integrated framework – IWRM requires devolution of powers to appropriate levels and this inherently requires a regulatory framework. The framework would go a long way in facilitating the transition of DWA to being a regulator.
- Water management financing integrated framework – implementation of the IWRM requires financial resources and an appropriate framework to guide sustainable funding. The framework can be used to guide the pricing strategy.
- Water allocation and use integrated framework – IWRM requires water to be allocated and used equitably, efficiently and sustainably; this requires a framework that brings together the different uses (i.e. water services, industry, energy, etc.) and in understanding the national benefits of their uses, draw an allocation plan.
- Capacity building integrated framework – IWRM is a new way of doing things and requires human capacity equal to the task. This requires capacity building initiatives that embrace the principles of IWRM.
- Research and development integrated framework – IWRM is not a goal but a process requiring continual improvement through research, and this requires a guiding framework to ensure that research produced adds value to the IWRM process.
- Domain/field specific integrated frameworks – the water sector is a multidisciplinary field combining different expertise which has its own framework (i.e. integrated hydrological modelling, integrated ecosystem modelling, integrated sediment modelling, integrated water quality modelling, etc.), this needs to be managed and brought together through a framework.

Therefore the integration at the third level of integration can structurally be depicted as the roof bringing together the Level-II-Frameworks grouped into the foundational and the pillarly frameworks as shown in **Figure 21.**

The integrated sediment management framework envisaged in this project can therefore, be viewed as a Level II – Domain/field specific integrated framework.

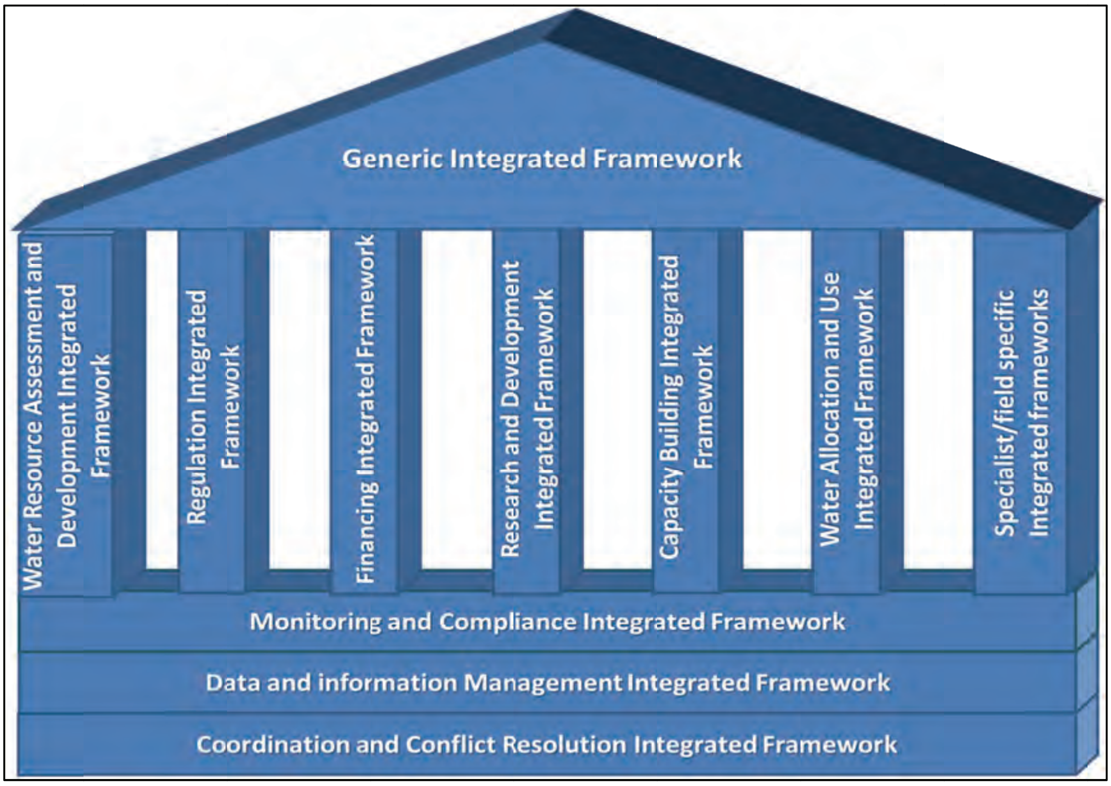

Figure 21: Integration structure of water management frameworks

In light of the above, the envisaged Sediment integrated Management framework is a Level II framework and falls under the specialist/field-specific Integrated frameworks focusing on sedimentation. Therefore, the development of the Sediment Integrated Framework in this project is based on the principles of the GICF.

6.3 SEDIMENT MANAGEMENT TOOLS

Integrated sediment modelling encompasses understanding the fate of a contaminant from its source point to its point of destination, and this requires the establishment of catchment or sub-catchment sediment yields, transporting the sediment through the river channel and transporting/depositing in the reservoir. The choice of the appropriate technique to estimate the sediment movements and impacts of a water resource system includes not only an assessment of the investigation aims and catchment condition, but also the potential impacts of system failure.

Visual and qualitative assessments are appropriate for sites where there is low risk and minimal change to an otherwise stable system. These can be accomplished with the aid of primarily judgment based tools. As the system of interest becomes more complex, and where there is a higher risk to life and property, more analytical approaches are used.

Many analytical techniques are available that typically require the calculation of hydraulic parameters for the range of natural discharges, such as velocity and shear stress. All of these techniques require data determined from field observations and measurements, as well as calculations.

As the risk and uncertainty increase, the use of more detailed models is recommended. However, the use of increasingly complicated models is not necessarily recommended. On its own, a more complicated analysis will not necessarily be sufficient or more accurate. The reliability of any model is dependent on the skill and experience of the assessor, as well as the input data. Engineering judgment becomes more critical with increasing risk, and the required field work and data collection become more labor intensive. Since each stream system is unique, assessors should review the assumptions and data requirements and consider their own experiences when determining the appropriate technique to use.

6.4 SEDIMENT MANAGEMENT SCALE

There are various scales at which sediment can be managed, i.e. Particle, Site, Reach, Catchment, Regional, National, Multinational and Global. Although local and site-specific sediment scales are still likely to be the main scales at which interventions are made, they need to be placed within a broader context and with full appreciation and consideration of their impacts within the river catchment (Owens, 2005). For sediment management to be effective the river catchment represents the most appropriate scale for consideration. This is the scale over which sediment supply, transfer and deposition occur (Apitz and White, 2003). Sediment is part of the hydrodynamic continuum, actions on a sediment unit can affect other parcels resulting in conflicting, counterproductive or inefficient management actions if not coordinated (Apitz et al., 2006).

Owens (2005) gave several reasons why the river catchment scale approach is required for effective sediment management. These include the fact that local interventions will in most cases impact on other parts of the river catchment, most large river catchments throughout the world are highly populated and/or modified by human activities (such as deforestation) and, in many cases source control will be the optimal long-term solution (environmentally, socially and economically). Thus, sediment management in a river catchment scale integrates the management of all activities that influence sediment generation and transport. Apitz and White (2003) noted that river catchment approach to sediment management ensures that the sediment balance is achieved throughout the river system meaning that ranges of spatially varying environmental benefits are achieved.

In a country context, there are three practical scales/levels within which sediments can be managed, and these are 1) Site-specific 2) Catchment and 3) Regional, representing the Operational, Tactical and strategic levels respectively. Integration is appropriately achieved at an intermediate level (Jeleni, 2009), which in this case is the Catchment Level. Therefore, the integration being sought after is the one that brings together the Site-specific, catchment and Regional objectives of sediment management to the integration platform and allows for trade-offs to take place as depicted in **Figure 22**.

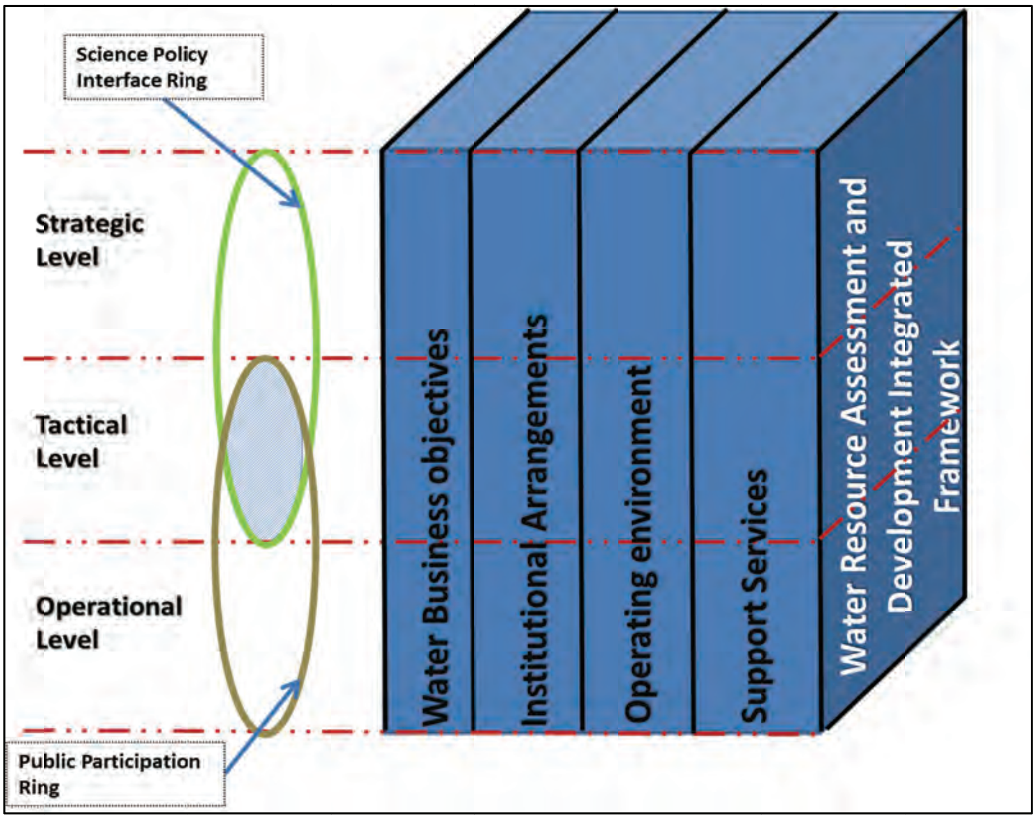

Figure 22: Level-II-Frameworks with the layers and management levels

A review of existing frameworks showed that current frameworks do not span the three scales (Site, Catchment and Regional), they at most either span Site and Catchment or Catchment and Regional, and therefore they are level I Frameworks.

Heise et al. (2004) noted that for effective and successful sediment management it is essential that the relevant stakeholders participate in the entire process, on both the local and catchment scales, during assessment, development and implementation, of sediment management plans. Stakeholder participation in water resources management has been emphasized in the National Water Act (NWA) of 1998 and National Water Resources Strategy (DWAF, 2004b). DWAF (2004a)

further provides guidelines for stakeholder participation in integrated water resources management (IWRM) in South Africa. Stakeholder participation in IWRM should, therefore, be based on a well-defined process leading to clear benefits to participation. As such, stakeholders need to be able to express their needs, but also to see how these needs are going to be progressively realized by ongoing participation. The guidelines include a detailed procedure for stakeholder participation in IWRM. The envisage level II Framework will essentially bring together the Level I frameworks to ensure consistent results whenever the Frameworks are applied, whether individually or in combination.

Table 16: List of Reviewed Frameworks

Framework	Scale of application	Addresses management of	Stakeholder participation	Case study example	Reference (s)
Conceptual framework for river-catchment-scale sediment management	Site-specific and river catchment	Quantity and quality	Yes	Not specified	Apitz and White (2003)
Sediment budget conceptual framework	Site-specific and river catchment	Quantity	No	Long Island, New York, and Ocean City Inlet, Maryland	Rosati (2005)
Sediment risk ranking conceptual model	Site-specific and river catchment	Quantity and quality	No	WFD River Basin, UK	Apitz *et al.* (2009)
A risk-based framework for contaminated sediment	Site-specific and river catchment	Quality	Yes	Canada and Ontario*	Chapman and Anderson 2005
Contaminated sediment decision tree/framework	Site-specific	Quality	No	Piraeu, Greece	Katsiri *et al.* (2008)
Driving Force-Pressure-State-Impact-Response (DPSIR) framework	Site-specific and river catchment	Quantity and quality	Yes	Northfolk Broads, England	White and Apitz (2008), Cranford et al., 2012)
Adaptive Management framework	Regional and river catchment	Quantity and quality	Yes	Perdido Pass, Alabama, US	Lillycrop *et al.* (2011)
Sediment evaluation framework	Regional	Quantity and quality	Yes	Pacific Northwest (the states of Washington, Oregon, and Idaho	U.S. Army Corps of Engineers *et al.* (2006)
Technical management framework	Regional	Quality	Not specified	US Corps navigation dredging	U.S. Army Corps of Engineers and USEPA (2004)

7 THE INTEGRATED SEDIMENT MANAGEMENT FRAMEWORK

7.1 OVERVIEW

Although there is a need to develop sediment management frameworks that can be used in any catchment, it is important to remember that each catchment is different and the complex role that sediment plays means that different objectives, pressures, impacts and mitigation measures will need to be considered in different catchments and even in different sites within a given catchment (Apitz et al., 2009). Thus, a conceptual model may assist in identifying the need for site-specific assessment or catchment-scale assessment. In order for river catchments to be used as sediment management units, it is vital to have a conceptual model of river catchment functioning that links different areas in space and time, and allows potential consequences (impacts) of drivers to be evaluated (White and Apitz, 2008).

The selection of the appropriate framework should be based on the specific aim(s) of the study and whether the framework fulfils the requirements of sustainable integrated sediment management and IWRM principles. This means an appropriate framework should be able to address sediment related problems at a river catchment scale while involving stakeholders in decision making throughout the whole process. The aim of the study may either be managing the quantity and/or quality of sediments in a river catchment. Thus, frameworks that can be applied on river catchment scale, for example, the conceptual framework for river-catchment-scale sediment management or the DPSIR framework can be used in a study that is aimed at managing the quantity and quality of sediments. If a framework is appropriate for a particular river catchment but it does not clearly incorporate stakeholder participation, it can be extended so as to include stakeholder participation and still be used in that particular river catchment.

7.2 THE FRAMEWORK

In developing the framework, three key Modules/building-blocks were identified as follows:

1. Objectives and Scale Selection Module
2. Tools Assessment and Selection Module
3. Strategies formulation and Selection Module

These are discussed in detail in the following subsections.

7.2.1 OBJECTIVES AND SCALE SELECTION MODULE

Jeleni (Jeleni *et al*., 2010) has developed steps necessary for integrated management in the water sector. The steps are said to be applicable at different levels of an organisation and it must be applied in a hierarchical manner building up to the highest level of interest in an organisation. Application of the steps can be undertaken through several mechanisms. Therefore, the steps can, for example, be used by managers using their own observational experiences to identify different elements of their organisation/departments within the steps. In doing so, managers in one functional area can compare their evaluation to those of managers in the other functional areas and engage in discussion around the points where there are gaps and overlaps. Managers might also consider gaining a wider range of input to the evaluation, including a sample of staff at different reporting levels from different departments and/or specialists' inputs. This could be done through a short survey instrument or perhaps as part of a staff meeting or focus group.

Once an organization identifies its mandate, objectives, required tools and data, stage of maturity of tools, the integration issues can be addressed at an appropriate level. The nine steps are as follows (also see **Figure 23**):

1. Step 1 – Identify the high-level mandate of an entity.
2. Step 2 – Identify actors and their objectives.
3. Step 3 – Identify the decision process and indicators.
4. Step 4 – Identify required tools and their maturity levels to achieve the objectives as per the indicators.
5. Step 5 – Identify the required data.
6. Step 6 – Identify the data sources and point of contact on the value chain.
7. Step 7 – Bring the actors with their objectives and data requirements to the unifying platform using the appropriate Level-II-Frameworks.
8. Step 8 – Identify overlaps and gaps on objectives, tools and data.
9. Step 9 – Streamline the processes accordingly.

In the objectives and scale selection module, it is only necessary to go through the first three steps and the rest are to be undertaken as part of the other two modules, i.e. Tools Assessment and Selection Module, and the Strategies formulation and Selection Module.

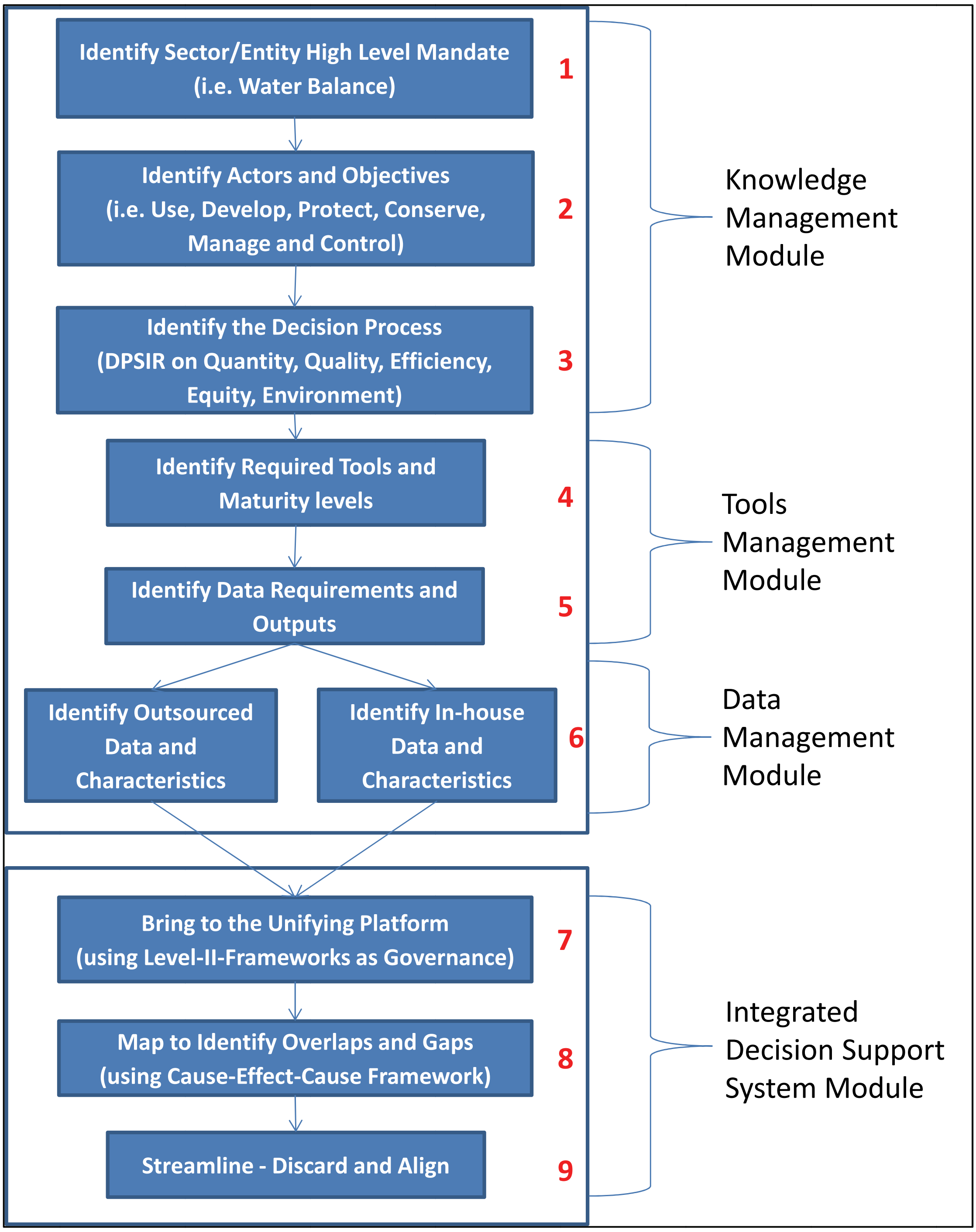

Figure 23: GICF application procedure (Jeleni *et al.*, 2010)

7.2.2 TOOLS ASSESSMENT AND SELECTION MODULE

In this module, users are assisted to select a combination of tools suitable for the task at hand. The selection of tools to be used is guided by the objectives and the scale at which assessment is to be undertaken. Jeleni (Jeleni *et al.*, 2010) has developed a tool assessment and selection module for a level III integration (see **Table 17**), however, this module is also applicable on level II frameworks and should be used as a first step in selecting tools to be used for any specialist field. Tools selected must further be refined using specialist parameters as shown in **Table 17**, with parameters that are particularly relevant to sediment management in **Tables 18 to 21**.

Table 17: Tools assessment – classification (Jeleni *et al,* 2010)

Red	Colour means boths WR and WS do not have tools in place for the Area
Green	Colour means boths WS do not have tools in place for the Area
Blue	Colour means boths WR do not have tools in place for the Area

The table gives a list of tools that were found to be in use in the Nokeng Tsa-Taemane Local municipality for the management of water resources and water services. From the water Services point of view the NWSS is the overarching tool required by the legilation and this is to be developed by DWA National, while on the local level the WSDP is the legislative required tools. From the Water Resource point of view the NWRS is the over arching with the CMS being the WMA level legislative required tool. The table maps the different tools to each and to the decision process to identify the gaps in required tools, identify duplications and identify areas of synergy where data requirement is concerned.

	Water Management Tools	Water Business						Problem life cycle				Functionality					Topics						Tool types							Intended users/ User Friendliness					Scientific Verification of tool				Extent of Current use				Relevance for IWRM							
		Protection	Use	Development	control	Conservation	Management	Identification	Designing	Implementation	Evaluation	Data handling	Model simulation	Communication	Participatory processes	Monitoring and evaluation	Surface water	Groundwater	Ecology	Economic aspects	Governance	Uncertainty aspects	Guideline (written, video, oral, etc.)	Questionnaire/checklist	Database and GIS	Model code with simple relations	Model code with complex processes	Decision Support Systems	Role playing game	Scientists	Professionals (e.g. consultants)	Water managers	Stakeholders	General public	Not verified	Poorly verified	Moderately verified	Well verified	Not documented	Only in hypothetical cases	Used in a few case studies	Widely used professionally	C1. Water Assessment	C2. Plans For IWRM	C3. Efficiency In Water Use	C4. Social Change Instruments	C5. Conflict Resolution	C6. Regulatory Instruments	C7. Economic Instruments	C8. Information Exchange
Water Resources Tools	**WRSM2000** (Water resources simulation model)			x			x	x			x		x				x	x									x			x	x	x						x				x	x	x						
	NWRS (National Water Resource Strategy)	x	x	x	x	x	x	x			x			x		x					x		x									x						x				x	x	x	x	x	x	x	x	x
	WRYM (Water resources yield model)			x			x	x			x		x				x					x					x			x	x	x						x				x	x	x						
	WQT2000 (Water quality model)	x		x			x	x			x		x			x	x		x								x			x	x	x						x				x	x	x						
	ISP (WMA Internal Strategic Perspective**)**	x	x	x		x	x	x			x			x		x					x		x									x						x				x	x	x	x					
	NGIS (National Groundwater Information System)						x	x				x				x		x							x			x		x	x	x						x				x	x	x				x		x
Water Services Tools	**SFWS** (Strategic Framework for Water Services)		x		x		x	x						x		x					x		x									x						x				x		x				x		
	WSNIS (Water Services National Information System)		x				x	x		x	x	x				x					x				x						x	x	x	x				x				x	x	x	x			x		x
	WQMS (Water quality management system)	x					x	x			x	x				x					x		x		x						x	x	x	x				x				x	x	x						x
	WSDP (Water Services Development Plan)			x			x	x			x					x																																		
	Blue drop - Green Drop	x					x				x			x	x						x			x					x			x					x					x						x		

Table 18: Applicability of Hydrodynamic Models to Water body Types (Imhoff *et al.,* 2003)

	CH3D-WES V.1	ECOM-3D	EFDC	EFDC1D V.1	HSCTM-2D V.1
FRESH WATER SYSTEMS					
River & Streams: Free-Flowing and Backwater Effects					
Vertically Well-mixed; laterally Well-mixed; Narrow & Shallow	*	*	*	*	*
Vertically Well-mixed; Lateral Gradients; Wide & Shallow	*	*	*		*
Vertically Stratified; Laterally Well-mixed; Narrow & Deep	*	*	*		
Vertically Stratified; Lateral Gradients; Wide & Deep	*	*	*		
Lakes/Bays & Reservoirs					
Vertically Well-mixed; Lateral Gradients; Wide & Shallow	*	*	*		*
Vertically Stratified; Laterally Well-mixed; Narrow & Deep	*	*	*		
Vertically Stratified; Lateral Gradients; Wide & Deep	*	*	*		
SALTWATER/TIDAL SYSTEMS					
Tidal Rivers & Embayments/Lagoons					
Tidal Rivers: Vertically Well-mixed; Laterally Well-mixed; Narrow & Shallow	*	*	*	*	*
Tidal Rivers: Vertically Well-mixed; Lateral Gradients; Wide & Shallow	*	*	*		*
Embayments/Lagoons: Vertically Well-mixed; Lateral Gradients; Wide & Shallow	*	*	*		*
Estuaries & Coastal Ocean					
Estuaries: Vertically Stratified; Laterally Well-mixed; Narrow & Deep	*	*	*		
Estuaries: Vertically Stratified; Lateral Gradients; Wide & Deep	*	*	*		
Coastal Ocean: Vertically Stratified or Vertically Well-mixed; Narrow & Wide Shelf	*	*	*		

Table 19: Dimensional Requirements for Modelling Water body Types (Imhoff *et al.*, 2003)

	1D(x)	2D (xy)	2D(xz)	3D(xyz)
FRESH WATER SYSTEMS				
River & Streams: Free-Flowing and Backwater Effects				
Vertically Well-mixed; laterally Well-mixed; Narrow & Shallow	*			
Vertically Well-mixed; Lateral Gradients; Wide & Shallow		*		
Vertically Stratified; Laterally Well-mixed; Narrow & Deep			*	
Vertically Stratified; Lateral Gradients; Wide & Deep				*
Lakes/Bays & Reservoirs				
Vertically Well-mixed; Lateral Gradients; Wide & Shallow		*		
Vertically Stratified; Laterally Well-mixed; Narrow & Deep			*	
Vertically Stratified; Lateral Gradients; Wide & Deep				*
SALTWATER/TIDAL SYSTEMS				
Tidal Rivers & Embayments/Lagoons				
Tidal Rivers: Vertically Well-mixed; Laterally Well-mixed; Narrow & Shallow	*			
Tidal Rivers: Vertically Well-mixed; Lateral Gradients; Wide & Shallow		*		
Embayments/Lagoons: Vertically Well-mixed; Lateral Gradients; Wide & Shallow		*		
Estuaries & Coastal Ocean				
Estuaries: Vertically Stratified; Laterally Well-mixed; Narrow & Deep			*	
Estuaries: Vertically Stratified; Lateral Gradients; Wide & Deep				*
Coastal Ocean: Vertically Stratified or Vertically Well-mixed; Narrow & Wide Shelf				*

Table 20: Various models and their capability in handling Toxic Chemical Transport and Fate Model State Variables and Processes (Imhoff *et al.,* 2003)

	AQUATOX V.2.0	EFDC & EFDC1D V.1	HSCTM-2D v.1	HSPF-RCHRES V.12	IPX 2.7.4	WASP5(6)-TOXI5(6)
STATE VARIABLES						
Toxicant Classes						
Single Generalized Toxicant						
Multiple Generalized Toxicants		*		*	*	*
Synthetic organic Chemicals	1	*			*	*
Radionuclides		*			*	*
Heavy Metals		*	*		*	*
KINETIC PROCESSES						
Toxicant Sorption & Desorption						
Partitioning of toxicant						
Two-phase Partitioning-solids Based (Kd, SS, dissolved)		*	*	*	*	*
Two-phase Partitioning-organic Carbon Based (Koc, POC, dissolved)		*			*	*
Three-phase Partitioning-organic Carbon Based (Koc, DOC, POC, dissolved)	*	*			*	*
Allows assignment of Different Coefficients (Koc or Kd) for Water Column & Sediment Bed	*	*		*	*	*
Allows Assignment of Different Fractions of Org-C (Foc) for Water Column & Sediment Bed		*			*	*
Dissolved Organic Carbon (DOC)						
Coupling with Time & Space Distributions of DOC for Partitioning of Toxicant		*			*	*
Allows Assignment of DOC Data as Input to Model		*			*	*
Internally Simulates DOC using a Biological Model	*	2				
Particulate Organic Carbon (POC)						
Coupling with Time & Space Distributions of POC for Partitioning of Toxicant		*				
Allows Assignment of POC Data as Input to Model		*				
Internally Simulates POC using a Biological Model	*	2				
Physical-Chemical Kinetics						
Generalized First-order Reaction		*		*	*	*
Hydrolysis	*	*		*	*	*
Photolysis	*	*		*	*	*
Volatilization	*	*		*	*	*
Microbial Degradation	*	*		*	*	*
Chemical Oxidation		*		*	*	*
Parent/Daughter Transformations for generalized Toxicants				*	*	*
Speciation of Heavy Metals						
Complexation of Organic Chemicals						

Table 21: Various models and their capability in handling sediment transport processes. (Imhoff *et al.,* 2003)

	ECOMISED V,1.3 & SEDZL	EFDC & EFDC1D V.1	HSCTM-2D V.1	HSPF-RCHRES V.12	IPX 2.7.4	WASP5(6)-TOXI596)	GSSHA (watershed and stress)	ADH	HEC-RAS	HEC-RAS + CONCEPTS	CEQUAL w2
SUSPENDED LOAD TRANSPORT (COHESIVE & NON-COHESIVE SOLIDS)											**2**
Cohesive solids (slits, clays, POM, 63 Micro grain size)								X			
Settling/Deposition/Resuspension provided as input					x	X					
Settling/Deposition/Resuspension computed internally	x	x	x	x			x	x	x	X	
Flocculation											
Not Represented				x	x	x	x		x	X	
Explicit Flocculation Model											
Implicitly Accounted for in settling Velocity Function	x	x	x					X			
Settling Velocity											
Settling Velocity Provided as input	x		x	x	x	x		X			
Accounts for Hindered Settling as f(high suspended sediment concentration)		x	X								
Accounts for Free/Discrete Settling as f(size class)		x	x	x			x	x	x	X	
Accounts for Organic Matter Content of Suspended Matter											
Resuspension											
Resuspension Velocity Provided as input					x	X					
Calculated as Function of Bed Bulk Density & Critical Shear Stress or Bed Shear Strength	x	x	x	1			x	x	x	X	
Accounts for Effect of Bed Armoring	x	x						x	x	X	
Accounts for Organic Matter Content in Bed											
Deposition											
Deposition Velocity Provided as input	x			x	x	x			x	X	
Calculated as Function of the Bottom Layer velocity/Bed Stress	x	x	x				x	X			
Accounts for Composition of Sediment Flocs in Predicting Deposition Rate											
Non-Cohesive Solids (sands, >63 Micro grain size)											
Settling/Deposition/Resuspension Provided as input					x	X					
Settling/Deposition/Resuspension Computed Internally	x	x						x	x	X	
Carrying Capacity Computed internally	x			x			x	x	x	X	
Settling Velocity											
Settling Velocity Provided as input	x				x	X					
Accounts for Hindered Settling as Function of High Suspended Sediment Concentration		x		X							
Accounts for Free/Discrete Settling as Function of Particle Size	x	x					x	X			
Resuspension											
Resuspension Velocity Provided as input					x	X					
Calculated as Function of Bed Bulk Density & Critical Shear Stress Or Bed Shear Strength	x	x					x	x	x	X	
Accounts for Effect of Bed Armoring	x	x						x	x	X	
Deposition											
Deposition Velocity Provided as input					x	x					
Calculated as the Function of the Bottom Layer	x	x					x	x	x	x	

	ECOMISED V,1.3 & SEDZL	EFDC & EFDC1D V.1	HSCTM-2D V.1	HSPF-RCHRES V.12	IPX 2.7.4	WASP5(6)-TOXI596)	GSSHA (watershed and stress)	ADH	HEC-RAS	HEC-RAS + CONCEPTS	CEQUAL w2
Velocity/Bed Stress											
Wave Current Interaction on Bed Shear Stress											
Not Represented			x	x	x	x	x				
Represented	x	x						x			
Bed Load Transport (non-cohesive solids)											
Not Represented	x		x	x	x	x					
Rates Computed Internally		x					x	x	x	x	

7.2.3 STRATEGIES FORMULATION AND SELECTION MODULE

While the Tools Assessment can highlight the gaps in the tools being used as well as map the data, the strategies Formulation and Selection Module ensures that assessments and decisions taken at the different levels of management are coherent, and gives a sector wide view of performance rather than a particular perspective. This module is essentially a platform for trade-offs between Quantity, Quality, Equity, Efficiency and sustainability on the sediment balance sheet. This uses the scientific results obtained using the selected tools, together with the selected objectives at the beginning, to arrive at a solution that is both scientifically sound and stakeholder accepted. The module is to evaluate the effects of actions, on the basis of different scenarios, alternatives and policies envisaged.

8 HIGH LEVEL GUIDE TO THE DEVELOPMENT OF SEDIMENT CATCHMENT MANAGEMENT PLANS

8.1 OVERVIEW

This report is aimed at providing guidelines for the development of sediment management plans (SMPs) and how SMPs can be incorporated in RCMPs. Literature on development of SMPs and examples of developed SMPs was reviewed. This literature provided background information which guided the development of the guidelines for developing SMPs. Literature review did not find any documented studies on existing SMPs or how such plans can be developed for South African river catchments. The study therefore recommended the development of SMPs in all river catchments in the country. The report further provided guidelines which can aid in the development of SMPs.

Literature on developed RCMPs was also reviewed in order to find out how the SMPs were incorporated in the RCMPs. The review found that most RCMPs recognize the importance of sediment management within river catchments, though no SMPs were included in the RCMPs. This creates the need to develop SMPs for such river catchments to be included in the RCMPs. The review showed that though SMPs have been developed in some river catchments there is no indication of how they will be incorporated in RCMPs. It is important to incorporate them within RCMPs in order to facilitate their implementation within the river catchments. The report provided an example of how an SMP can be incorporated into RCMPs.

8.2 DEVELOPING SEDIMENT MANAGEMENT PLANS

A sediment management plan (SMP) is required to achieve a balance between fulfilling sediment management objectives, and the need to secure human activities and legal requirements (Netzband, 2006). To be effective, the SMP must be technically sound and practical, environmentally sensitive, politically realistic and financially feasible and sustainable (Noble Consultants *et al.*, 2012). Developing a sediment management plan (SMP) will provide guidelines for more effective management of sediment resources, recognizing they are part of a regional system involving natural processes (Gulf of Mexico Foundation, 2009).

According to Apitz (2008), issues faced by sediment managers are complex; the problems involve a large number of variables and dynamic systems, associated with large uncertainties which often dominate the decision-making process. SMPs should therefore be developed to balance these issues. SMPs should consider the high natural variability of sediment dynamics and should not compromise the ability of the system to respond (Netzband, 2006). A site-specific adaptive management which allows for variations in a given range is needed (Netzband, 2006). Thus, Catchment Management Plan should define/list the goals for both the river catchment and individual sites (Heise *et al.*, 2004).

Heise *et al.* (2004) recommended that a Catchment Management Plan can be developed by setting up a Conceptual Catchment Model, describing the dynamic processes (soil-sediment-water-contaminant) within the catchment, and identifying the catchment-scale management objectives.

In order to develop a meaningful and relevant plan for coastal areas, Noble and Moore (2010) reported that great understanding and knowledge of the interrelationships between coastal and offshore sediment deposits, inland origins of coastal sediment, sediment pathways to the coast, and how sand moves on the shoreline is required. Noble and Moore (2010) demonstrated that in order to be technically, environmentally, economically, and politically effective, regional sediment management plans should consist of a suite of diverse studies, management, policy, and capital project activities. Its development can follow a traditional approach to any planning processes which include understanding the baseline science and relevant physical processes, identifying the challenges that currently exist and the corresponding opportunities that can be seized to positively move forward and formulating appropriate action plans and solutions that have unanimity of purpose as indicated in Noble and Moore (2010).

8.3 REVIEW OF EXAMPLES OF DEVELOPED SEDIMENT MANAGEMENT PLANS

Delaware Estuary Regional Sediment Management Plan Workgroup (DERSMPW) (2012) developed a regional sediment management plan (RSMP) for the Delaware Estuary and River Catchment in the United States. The Delaware RSMP is a comprehensive long-term plan to identify a new sediment management program, procedures, and practices with regionally targeted goals, objectives, and strategies (DERSMPW, 2012). The short-term and long-term actions developed to aid in the implementation of the SMP include:

- Establishment of a Regional Sediment Management Implementation Workgroup to guide the plan

- Immediate need for funding of priority demonstration projects to show short-term success
- An outreach campaign to educate the public on opportunities and implementation.

KGS Group (2012) developed a SMP required during the construction of a spillway by the Pointe du Bois Spillway Replacement Project at Winnipeg River in Canada. The SMP was aimed at minimizing the impacts of in-stream construction activities in the Winnipeg River and it outlines the monitoring and management of Total Suspended Solids inputs into the waterway that may occur as a result of in-stream construction, river management and the commissioning of the new spillway.

The CCSMW (2009) compiled the California Coastal Sediment Master Plan in order to facilitate implementation of regional sediment management throughout the entire California Coast. The developed SMP is a compilation of tools, strategies and informational documents designed to assist and guide sediment managers and others in implementing regional sediment management throughout the California Coast. Pacific Surveying and Engineering (2011) established a civil works strategy aimed at controlling sediment transport, deposition, and flooding caused by the Swift Creek landslide in Whatcom County, Washington. The plan presented proposed and designed engineered civil works structures which are expected to reduce flooding by Swift Creek and control the downstream transport of landslide sediments.

Janicki Environmental (2012) developed a Sediment Management Plan (SMP) to accompany the Comprehensive Conservation Management Plan for the catchments of Clearwater Harbor and St. Joseph Sound. The four objectives of the management plan included:

- Identify erosion/deposition problem areas in the catchment;
- Identify principal sources of sediment in the catchment;
- Identify alternative methods of reducing erosion rates; and
- Evaluate and recommend methods to reduce impacts resulting from sediment erosion and deposition.

The development of the Clearwater Harbor and St. Joseph Sound SMP as stated in Janicki Environmental (2012) included the following tasks:

- Conducting a desktop evaluation to identify potential problem areas,

- Completing field reconnaissance to identify areas of sediment erosion and accumulation,
- Collecting sediment samples for laboratory analysis of grain size and metals content,
- Reviewing and summarizing existing and proposed management plans and projects that address sediment management in the Clearwater Harbor and St. Joseph Sound, and
- Developing recommendations to reduce adverse impacts from sediment erosion and deposition.

The developed recommendations included projects such as maintenance dredging of fine-grained sediment, channel bed and bank stabilization, enhancement of an existing sediment sump in order to reduce sediment transport and enhancement of in-stream and stream bank habitat while stabilizing channel banks in several streams.

A comprehensive catchment-based approach was undertaken by U.S. Army Corps of Engineers (2012a) to gain a better understanding of sediment sources and their relative contributions to sediment in the lower Snake River and assess opportunities for controlling sediment sources, sediment transport, and sediment deposition as alternative methods to dredging for managing sediments. This approach was based on public and stakeholder input gathered during scoping meetings, extensive coordination and partnering with resource agencies and technical experts with the knowledge and tools to aid in the understanding of sediment yield and transport in the lower Snake River catchment. The approach was used in the development of sediment management plan for the lower Snake River catchment. The purpose of the SMP is to establish a programmatic framework to evaluate and implement potential sediment management measures to address problems of sediment accumulation (U.S. Army Corps of Engineers, 2012b).

ICPR (2009) developed a SMP for contaminated sediments in the Rhine River. The SMP was developed based on an inventory of available information for relevant amounts and relevant sediment contaminations in the Rhine catchment, an assessment and classification of contaminated sediments and drafted proposals for measures for treatment of contaminated sediments. The SMP included proposed measures for reducing risks in polluted areas, surveillance, strategies to reduce sedimentation, and improvement of the overall data basis.

The current literature review did not find any documented studies on existing SMPs or how such plans can be developed for South African river catchments. It is therefore crucial that SMPs are developed for all catchments in the country.

8.4 GUIDELINES FOR DEVELOPING SEDIMENT MANAGEMENT PLANS

Figure 24 shows a simplified guideline showing the steps to be followed in the development of SMP. The details of each step are provided in **sub-sections 8.4.1** to **8.4.5**.

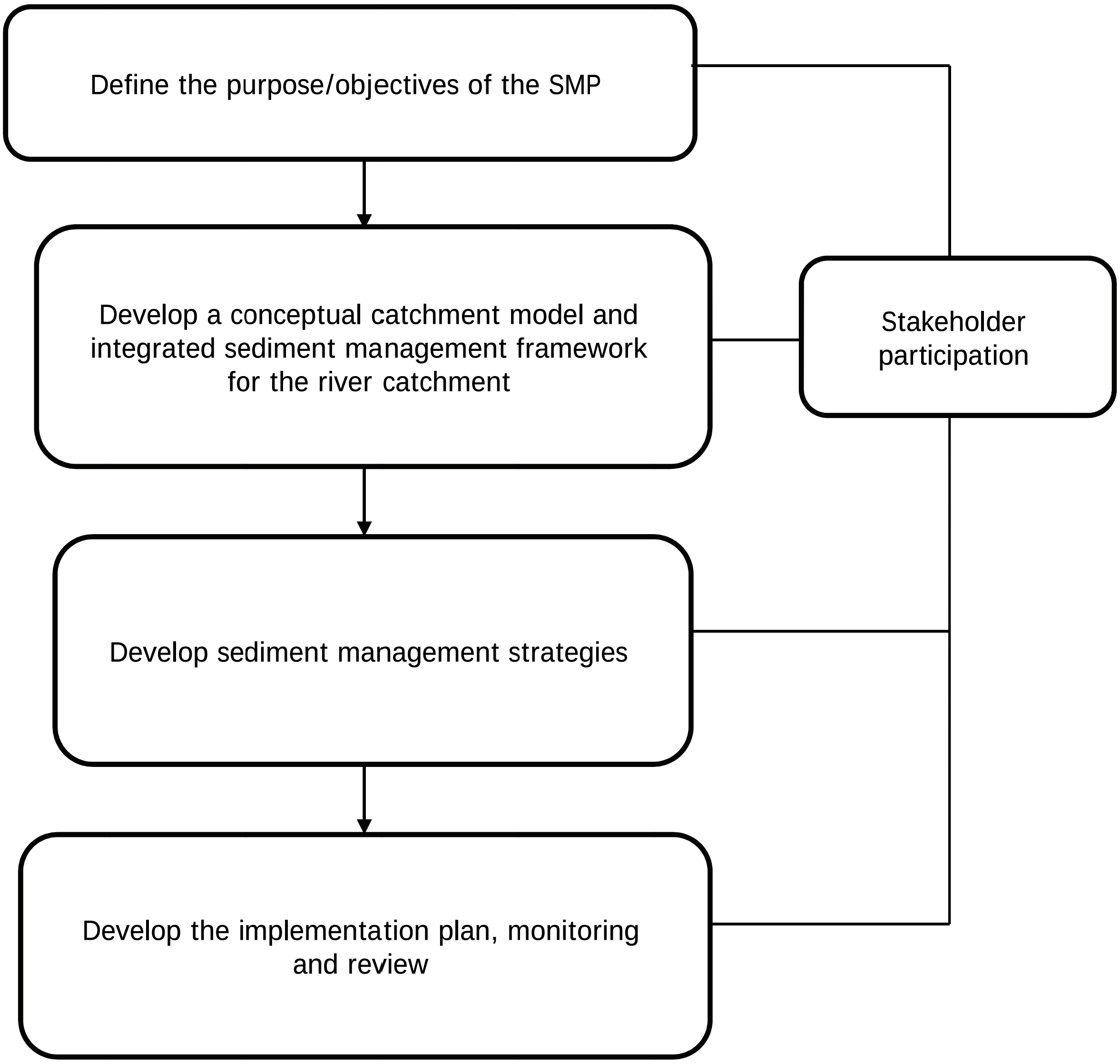

Figure 24: Guideline for developing SMP

8.4.1 DEFINE THE PURPOSE/OBJECTIVES OF THE SMP

The first step in the development of a SMP is to define its purpose/objectives. This should clearly state the need for the plan and what it will achieve in terms of sediment management. This will aid in providing the direction and pathway of SMP. The objectives of the SMP should take into account the sediment management objectives for a river catchment. If sediment management objectives for a particular river catchment have not yet been developed, it is crucial to develop them at this stage. However, the report stated that reviewed literature showed no documented studies on sediment management objectives and formulation in South Africa. This showed an urgent need to develop sediment management objectives, guidelines and plans in South Africa.

8.4.2 DEVELOP A CONCEPTUAL CATCHMENT MODEL AND INTEGRATED SEDIMENT MANAGEMENT FRAMEWORK FOR THE RIVER CATCHMENT

Developing a conceptual catchment model for the river catchment will aid in understanding relevant physical processes governing sediment transport, movement and deposition. This will also aid in identifying the challenges that currently exist in the river catchment and corresponding alternatives for sediment management. A conceptual model may assist in identifying the need for site-specific assessment or catchment-scale assessment since each catchment is different and the complex role that sediment plays means that different objectives, pressures, impacts and mitigation measures will need to be considered in different catchments and even in different sites within a given catchment as reported by Apitz *et al.* (2009).

Sediment management frameworks help to understand the interactions, intersections and information exchanges necessary to manage sediment sustainably (White and Apitz, 2008). Effective sediment management requires a holistic approach taking into account system understanding, integrated management of soil, water and sediment, trans-boundary cooperation, upstream-downstream interrelationships and stakeholder involvement (SedNet, 2009) and partcipation.

The reports further provided recommendations on how to develop integrated sediment management frameworks for South Africa. They suggested that frameworks that can be applied on river catchment scale, for example, the conceptual framework for river-catchment-scale sediment management or the DPSIR framework can be adopted for a study that is aimed at managing the quantity and quality of sediments. If a framework is appropriate for a particular river catchment but it does not clearly incorporate stakeholder participation, it can be extended so as to include stakeholder participation and still be used in that particular river catchment.

8.4.3 DEVELOP SEDIMENT MANAGEMENT STRATEGIES

The process of making decisions and taking actions on sediments (including no action), take into consideration a wide range of factors (Apitz and Power, 2002), and can be achieved through the use of sediment management tools/strategies.

Detailed literature on sediment management tools/strategies is provided in chapter 3 of this report. Sediment management tools/strategies that have been reviewed include measures in the catchment area, in the reservoir and measures in the dam. The studies reviewed showed that analysis of different strategies should be done in order to select the most feasible strategies for a particular site or region. Apitz (2008) reported that using past experience, research, scenario studies, models and pilots, the responses to various actions can be quantitatively predicted, and the "best" actions selected based upon the chosen set of criteria. This calls for continuous review of sediment management tools/ strategies for a river catchment.

8.4.4 DEVELOP THE IMPLEMENTATION PLANS, MONITORING AND REVIEW

The DERSMPW (2012) provides an example of a SMP which has a good implementation plan. The short and long term actions of the plan include:

- Regional Sediment Management Implementation Workgroup to be established with a series of focus groups to continue to guide the plan
- Immediate need for funding of priority demonstration projects to show short-term success
- An outreach campaign to educate the public on opportunities and implementation.

This shows that the SMP should state how sediment management implementation work group will be established, the plan for funding for the implementation and how stakeholder participation will be undertaken. The implementation of the plan should continuously be monitored to ensure that it adheres to the purpose/objectives of the SMP. The review plan should indicate the frequency at which the SMP will be reviewed and by who. This should essentially involve all stakeholders so as to ensure sustenance of the SMP.

8.4.5 STAKEHOLDER PARTICIPATION

The identification of key stakeholders in sediment issues needs to be a primary step in the development of SMPs (ISI, 2011). Stakeholder involvement can be seen as very valuable for the process of finding solutions for sediment-related problems (Gerrits and Edelenbos, 2004). Dealing with sediment management at the river catchment scale is a complex policy issue with a wide variety of different policy levels and stakeholders involved with different interests and perspectives (Slob *et al.*, 2008a). Different stakeholders' views should be recognized and respected as they can be used to create joint solutions to sediment management. Key stakeholders can be grouped into the following main categories including agricultural (including irrigation), mining and industrial uses, communities in flood-prone areas, reservoir managers and wetland and environmental organizations (ISI, 2011). For effective and successful sediment management it is essential that the relevant stakeholders participate in the entire process, on both the local and catchment scales, during assessment, development and implementation, of sediment management plans (Heise *et al.*, 2004).

Gerrits and Edelenbos (2004) reviewed literature on management of sediments through stakeholder involvement. The study showed that there is no single and best way of stakeholder involvement and there is still lack of knowledge about stakeholder involvement in sediment management studies. **Table 22** provides a summary of the degrees of stakeholder involvement as described in Gerrits and Edelenbos (2004). It shows that knowledge of stakeholder can determine the degree and style of participation. For example, delegating, co-operative and facilitating styles of participation require that the stakeholders are equipped with relevant knowledge since they are expected to contribute knowledge during the participation process. A summary of stakeholder approaches is provided in **Figure 25** Detailed discussion of the approaches is provided in Oen *et al.* (2010).

Table 22: Degrees of participation and influence in policy processes (Oen *et al.*, 2010)

Degrees of influence according to scale	Governance styles within scale of participation	Role of stakeholder	Role of expert	Role of policy maker
Stakeholders are not involved	Closed authorization	None	Delivers information to the policy makers on demand; no information to stakeholders	Policy makers determine policy; policy process is closed, no information issued
Stakeholders are informed- they remain passive	Open authorization	Stakeholder receive information but do not deliver input into the process	Delivers information to stakeholders on demand of the policy makers	Policy makers determine policy; policy process is closed, information is issued to stakeholders

Degrees of influence according to scale	Governance styles within scale of participation	Role of stakeholder	Role of expert	Role of policy maker
Stakeholders are consulted	Consulting style	Stakeholders are consulted, act as interlocutors	Delivers information to participants on demand of all parties; experts provide flow of information to the process, next to the flow of stakeholders	Policy makers determine the policy and opens the process to input by stakeholders but is not obliged to adopt their recommendations
Stakeholders give advice	Participative style	Stakeholders become advisors to the process	Delivers information to all parties on demand of all parties and investigates suggestions from participants on demand of policy makers	Policy process is open to input (ideas, suggestions, etc.) by stakeholders, but have the right to deviate from it in their decisions
Stakeholders become co-producers	Delegating style	Co-decision makers within the set of pre-conditions	Experts treat policy makers and stakeholders as equal clients; advice and knowledge provision to both actors	Policy makers take input of stakeholders into account, and honour it if it fits into the set of pre-conditions
	Co-operative style	Policy-partners on the basis of equivalence	Experts treat stakeholders as equal knowledge providers; keep an open mind to suggestions and ideas from stakeholders	Policy-makers interact with stakeholders on the basis of equivalence, they take the input of stakeholders very seriously
Stakeholders do not only produce solutions, but also decide about them	Facilitating style	Taking initiatives, making decisions	Experts support stakeholders with knowledge; experts treat stakeholders as their clients; no need for approval of policy makers	Offers support (money, time of civil servants, etc.) and leaves the production of solutions and decisions to the participants

Sparrevik *et al.* (2011) proposed and applied a multi-criteria involvement process to enhance transparency and stakeholder participation to a contaminated sediment management case study for Bergen Harbor, Norway. The methodology was built on quantitative principles of multi-criteria decision analysis (MCDA) and also incorporated group interaction and learning through qualitative participatory methods. The study reported that MCDA has been proposed as a method to enhance stakeholder involvement in sediment management and to facilitate decision making of complex problems in studies such as Linkov *et al.* (2005), Yatsalo *et al.* (2007), and Kim *et al.* (2010). The study found that a multi-criteria involvement process resulted in consistent ranking of remediation alternatives across residents, stakeholders, and experts.

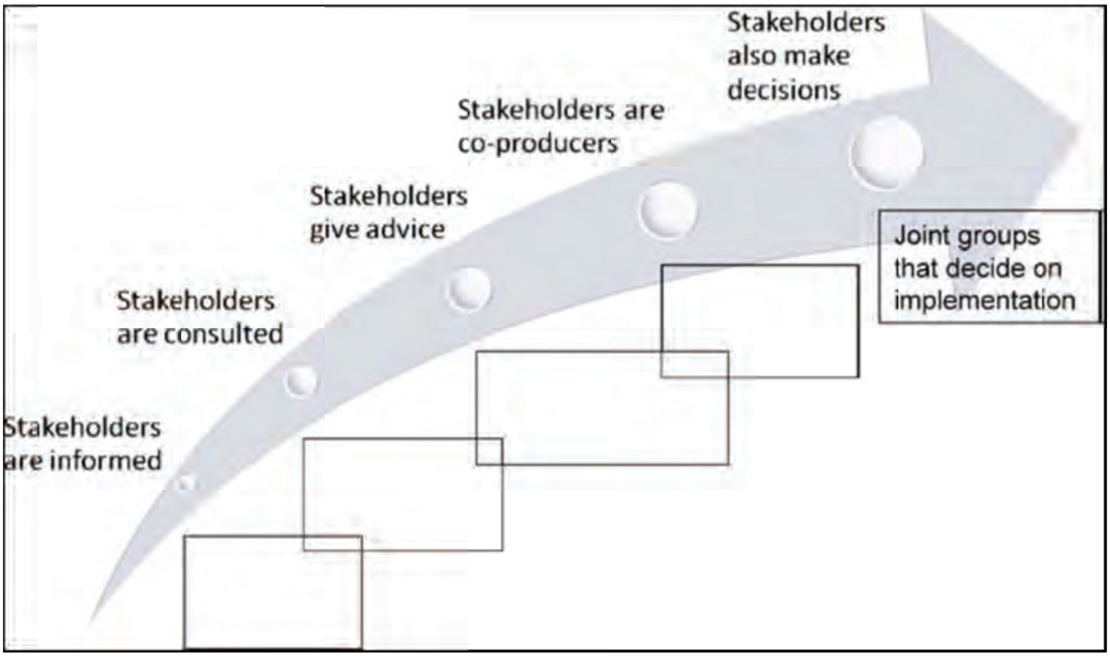

Figure 25: Stakeholders dialogue approaches, degrees of influence and possible tools and processes that complement the different degrees of influence (Oen et al., 2010)

Oen *et al.* (2010) assessed and employed alternative approaches of stakeholder involvement including informative, consultative and participatory approaches in sediment remediation planning. The results suggested that three important challenges for stakeholder involvement included how to:

- Include people who have important management information and local knowledge, but not much influence in the decision-making process
- Secure resources to ensure participation
- Engage and motivate stakeholders to participate early in the sediment remediation planning process.

The findings of the study by Oen *et al.* (2010) also show that stakeholders were in general very willing to cooperate with the project; stakeholder involvement in the decision making is necessary even if the process will take a lot of time and they should be informed as early as possible before taking decisions.

The literature provided in this review will guide the developer(s) of SMPs to understand and select the best stakeholder involvement approach. It is important that stakeholders involvement should be incorporated in each of the above 3 steps as it will ensure sustainable sediment management as shown in this literature.

8.5 INCORPORATING SEDIMENT MANAGEMENT PLANS INTO RIVER CATCHMENTS MANAGEMENT PLANS

SedNet (2009) reviewed RCMPs for European Rivers (Danube River, Sava River, River Rhine, River Elbe, Scheldt River and River Meuse), Italian river (River Po) and UK river catchments (River Ebro and Anglian River Catchment) in order to find out how they incorporate sediment management. The review indicated a range of important links between sediment and water management, and highlighted the potential benefits associated with achieving better integration of certain sediment issues into a holistic approach to practical management (SedNet, 2009).

Government of the Kingdom of Lesotho (2010) identified erosion and sedimentation as key challenges in the catchment that must be addressed. The study further reported that a sediment management programme, a reservoir management plan and a dam sedimentation study are amongst a series of catchment-wide projects that have been proposed, or are already in place, and need to be co-ordinated and implemented. The Spey River Catchment Management Plan (CMP) (Spey Catchment Steering Group, 2003) states that periodic intervention to restore alignment of the river mouth and prevent erosion of the west bank near to Kingston is carried out at intervals of about 25 years to manage sediments deposition due to lateral drift. D’Cruz and Manasi (2008) reported the need to place sediment traps or other devices to control sediment runoff from the access road which crosses the creeks that drain into Lake Kutubu. This was one of the actions that needed to be undertaken to achieve the management objective on improvement of the management of water resources in the Lake Kutubu Catchment Management Plan.

There is limited literature on developed CMPs for river catchments in South Africa. DWAF (2001) emphasized that CMPs should be developed for all catchments in Water management Areas (WMAs) of South Africa as part of the framework for catchment management strategies. The report noted that CMPs for stressed catchments will receive priority while those for catchments with little or no stress can be prepared in a phased manner as resources permit.

The CMP for Palmiet River catchment (Paxton and Ractliffe, 2010) located in the Western Cape Province of South Africa was mostly focused on the implementation of ecological water requirements for the Palmiet River though it recognized the importance of sediments in maintaining aquatic habitats. The Mgeni CMP (DWAF and Umgeni Water, 1996) developed for Mgeni Catchment located in KwaZulu-Natal Province of South Africa identified soil loss and sedimentation from commercial crop lands and dense rural settlements as some of the issues that require urgent management. Different strategies for sediment management were included in the CMP. These include:

- Increase in-stream sediment, phosphorus and pathogen assimilation and flood attenuation in smaller tributaries through wetlands/pond systems at the Camps Drift and Inanda dam
- Dredge Camps Drift to remove sediment and other contaminants
- Identify appropriate operation of Nagle bypass to minimize sediment and phosphorus loads to Nagle and Inanda dams
- Scour sediment from Inanda dam when possible and purge sediment laden flood waters

This review indicates that most RCMPs recognize the importance of sediment management within river catchment, though no SMPs were included in the RCMPs. The reviewed studies have developed sediment management strategies some of which are already in practice. There is therefore a need to develop SMP for such river catchments to be included in the RCMPs.

Though SMPs have been developed in some river catchments there is no indication of how they will be incorporated in RCMPs. The SMPs have also been developed as independent plans to aid in sediment management. It is important to incorporate them within RCMPs in order to facilitate their implementation within the river catchments. The SMPs can be included as part of the components of RCMPs. This will aid in sustainable sediment management within river catchments.

The structure of RCMPs typically includes strategic aims, objectives, targets and actions (**Figure 26**). The Tweed CMP (Tweed Forum, 2010) is an example of a CMP which follows this structure. It has seven strategic aims which set out a broad, aspirational statement for a given management area for the next 3 years. For each of the strategic aims of the Tweed CMP there are a number of objectives (which broadly indicate how the aims of the plan will be pursued), targets (which represent achievable steps towards those aspirations set out in the strategic aims and objectives) and actions (which are actual activities and initiatives necessary to meet the targets).

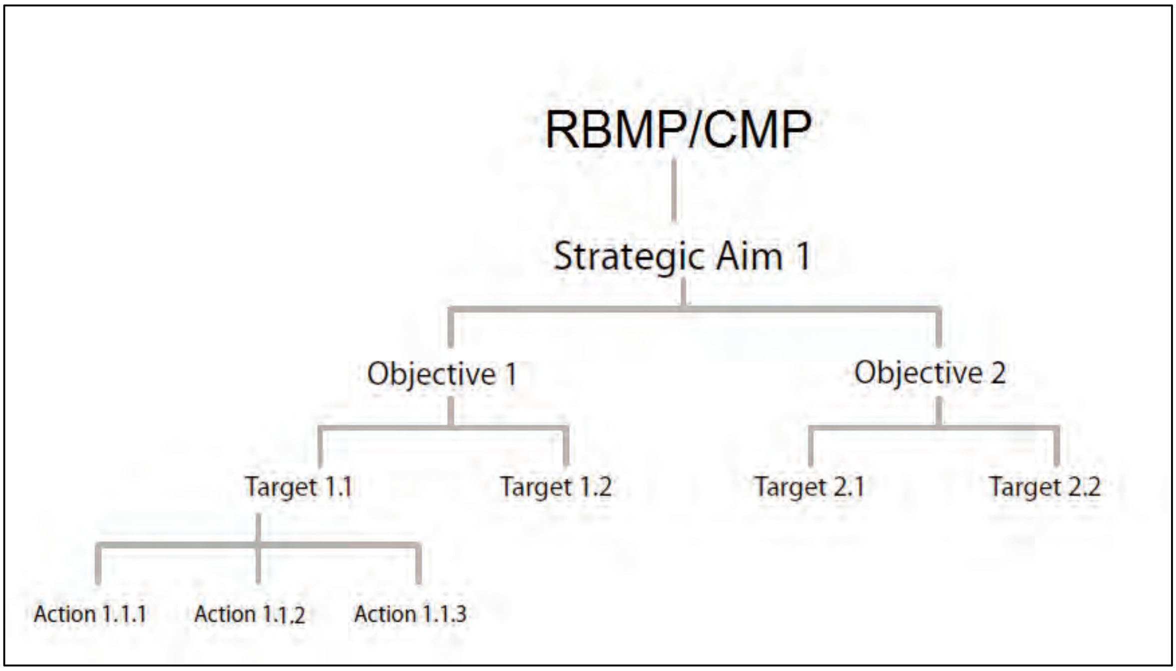

Figure 26: Structure of CMP (modified from Tweed Forum, 2010)

As an example, a RCMP can have a strategic aim on maintenance of the quality of surface water bodies within a river catchment. To achieve this strategic aim, an objective on integrated sediment management can be formulated in order to minimize water pollution by contaminated sediments. A SMP developed on the basis of guidelines in **Figure 24** can be considered as a target that can meet the objective. The SMP will therefore list all actions that can be undertaken in order to ensure integrated sediment management. Such SMP fits well within a RCMP. **Figure 27** shows a flow diagram illustrating this example. It is important to note that **Figure 27** only shows the component of the RCMP where a SMP can fit as this is the main purpose of this report.

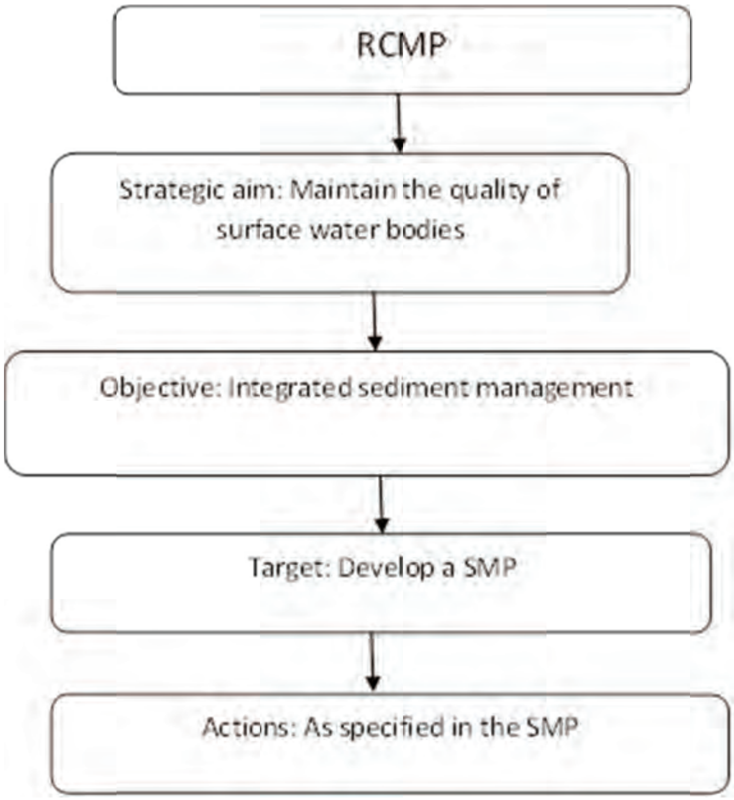

Figure 27: An example of how SMP can fit in a RCMP

9 CASE STUDY

9.1 CASE STUDY AREA OVERVIEW

The case study is to be conducted in Welbedacht dam located on the Caledon River in the Free State Province, South Africa. It is located on E: 26 53 32, S 29 45 58 on the south of Caledon Nature Reserve which is about 15km south of Wepener on the R701 and This dam began to store water in August 1973 with the purpose of supplying the water to the city of Bloemfontein. The Caledon River is the largest tributary to the Orange River within the Upper Orange water management area. Caledon River has a drainage area of about 22,000 km^2 and total length is about 480 km. Major tributaries of Caledon River are Little Caledon, Grootspruit, Moperi, Meulspruit, Leeu and Skulpspruit. Welbedacht Dam on the Caledon River is one of large dams situated in the catchment. The Welbedacht dam has a catchment area of approximately 15 245 km^2 and a mean annual runoff of approximately 1210 million m^3/a (1920 to 1987). Due to siltation, the storage capacity of the Welbedacht dam has reduced rapidly from 115 million m^3 to approximately 16 million m^3 during the twenty years since it has been completed and this reduction in storage created problems in meeting the Bloemfontein demand at an acceptable level of reliability and as a result of this, the 50 m high Knellpoort dam was constructed.

The Caledon River flows south-west, marking the border with South Africa and Lesotho before entering South Africa's Free State province (north of Wepener). It then flows west before meeting the Orange River near Bethulie in southern Free State, just before the Gariep dam. The river is the primary source of water for Maseru and the capital of Lesotho, which stands on the river. The two major dams within the Caledon River Catchment are the Welbedacht Dam and the Knellpoort Dam. The Knellpoort Dam is situated on the Rietspruit River, a tributary of the Caledon River. The Knellpoort Dam is operated as an off-channel storage dam by pumping water from the Caledon River into the dam. The Knellpoort Dam was built to augment the storage capacity of Welbedacht Dam and to transfer water to the upper reaches of the Modder River. Water is also supplied from this system to De Wetsdorp and Botshabelo. Knellpoort Dam is filled mainly by pumping from the Caledon River using Tienfontein Pump station. Natural runoff from the Knellpoort Dam catchment contributes to a very small portion of its yield. Water is also released from Knellpoort dam to support Welbedacht Dam when required.

The water quality and the water infrastructure in the Caledon River catchment are impacted on by sedimentation. The soils have a moderate to high erosivity index, which coupled with poor land use practices, has resulted in high erosion rates. This is reflected in the sedimentation of Welbedacht Dam and the operating rules that have to be adopted for the water supply infrastructure in this area.

From the Integrated management point of view, Welbedatcht Dam is viewed as the site-specific, while the Upper Orange water management area is viewed as the Catchment and the provinces and national objectives are viewed as the regional.

9.2 OBJECTIVES SELECTION

There can be a number of objectives in managing sediments but these are generally a subset of the following two:

1. Not enough sediment where we want it – land degradation, Ecosystems, beaches, etc.
2. Too much sediment where we don’t want it – Tons of sediment dredged annually

For this case study, Welbedacht being at the centre of the investigation, it can be said that the objective is to minimise the amount of sediments moving towards the dam as well as the amount of sediments being deposited in the reservoir. Only the quantity and the upstream impacts were considered in the case study.

9.3 REQUIRED DATA FOR INTEGRATED SEDIMENT MANAGEMENT

Type and frequency of sediment observations depend on the needs of the users. They are needed to describe the most relevant processes and to understand how they are influenced by natural and anthropogenic changes. The sediment observations are needed for all issues related to the optimal use of the water resources, protection of the water and the protection of the population against harmful impact of the water. Methods and tools as, e.g., soil erosion assessment, sediment transport equation, methods of assessment of sediment potential and sediment budget, mathematical and empirical models for rock fall, debris flow arson, risk assessment procedures, chemical methods to provide qualitative information and decision support systems need a large number of sediment observations. Sustainable sediment management is based on sediment observations, but also on ecological, economical and sociological information and needs, which must be in an equilibrium (MANFRED S, Undated). **Table 23** list necessary sediment observation required for proper sediment management and **Table 24** presents additional parameters that should also be observed.

Table 23: A list of necessary sediment observations (MANFRED S, Undated)

Torrents	Rivers	Reservoirs and lakes
• Bed load • Bed load potential • Transport capacity (maximum bed load discharge) • Bed load discharge during floods • Bed load discharge graph • Grain size distribution during floods events • Bed load discharge of floods of different size (recurrence intervals) • Suspended sediment • Suspended sediment concentration • Relation between water discharge and suspended sediment concentration • Suspended sediment discharge • Sediment features • Grain size distribution • Grain shape and petrography • Bulk density of accumulation	• Bed load • Bed load potential • Transport capacity (maximum bed load discharge) • Bed load discharge during floods • Bed load discharge graph • Grain size distribution at flood events • Bed load discharge of floods of different size (Recurrence intervals) • Suspended sediment • Suspended sediment concentration • Relation between water discharge and suspended sediment concentration • Suspended sediment discharge • Sediment features • Grain size distribution (as function of place, time and water discharge) of moving and laying bed load and suspended sediment • Grain shape and petrography • Specific weight • Transported wood volume per flood event	• Sediment in-and output • Sediment load (to be determined in in-and outflowing rivers) • Bed load • Delta survey • Suspended sediments • Suspended sediment concentration (as function of time and space) • Turbidity profiles • Composition of suspended sediments (grain size distribution, organic/inorganic, chemical/mineralogical, clastic) • Features of adsorption • Sedimentation rate • Volume change by redeposition and diagenesis of sediments • Grain shape and petrography • Composition of suspended sediments (grain size distribution, organic/inorganic, chemical/mineralogical, clastic) • Transported wood volume per time

Table 24: Supplementary information for solving sediment related problems (MANFRED S, Undated)

Torrents	Rivers	Reservoirs and lakes
• Cross sections profiles • Longitudinal profiles of torrents and their changes with time • Flood traces • Accumulation volumes in and out of river bed • Volumes of landslides and bank erosion • Volumes of erosion in torrents • Water quality • Channel roughness	• River morphology • River shape (outlines) • Cross section profiles • Bed shape (banks, Thalweg, etc.) and the changes by time including the features derived (Slope, accumulation and erosion volumes, etc.) • River bed roughness • Water quality • Longitudinal profiles	• Reservoir, lake geometry • Soil mechanic parameters • Origins of sediments • Rivers • Bank erosion • Rockfall • Landslides • Avalanches • Dust fall • Artificial earth deposits and intakes • Chemical and biogenic production • Dredgings • Survey of extraordinary events • Bathymetric surveys, delta formation • Sediment budget of catchment area • Water quality • Flow measurements

9.4 MODEL SELECTION AND CONFIGURATION

To be able to analyse the problem as per the objectives, it is important to understand the sources of sediments and how they can be minimised. Hence, the Revised Universal Soil Loss Equation (RUSLE) (Renard *et al*., 1995) was selected for modelling soil erosion. The reason is that, it is one of the least data demanding erosion models that has been developed and it has been applied widely at different scales. Moreover, the model can estimate long-term annual erosion rates on agricultural fields. Lastly, the model is useful for construction sites and other non-agricultural condition. The RUSLE input parameters are rainfall, soil, topographic, land cover and practice management. These input parameters are important in order to reliably compute rates of sediment transport.

The RUSLE requires six inputs parameters to be applied as in equation 9.1 and these parameters were multiplied together for calculating the annual average soil loss (A). **Table 25** present the results of annual average soil loss rate based on land cover, assuming land cover and management factors of entire catchment is one (1), meaning there is no physical evident of erosion control in these areas. The soil erosion results provide information about the erosion situation in the catchment for the existing condition or scenario.

$$A = R * K * LS * C * P \qquad (9.1)$$

Where:

A = Mean annual soil loss (in ton/ha/yr)

R = Rainfall and Runoff Erosivity Index (in MJ/ha/mm/yr)

K = Soil Erodibility Factor (in ton/MJ/mm)

LS = Slope and Length of Slope Factor

C = Cropping – Management Factor

P = Erosion Control Factor Practice

Table 25: Average annual soil loss rate based on Land cover

Land cover type	**Average Annual Soil Loss (ton/ha/year)**
Build up land	103.3
Cultivated land	273.0
Degraded land	9.8
Grassland	3.9
Thicket bush land	80.0
Mining & Quarry	5.3
Woodland	7.5
Forest Plantations	16.6
Forest	103.3
TOTAL	**602.58**

Table 25 shows that agricultural practices contribute the greatest volume of sediment, with the bulk coming from cultivated land at 273 ton per hectare per year. The next most extensive sediment sources are forest and built-up which includes urbanization and construction areas contributing 103.3 ton per hectare per year, followed by thicket bush land and forest plantations contributing 80.0 and 16.6 ton per hectare per year each. Grassland, degraded land, mining and quarry contribute 3.9, 9.8 and 5.3 ton per hectare per year respectively. The total annual soil loss in the catchment is approximately 602.58 ton per hectare per year since 1992 to 2011.

Figure 28 presents the main sources of sediment in the catchment. The Pie chart shows that cultivated land accounts for (48%), built- up and forest (17%) each, thicket bush land at 13%, forest plantations (3%) and degraded land (2%).

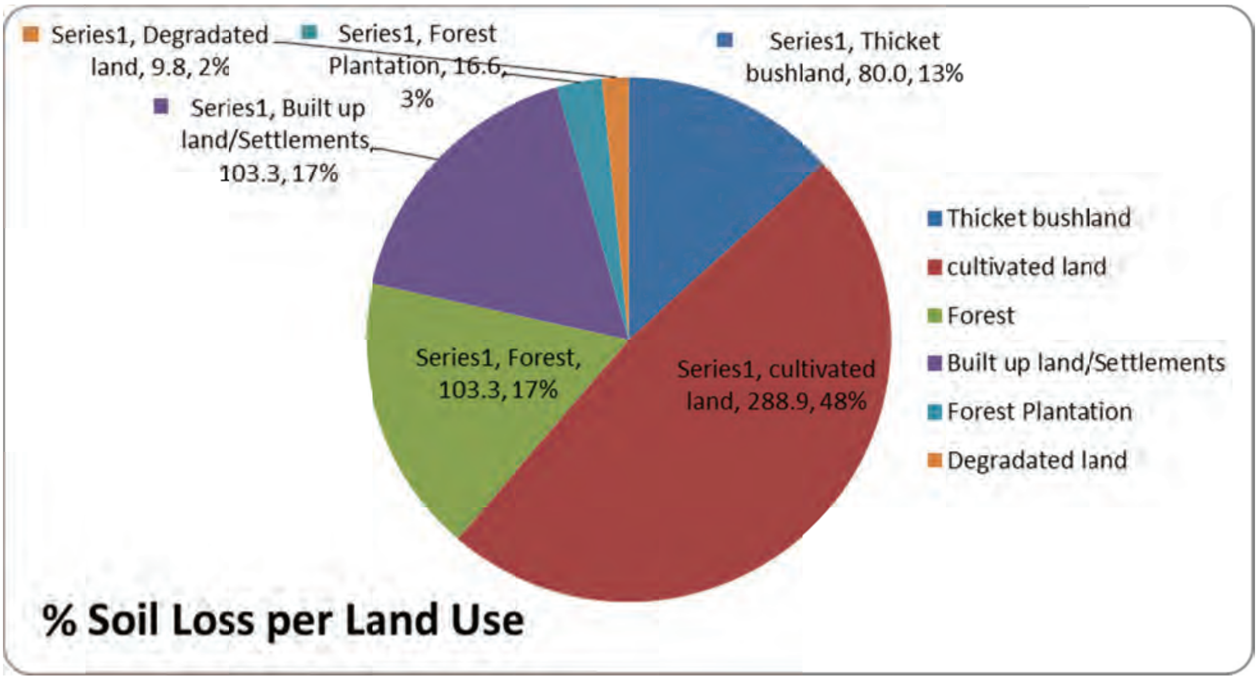

Figure 28: Magnitude of soil loss per land covers in percentage

Figure 28 shows that Wepener experienced the highest sediment of 146.85 ton per hectare per year, followed by Fouriesburg, Clarens and Ficksburg 90.67, 82.4, 53.3 ton per hectare per year respectively. Hence, Clocolan, Dewetsdorp, Excelsior, Thaba Patchoa, Bloemfontein and Thaba Nchu yielded low sediment. The assumption is that, this erosion may have been from cultivating land that is under inappropriate cultivation practices such as steep slopes and lack of contouring on sloping land.

Figure 29 shows that areas such as Fouriesburg, Clarens and Ficksburg have higher K values which lead to higher sediment yields and these high sediment yields can be expected in future due to the increasing high rainfall. Results show that higher sediment outputs are linked to areas with higher run-off and consequently higher soil erodibility (K).

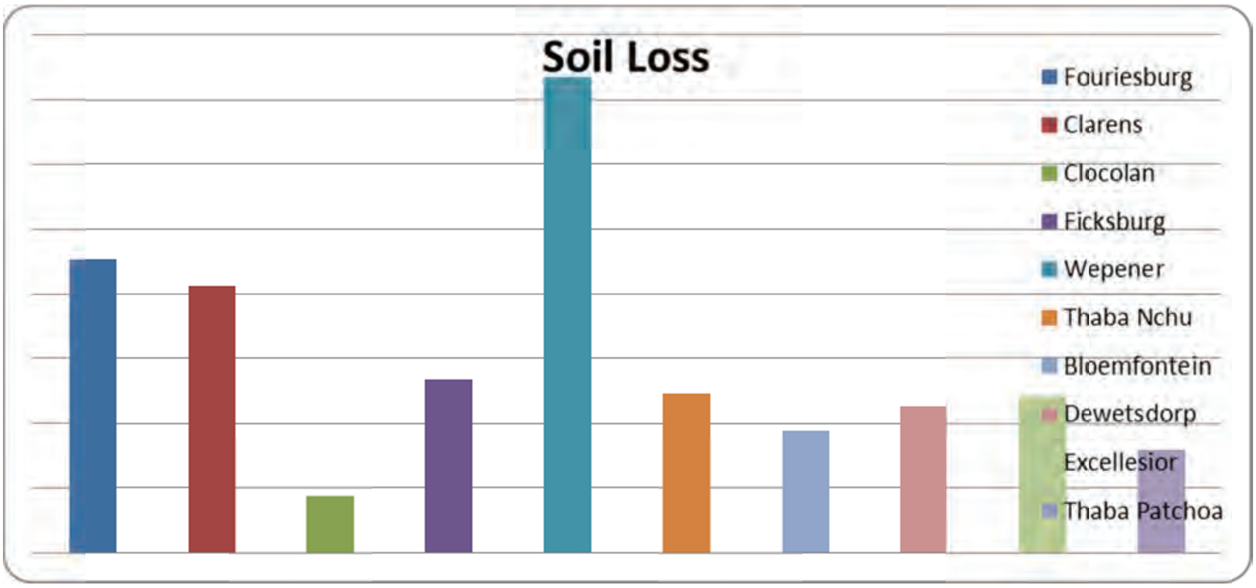

Figure 29: Soil losses per area

9.5 DATA COLLECTION AND ANALYSIS

9.5.1 PRECIPITATION

Ten meteorological stations were used in this study and were chosen to represent the possible coverage of the catchment. A manual in-filling approach of using neighbouring and annual average rainfall data was used to estimate the missing values so that the data set has a complete record of 20 years. The monthly average precipitations for period 1992 to 2011 are shown in **Figure 30**. **Figure 30** presents the annual rainfall for 20 years with maximum rainfalls occurring in summer (November-April) while the minimum occurs in winter (May-August). Maximum rainfall occurs in the month of January with a total precipitation of 1077.66 mm while minimum rainfall of 48.56 mm occurs in the month of July. The average rainfall for the 20 years is 509.67 mm. Rainy season starts in October and ends towards the latter part of April with an approximate period of 7 months.

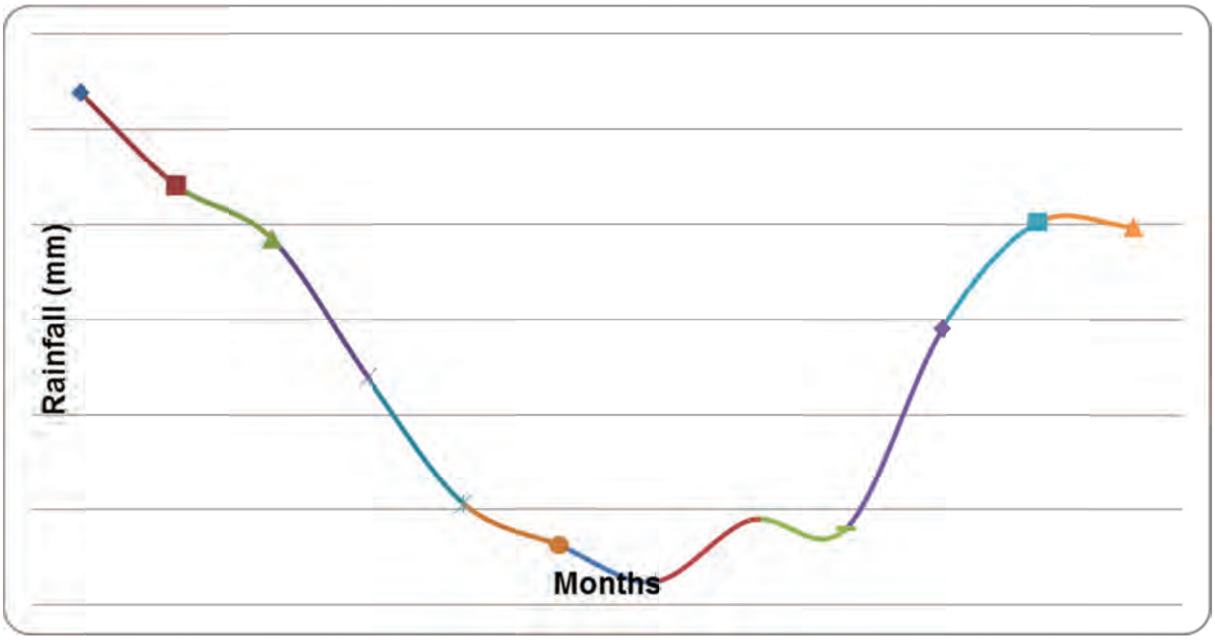

Figure 30: Monthly average precipitations for period 1992 to 2011

The mean annual precipitation of the catchment shown in **Table 26** was computed through adding the monthly average precipitation in Figure 4 for each month at a location and divided by number of months (12) to get the mean annual precipitation for a given location in the study area. The rainfall data records from South African Weather Services rain gages were analysed and was transferred to an Excel spreadsheet to work out the total rainfall for each of the twenty years and divide by the total number of years which is twenty. The reason for computing these averages is to establish temporal trend because rainfall is critical for erosion prediction.

Table 26: Mean Annual Precipitations

Station name	Mean Annual Precipitation (mm)
Wepener	976.20
Dewetsdorp	922.35
Ficksburg	1180.30
Excelsior	872.26
Clarens	1057.40
Thaba Patchoa	742.53
Bloemfontein	922.92
Fouriesburg	1132.86
Clocolan	1114.61
Thaba Nchu	1070.78

Table 26 shows that Ficksburg, Fouriesburg, Clocolan and Thaba Nchu receive the highest mean annual precipitation of 1180.30, 1132.86, 1114.61 and 1070.78 mm respectively. These are followed by Clarens, Wepener, Bloemfontein and Dewetsdorp with the mean annual precipitation of 1057.40, 976.20, 922.92 and 922.35 mm respectively, while Excelsior and Thaba Patchoa receive the lowest mean annual precipitation of 876.26 and 742.53 mm respectively.

9.5.2 RAINFALL-RUNOFF EROSIVE INDEX (R)

The rainfall-runoff erosive index (R) represents the erosivity of rainfall and runoff at a particular location. The value of R increases as the amount and intensity of rainfall increase. **Table 27** shows the Rainfall-runoff erosive (R) factor which was calculated by substituting mean annual precipitations of each station in Table 1 into the regional specific formula (equation 9.2) developed by the former Department of Agriculture and Water Supply in 1984 (adaptation of the USLE for South African conditions). The total annual R-factor is equal to the sum of all events within the year and finally annual averages are determined. As the catchment is located in the J. B. M Hertzog region, the Mean Annual Precipitation (MAP) was then substituted in equation 9.2 of map area E.

$$R = 0.54\,MAP - 166.83 \text{ at E Area} \qquad (9.2)$$

Where, MAP = mean annual precipitation in mm and R = rainfall erosivity factor in MJ/ha.mm/h.

For example, the calculated rainfall erosive factor (R) for Wepener will be:

R = (0.54*976.20) – 166.83

= 425.93 MJ/ha/mm/yr

Table 27: Calculated Rainfall-Erosive (EI30) for South African regions

MAP AREA	EQUATION	STATION
A	R = 0.23 P - 47.61	D. F. Malan Airport
B	R = 0.38P - 25.36	Upington
C	R = 0.80P - 371.16	Port Elizabeth
D	R = 0.25P - 18.67	Grootfontein
E	R = 0.54P - 166.83	J. B. M. Hertzog
F	R = 1.12P - 730.97	East London
G	R = 0.32P - 15.34	Kimberley
H	R = 0.68P - 135.54	Pietersburg
I	R = 0.41P - 38.51	Pretoria
J	R = 0.69P - 289.29	Jan Smuts Airport
L	R = 0.65P - 245.42	Louis Botha Airport
M	R = 0.88P - 420.46	Mount Edgecombe
N	R = 0.65P - 192.46	Richards Bay
O	R = 0.42P - 38.79	Makatini
P	R = 0.37P - 11.93	Newcastle
Q	R = 0.48P - 136.55	Cedara
R	R = 0.40P - 35.62	Kokstad
S	R = 0.65P - 145.36	Ladysmith
T	R = 0.63P - 153.72	Estcourt
U	R = 0.64P - 239.68	Waterford
R = EI30 P = Annual Rainfall		

Table 28: Rainfall-runoff erosive factor (R)

Stations	**R (MJ/ha/mm/yr)**
Wepener	425.93
Dewetsdorp	331.24
Ficksburg	470.53
Excelsior	324.77
Clarens	404.17
Thaba Patchoa	259.48
Bloemfontein	324.69
Fouriesburg	444.91
Clocolan	128.68
Thaba Nchu	411.39

The R values for each station show in **Table 28** are different and this lead to differences in erosiveness of the areas. Ficksburg, Fouriesburg, Wepener had the highest R value of 444.91, 444.91, 425.93 MJ/ha/mm/yr and this implies that these areas are highly erosive, while Thaba Nchu, Clarens, Dewetsdorp, Excelsior, Bloemfontein had 411.39, 404.17, 331.24, 324.77, 324.69 respectively. This means that these areas are moderately erosive, while Thaba Patchoa and Clocolan had low R values of 259.48 and 128.68, which means that these areas are less erosive.

9.5.3 TOPOGRAPHY

A topographic analysis of the entire catchment was performed through Digital Elevated Model obtained from the Free State Department of Agriculture. A Digital Elevation Model gives the elevation, slope and defines the location of the stream network in the catchment. Welbedacht catchment with a spatial resolution of 50 x 50 m was used in this study. The area is slightly irregular undulating lowlands with hills, low mountains, parallel hills, slightly irregular undulating plains and pans, and this means that the area may encounter higher erosivity factor due to high rainfall (**Map 2 in Appendix B**).

9.5.4 SOILS

The catchment is predominantly occupied by soils with marked clay which are strongly structured (reddish, red-yellow and greyish in colour having a high base status, rock with limited soils). These soils are shallow on hard or weathering rock with the clay classes of the top soil greater or equal to 15% and less than 35% (**Map 5 in Appendix B**). The geological formation mainly consists of fine grained sedimentary rock which consists of sandstone, migmatite and tillite that dominates the upper reaches of the river and mudstones at the bottom part (**Map 3 in Appendix B**).

9.5.5 SOIL ERODIBILITY FACTOR

Erodibility is defined as the resistance of the soil to both detachment and transport, while soil erodibility (K) factor represents both susceptibility of soil to erosion and the amount and rate of runoff. Soil texture, organic matter, structure, and permeability determine the erodibility of a particular soil. The different between soil erodibility factor (K) and erosive factor (R) is that, K factor reflect the rate of soil loss per rainfall-runoff (R) erosion index, while R reflect soil erodibility per rainfall. The K-factor for the catchment was estimated using the soil erodibility maps developed by Rooseboom *et al*., (1992) in appendix A. The K values for this study area ranges between 0.05 and 0.65 and was selected based on soil types and (K) values presented in **Table 29**.

Table 29: Soil characteristics associated with K values

SOIL TYPE	ERODIBILITY	K VALUE
Fine – textured: high in	Low	0.05-0.15
Course – textured: Sandy	Low	0.02-0.20
Medium – textured:	Moderate	0.25-0.45
High silt content	High	0.45-0.65

9.5.6 SUPPORT PRACTICE FACTOR (P)

Table 30 shows the support practice factor (P) values which mainly express how surface condition affects the flow paths and flow hydraulics. These values represent for control practices that can reduce the erosion potential of the runoff by their influence on drainage patterns, runoff concentration, runoff velocity, and hydraulic forces exerted by runoff on soil. The supporting mechanical practices include the effects of contouring, strip cropping, or terracing. It is applied after calculating the estimated soil loss, and it is adjusted to forecast various erosion prevention or conservation measures. This is an important factor in recalculation of each proposed measure in order to determine how much the soil loss is reduced.

Table 30: Support practice factor values for contour tillage on contoured lands in South Africa (Breetzke, 2004)

% LAND SLOPE	SUPPORT PRACTICE FACTOR VALUE *P*
0-3	0.6
3-8	0.5
8-15	0.6

9.5.7 LAND COVER (C)

Table 31 shows the cover-management factor (C) values which represent how vegetation management affects soil loss. This value mainly relates to the vegetative cover and it defined the ratio of soil loss from specific soil-disturbing activities. The land cover of the study area consists mainly of natural vegetation, cultivated land, built-up areas or settlement and towns, bare lands, and natural water bodies. The natural vegetation consists of forest, bush lands and grasslands, and woody vegetation. This means from Table 9, one can pick the relevant cover management values that can assist in reduce sediment yields.

Table 31: C-Factors ranges defined for each land cover in the catchment (Breetzke, 2004)

Land cover/Cover type	Cover
Forest	0.006
Forest plantation	0.006
Waterbodies	0
Unimproved grassland	0.038
Improved grassland	0.008
Thicket, Bushland, Scrub forest and high fynbos	0.008
Cultivated: temporarily commercial dryland	0.43
Cultivated: temporarily subsistence dryland	0.17
Cultivated: temporarily commercial irrigated	0.70
Urban or Built-up land: Residential	0.58

Table 31 shows that built-up or construction areas have the highest factor of 0.58, followed by cultivated land (temporarily commercial dry land, subsistence dry land and commercial irrigation) at 0.43, 0.17 and 0.70 respectively. While unimproved grassland areas have 0.038, followed by thicket, bushland, scrub forest and high fynbos, improved grassland

having factor at 0.008 each, forest and forest plantation have a lowest sediment yield of 0.006 each.

9.5.8 WELBEDACHT SEDIMENTATION RATES

Figure 31 show the observed loss of storage of Welbedacht dam overtime and **Figure 32** show the longitudinal bed profiles for different surveys over time as well as future projections.

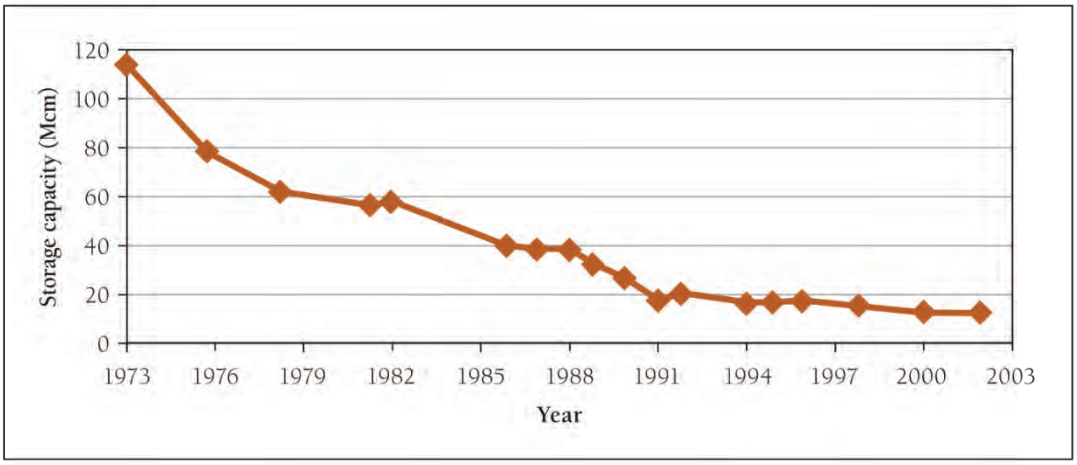

Figure 31: The observed loss in storage capacity due to sedimentation at Welbedacht Dam (Clark 1990)

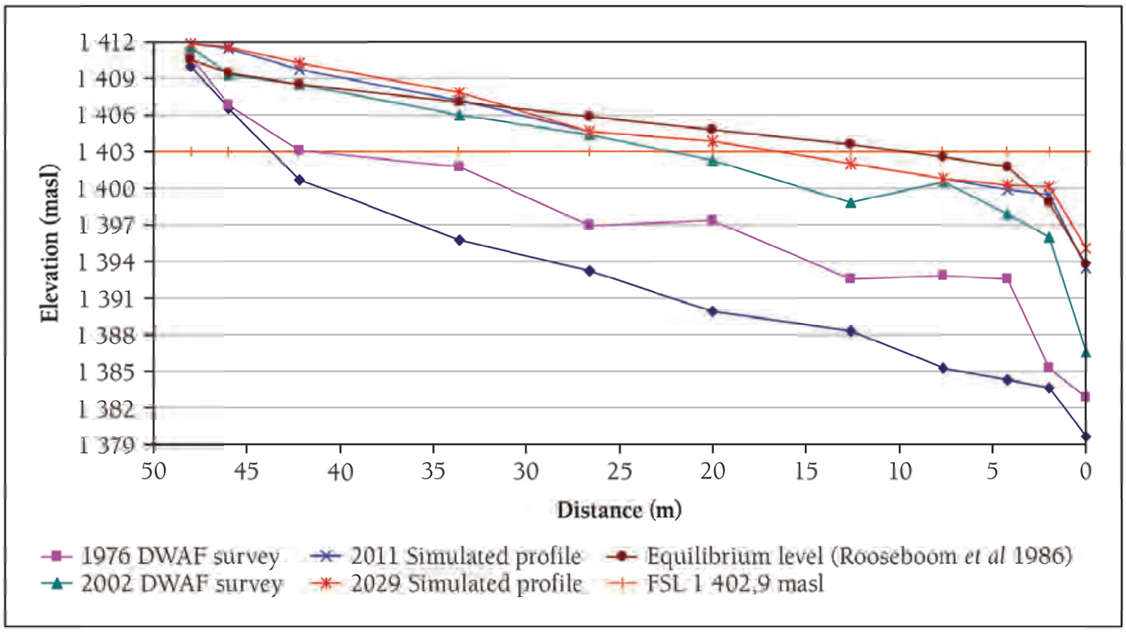

Figure 32: Historical longitudinal bed profiles with future sedimentation levels

9.6 ANALYSIS AND RESULTS

Modelling of erosion and sediment yield plays an important role during the design stages of a water resource project, particularly in the development of effective catchment management and sediment control strategies. This is in most cases achieved by spatially distributed models having the ability to provide spatially distributed information on erosion and sediment yield within the catchment which can be used for planning catchment management and sediment control strategies.

RUSLE was applied for the Welbedacht catchment. The model was set up to simulate different land-use and support practices scenarios in order to explore their impacts on sediment generation and to suggest catchment management strategies. The land use scenarios were divided into two scenarios namely: completely under agricultural practices and secondly under built-up or construction sites. This is because the main drivers of sediment production have been shown to be the agricultural and built-up or construction sites, which can be used to reduce sediment yields to Welbedacht reservoir.

The support-practice (P) and cover-management (C) factors are very important in soil-loss estimates for agricultural practices and construction-site reclamation planning because these factors represent practices designed to reduce erosion. The support practices (P) factor account for control practices that reduce the erosion potential of the runoff by their influence on drainage patterns, runoff concentration, runoff velocity, and hydraulic forces exerted by runoff on soil. The supporting mechanical practices include tillage such as furrowing, seeding, terraces, and other soil-management practices orientated on or near the contour that result in the collection and storage of moisture and reduction of runoff.

The simulation was performed to examine the impacts of conservation measures largely driven by the practice factor *(*P) and land cover management or land use factor (C). Support practice (P) factor and cover management (C) factor was applied in the model. The support practice factor value (P) of 0.6 was used because the average slope of this catchment lies between 0-3%. The rest of the catchment was assigned a support practice factor (P) factor value of 1, meaning there is no physical evident of erosion control in these areas. **Figure 33** presents the results of the management solution from RUSLE model applied.

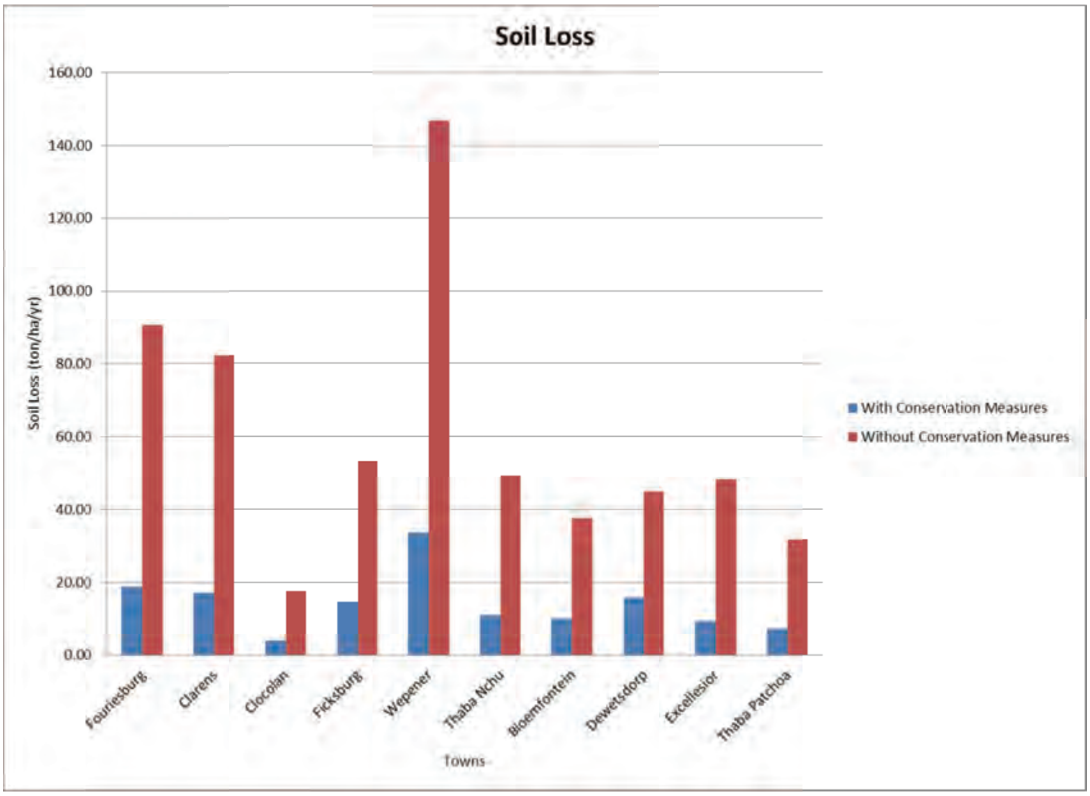

Figure 33: Results of the management solutions from RUSLE model

Figure 33 presents the results of the management solutions from RUSLE model under the different rehabilitation scenarios. The results further shows that Sediment yield coming from cultivated land has decreased from 273 to 67.1 ton per hectare per year, while sediment from built-up and forest decreases to 59.5 ton per hectare per year and 0.62 ton per hectare per year respectively. Total average annual soil loss in the catchment decreased to 141.7 ton per hectare per year. This leads to a value of about 7.09 ton per hectare per year when divided by the number of years over which it was simulated.

If we apply the same reduction to the amount deposited in the Welbedacht dam we see that the storage capacity would have only been reduced by 57% compared to the current 87% (**Figure 34**).

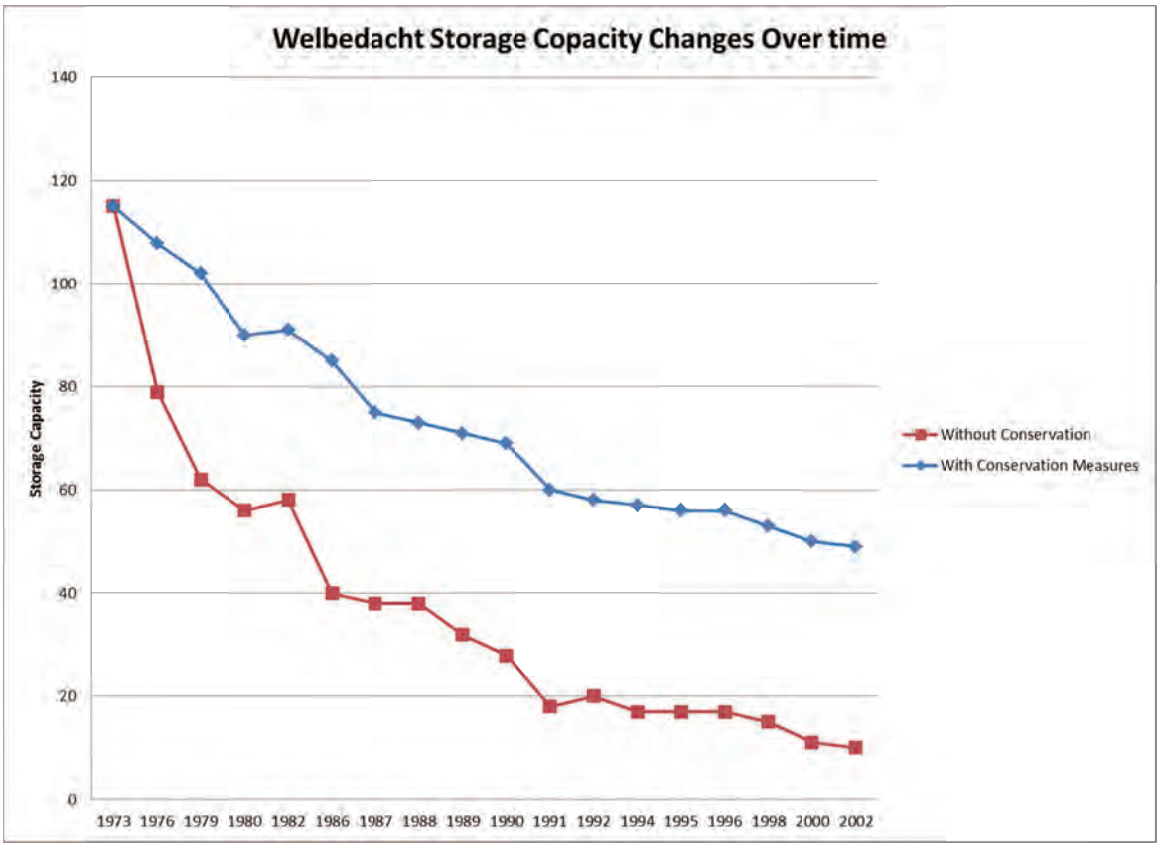

Figure 34: Results of the management solutions from Applied on Welbedacht

9.7 CASE STUDY RESULTS CONCLUSIONS

The study aimed at demonstrating an integrated approach to sedimentation processes and management for the reservoir. Firstly, it intended to determine the various sources and rates of sediment transport. Secondly, to select a model for integrated catchment sedimentation processes, and lastly, to apply the model developed to design integrated catchment sedimentation management strategies for Welbedacht reservoir.

In an attempt to accomplish the objectives outlined above, RUSLE model developed by Wischmeier and Smith (1978) was selected for this research. The data was analysed and used in RUSLE model to compute annual soil loss in a catchment. Based on the findings of this study, the following conclusions and recommendation can be drawn:

1) The results obtained indicated the total annual soil loss of approximately 602.58 ton per hectare per year since 1992 to 2011 for scenario without conservation measures, which leads to a value of about 30.13 ton per hectare per year when divided by the number of years over which was computed.
2) It further shows that agricultural practices contribute the greatest volume of sediment, with the bulk coming from cultivated land at 273 ton per hectare per year.

The next most extensive sediment sources are forest and built-up which includes urbanization and construction areas contributing 103.3 ton per hectare per year, followed by thicket bush land and forest plantations contributing 80.0 and 16.6 ton per hectare per year each. Grassland, degraded land, mining and quarry contribute 3.9, 9.8 and 5.3 ton per hectare per year respectively.

3) After application of soil conservation practices to RUSLE model, the results shows sediment yield coming from cultivated land decreased from 273 to 67.1 ton per hectare per year, while sediment from built-up and forest decreases to 59.5 ton per hectare per year and 0.62 ton per hectare per year respectively. Total average annual soil loss in the catchment decreased to 141.7 ton per hectare per year (to about 24% or rather a decrease of 76%). This leads to a value of about 7.09 ton per hectare per year when divided by the number of years over which it was simulated.
4) Applying this reduction to the Welbedacht storage assuming a linear relationship would mean that Welbedacht would have only lost about 57% of storage compared to 87%. This is an indicative figure, it should be noted that most of the storage was lost within the first three years, hence the assumption of a linear relationship is used here only to indicate a potential reduction.
5) The overall results showed that the Framework can be a useful tool to logically getting to an optimal solution for an area in question.
6) The proposed Integrated Catchment Management Strategies for Welbedacht catchment are:

   - Soil conservation measures such as contour banks, tillage practices, and terracing must be implemented to reduce the high rates of soil erosion, especially in the cultivated land.

   - Construction site stabilization activity, such as mulching, sediment catchments, seeding of grasses and planting of trees need to be implemented during and after constructions to protect the vulnerable soil from erosion.

10 DATA ARCHIVING

The main data outputs from the project are the literature review material, the Framework and the data used for the case study. The literature review material has been summarised in the Final Report including the Framework, and these will be delivered to the WRC with its data elements used in the case study. This will ensure that the data from this study is available for future research or reference. It is also understood that there will be some raw data or data that was collected during the project but not necessarily used in the project and for this the Project leader will, in the short term, keep the data for distribution where required by other parties. The project manager will also keep the same copies of data as handed over to the WRC in the short term to be able to assist those who may need information from this project.

11 CONCLUSIONS

The research found that there are no documented sediment management frameworks in South Africa. However, there are various legislations concerned with water and environmental protection that may indirectly include sediment management. These include the NWA No. 36 of 1998 and National Environmental Management Act (NEMA) No. 107 of 1998. Section 21(g) of the NWA stipulates that the disposal of waste in a manner which may detrimentally impact on a water resource is a water use. According to DWAF (2008) the waste includes any solid material or material that is suspended, dissolved or transported in water (including sediment) and which is spilled or deposited on land or into a water resource in such a volume, composition or manner as to cause, or to be reasonably likely to cause, the water resource to be polluted.

Therefore, a conceptual Integrated Sediment Management Framework was designed and presented in this report. The Integrated framework essentially provides a platform whereby sediment management tools/models/frameworks, etc. can be brought together such that their results are consistent when applied by different people. The Developed Integrated framework is therefore not meant to be a replacement of the existing frameworks, as it has been shown that each of the frameworks has their focus and strong points which if logically brought together can enable management to assess the holistic situation by combing the results from the various frameworks.

It has been shown that integrated sediment management is effective on river catchment scale, it is therefore crucial to develop sediment management frameworks for different river catchments in South Africa while following the basic concepts outlined in the existing/reviewed frameworks. Thus, it is essential for each river catchment to have its own integrated sediment management framework.

The selection of the appropriate framework should be based on the specific aim(s) of the study and whether the framework fulfils the requirements of sustainable integrated sediment management and IWRM principles. This means an appropriate framework should be able to address sediment related problems at a river catchment scale while involving stakeholders in decision making throughout the whole process. The aim of the study may either be managing the quantity and/or quality of sediments in a river catchment.

The development of the sediment management framework should be based on the catchment area contributing runoff. Any framework that can meet these criteria can be tested for use in SA river catchments. Frameworks such as sediment budget conceptual model can also be tested if stakeholder participation is incorporated within them. However, issues such as data requirements and availability should be considered while selecting or adopting a specific framework. These are dependent on the scale of application (size of the river catchment) and the aims of the study.

12 RECOMMENDATIONS

Based on the conclusions it is recommended that:

1. In a South African context, the unavailability of national guiding principles on sediment management is seen as a challenge to the implementation of the integrated Sediment management framework, and it is therefore recommended that as a first step South Africa should develop high level policies to guide the various organs of the state in managing sediments sustainably.
2. Management of sediments spans a number of independent institutions, hence for an integrated approach to be successful, there must be an institutional co-operation strategy and a committee that will facilitate engagements between the various institutions. Hence further research should be geared towards identifying the key role players in sediment management and development a co-operation strategy.
3. Sediment Management Plans should be developed and incorporated into the catchment management strategies as a matter of urgency.
4. Researchers, policy-makers and community education have to go hand in hand to face the problems of land degradation and soil erosion as the successful implementation of soil conservation measures and road drainage control is only possible through a combination of socio-economic, political, and scientific considerations.
5. There must be community education and awareness about the long term consequences of human interference into their natural environment as people understand their present impact on the future productivity of their land.
6. The must be a development of conditions to be used in initial site selection for the project such as select a site that is suitable rather than force the terrain to conform to development needs. This will ensure that development features follow natural contours.
7. Further studies should be undertaken in view of improving the relevance of the Framework for all catchments in South Africa. What would also be important would be to add an economic model to assist with the choice of strategies relative to the implementation cost.

13 CAPACITY BUILDING

13.1 STUDENT TRAINING

As proposed and detailed in the inception report, the following individuals have been identified for capacity building**:**

1. **Thomas Chabalala** – Thomas was involved in this project as a Masters Student (MTech Civil Engineering) at the Tshwane University of Technology, and his registration was finalised in June 2011 after approval of his proposal.

2. **Itumeleng Molobela** – Itumeleng was involved in this project as a postdoctoral student with UNISA.

3. **Mpho Ramalivhana** – Mpho was involved in the project as a team project manager in training, and he has been driving the project and co-authored deliverables no 2, 3, 4 and 6.

4. **Lilian Novela** – Lilian is involved in this project as a project administrator as part of her learner-ship requirement to graduate for her diploma in marketing at Tshwane North College**.** She has graduated in December 2012.

A fourth person was identified to join the team for capacity building as of August 2011 as follows:

1. **Ave Mlungwana** – Ave is registered for a Diploma in Civil Engineering at UNISA and he is required to undergo Work integrated learning to be able to graduate. He is participating in this project for that purpose and he is involved in research, project management as well as modelling.

13.2 TECHNOLOGY TRANSFER

The Sediment Integrated Framework is a key output that can be used by the targeted users. These include a wide range of stakeholders, from policy and decision makers in all spheres of government, to researchers and communities.

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APPENDIX A - GENERALIZED SOIL PATTERNS OF SOUTH AFRICA

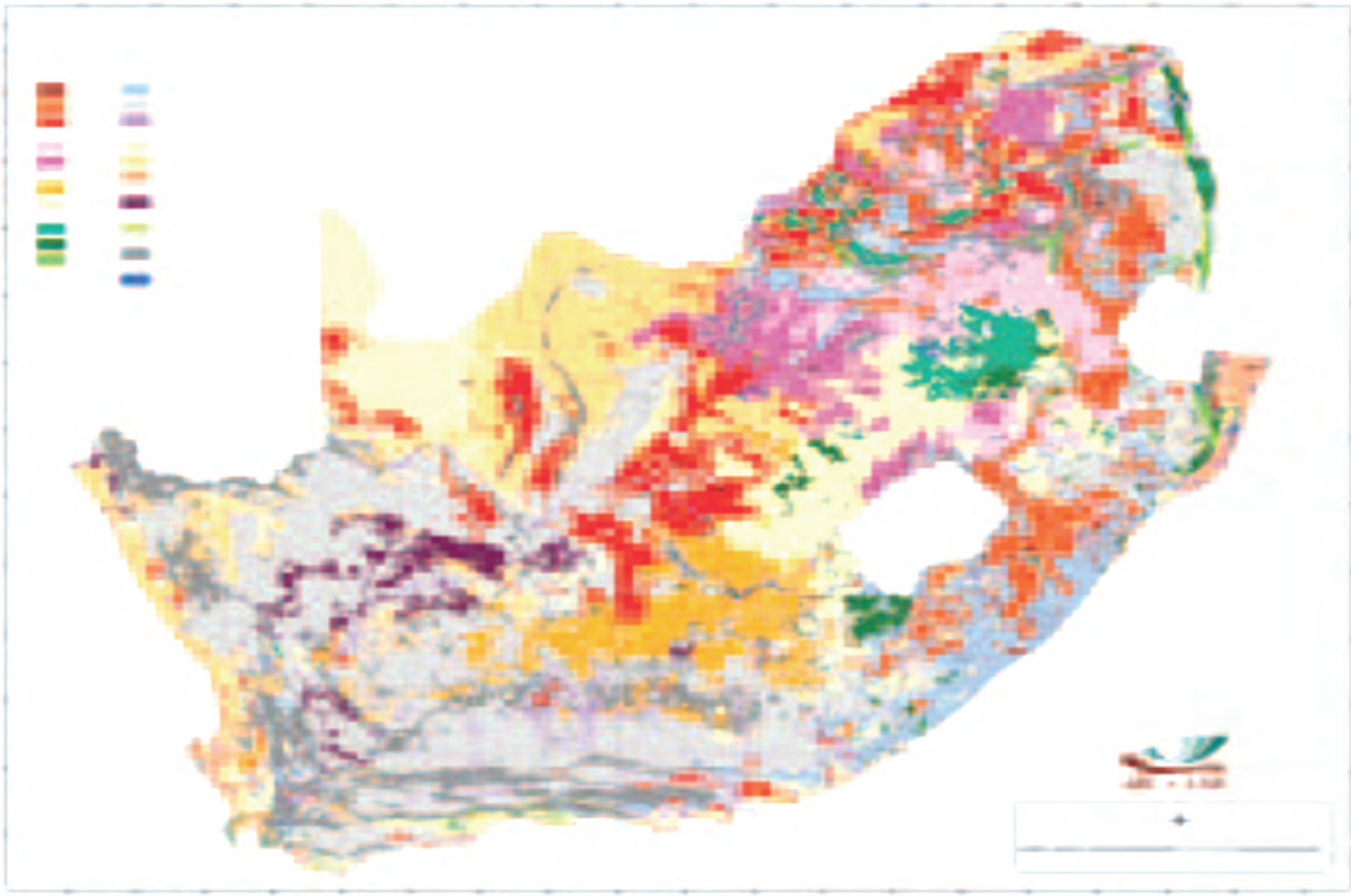


Figure 35: Generalized soil patterns of South Africa 2004 (Source: Gichangi, 2007)

Legend

GENERALIZED SOIL PATTERNS

RED-YELLOW WELL DRAINED, MASSIVE OR WEAKLY STRUCTURED SOILS

FR *Red and yellow soils with a low base status and a humic topsoil horizon.*

AC *Red and yellow soils with low to medium base status.*

CM *Red soils with high base status.*

SOILS WITHIN A PLINTHIC CATENA

PT1 *Red, yellow and / or greyish soils with low to medium base status.*

PT2 *Red, yellow and /or greyish soils with high base status.*

SOILS WITH A STRONG TEXTURAL CONTRAST

PL1 *Soils with a marked clay accumulation, strongly structured and a reddish colour.*

PL2 *Soils with a marked clay accumulation, strongly structured and a non-reddish colour. They may occur associated with one or more of vertic, melanic and plinthic soils.*

STRONGLY STRUCTURED SOILS, GENERALLY WITH A HIGH CLAY CONTENT

VR *Strongly structured cracking soils, mainly dark coloured, dominated by swelling clays (vertic soils). They may occur associated with one or more of melanic and red structured soils.*

PH *Soils with dark coloured, well structured topsoil and high base status (melanic soils). They may occur associated with one or more of vertic and red structured soils.*

NT *Well drained, dark reddish soils having a pronounced shiny, strong blocky structure (nutty), usually fine (red structured soils). They may occur associated with one or more of vertic and melanic soils.*

SOILS WITH LIMITED PEDOLOGICAL DEVELOPMENT

LP1 *Soils with minimal development, usually shallow, on hard or weathering rock, with or without intermittent diverse soils. Lime rare or absent in the landscape.*

LP2 *Soils with minimal development, usually shallow, on hard or weathering rock, with or without intermittent diverse soils. Lime generally present in part or most of the landscape.*

FL *Soils with negligible to weak profile development, usually occurring on deep alluvial deposits.*

SANDY SOILS WITH LITTLE OR NO PROFILE DEVELOPMENT

AR1 *Red, excessively drained sandy soils with high base status, mainly dunes.*

AR2 *Red and yellow, well drained sandy soils with high base status.*

AR3 *Greyish, sandy soils.*

STRONGLY SALINE SOILS

SC *Strongly saline soils generally occurring in relatively deep deposits in low lying arid areas.*

PODZOLIC SOILS

PZ *Soils with a sandy texture, leached and with subsurface accumulation of organic matter and aluminium, with or without iron oxides, either deep or on hard or weathering rock.*

ROCKY AREAS

R *Rock with limited soils.*

LARGE WATER BODIES

W *Water.*

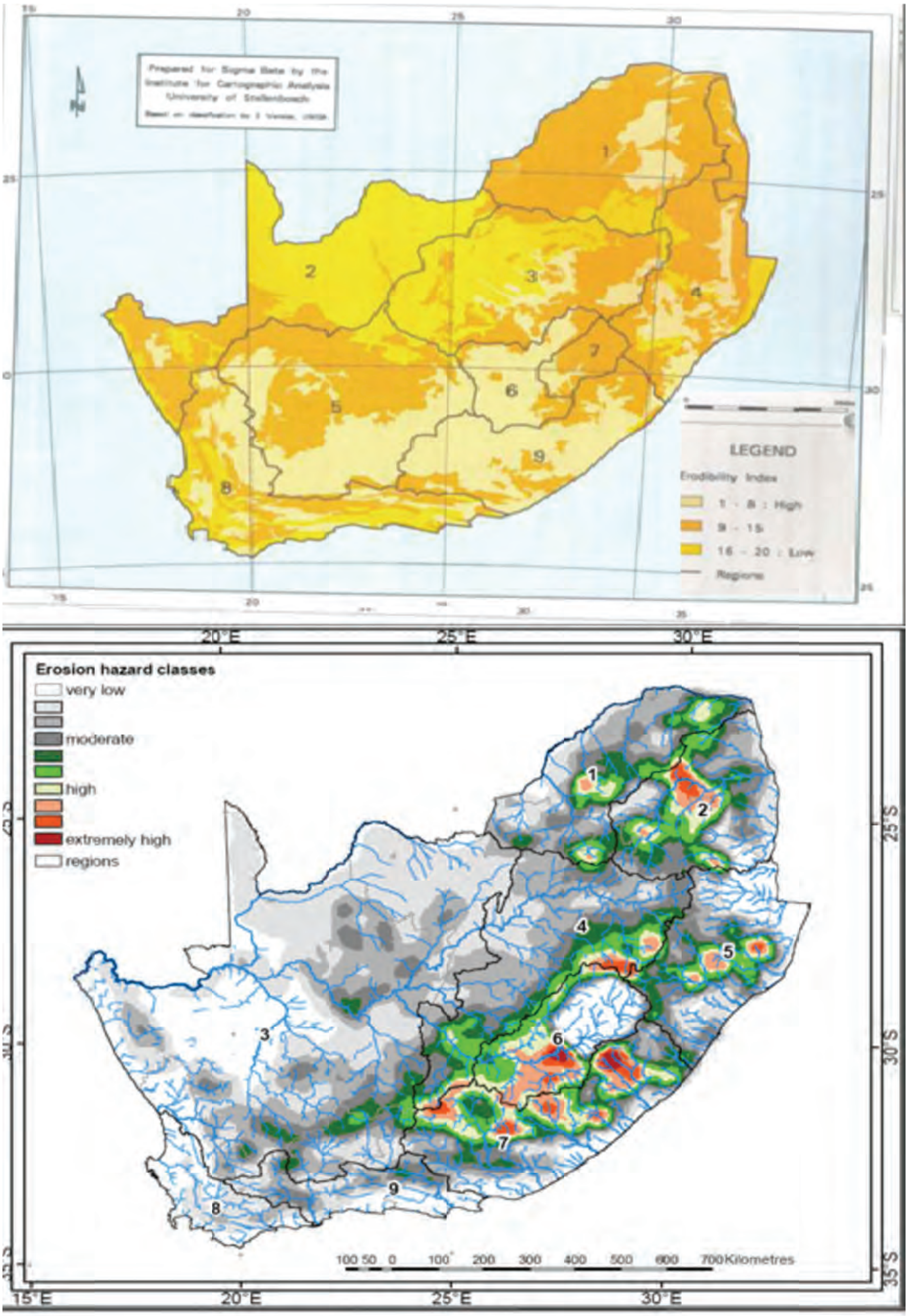
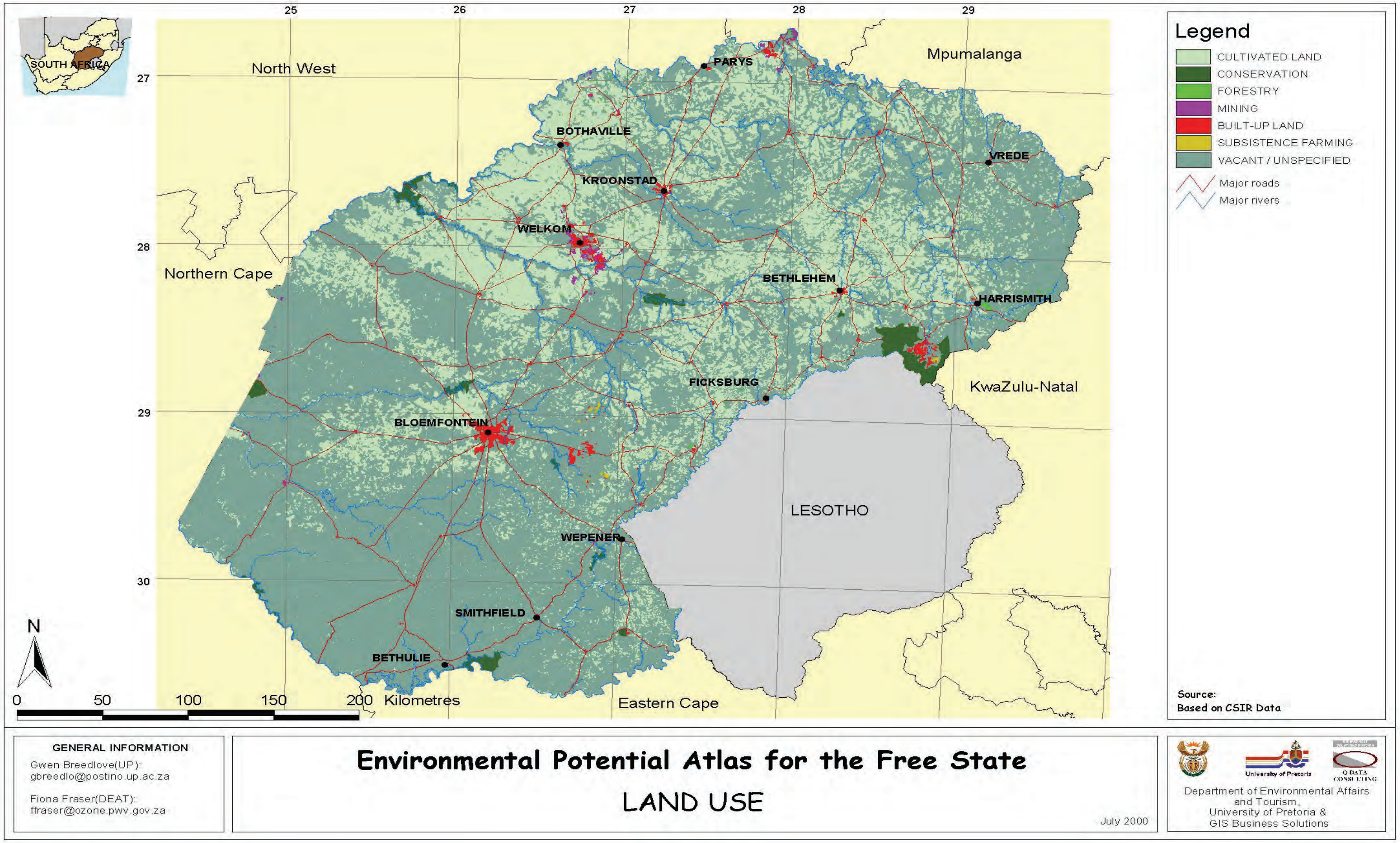
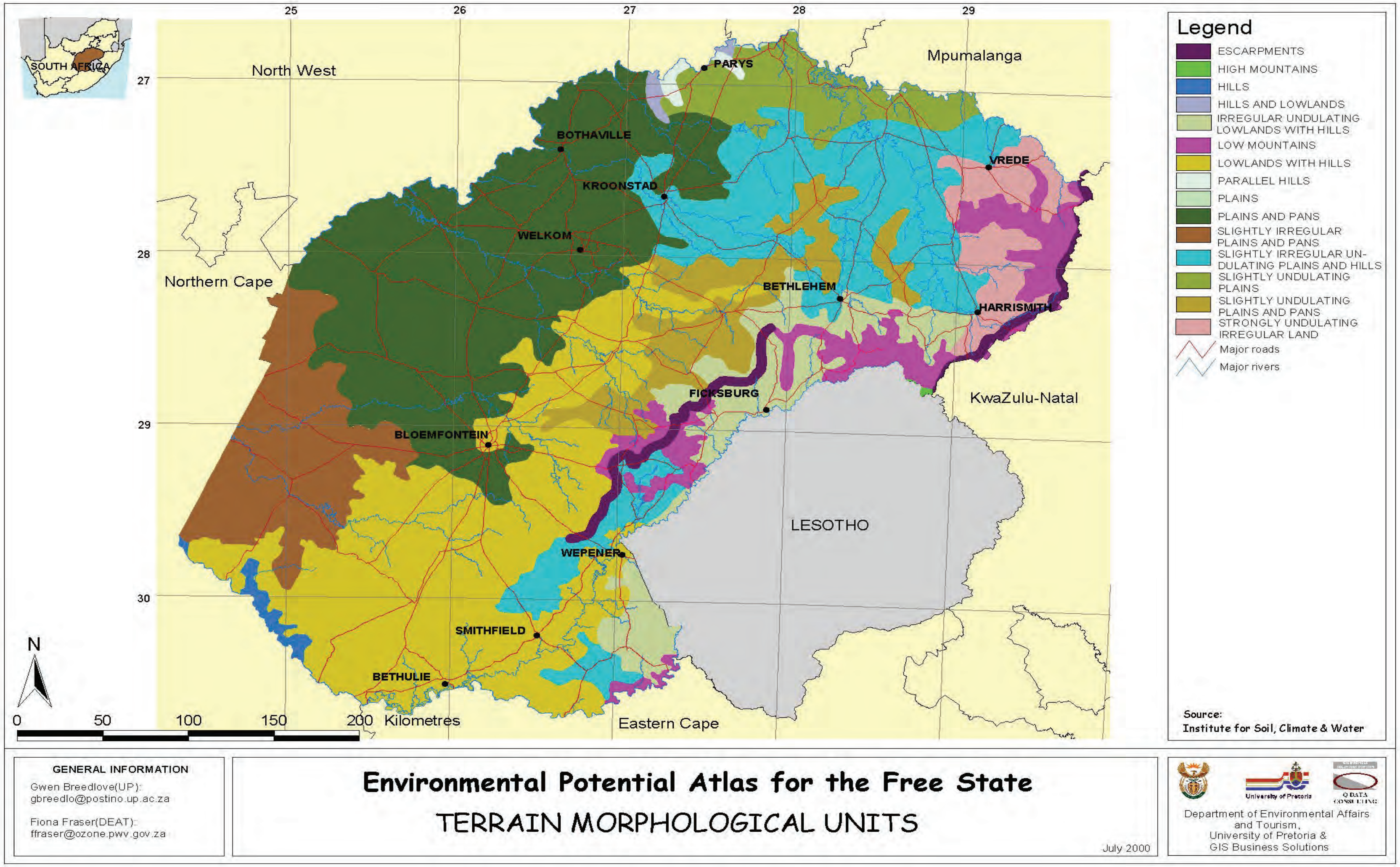


Figure 36: Erosion hazard classes

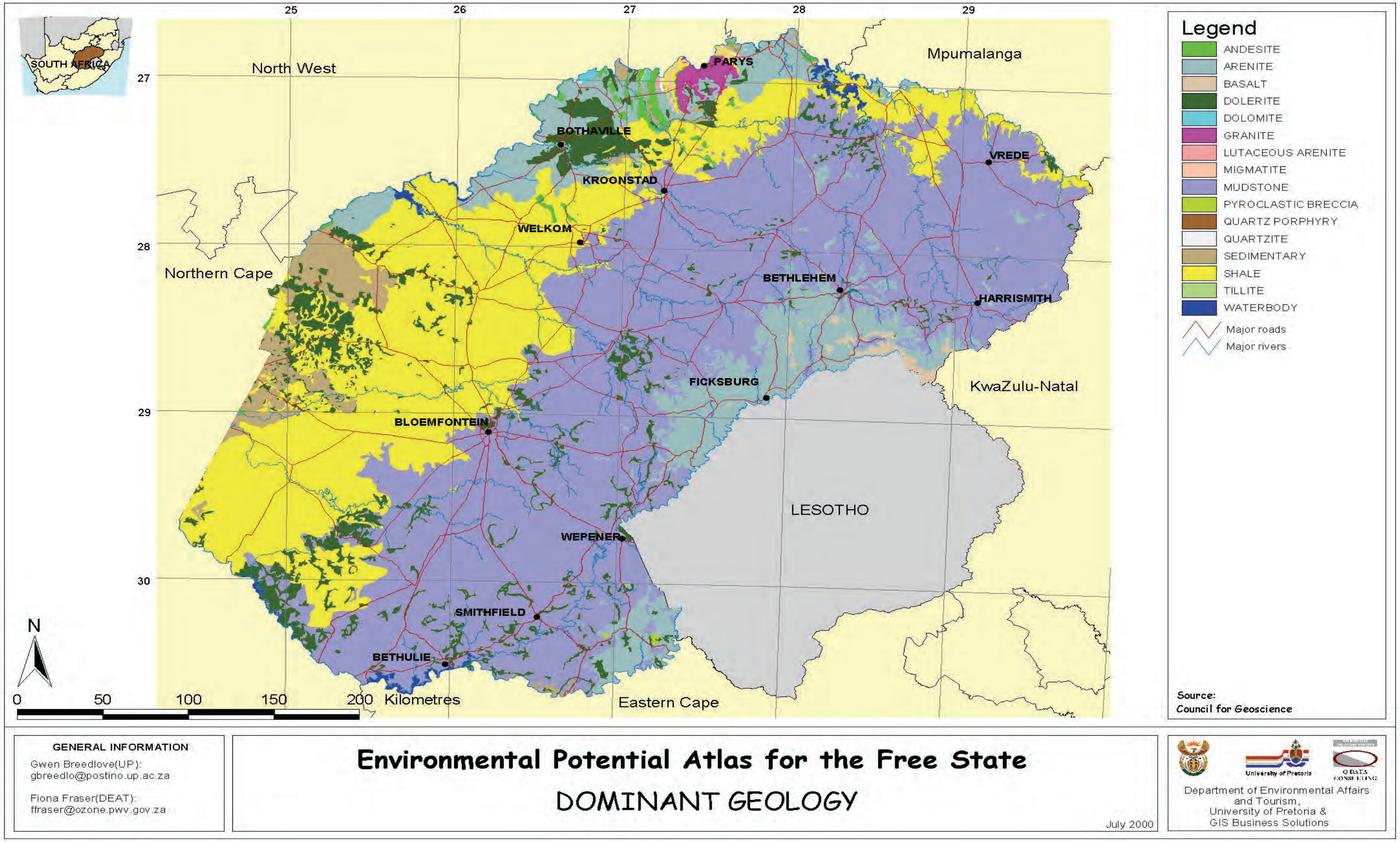
APPENDIX B - MAPS



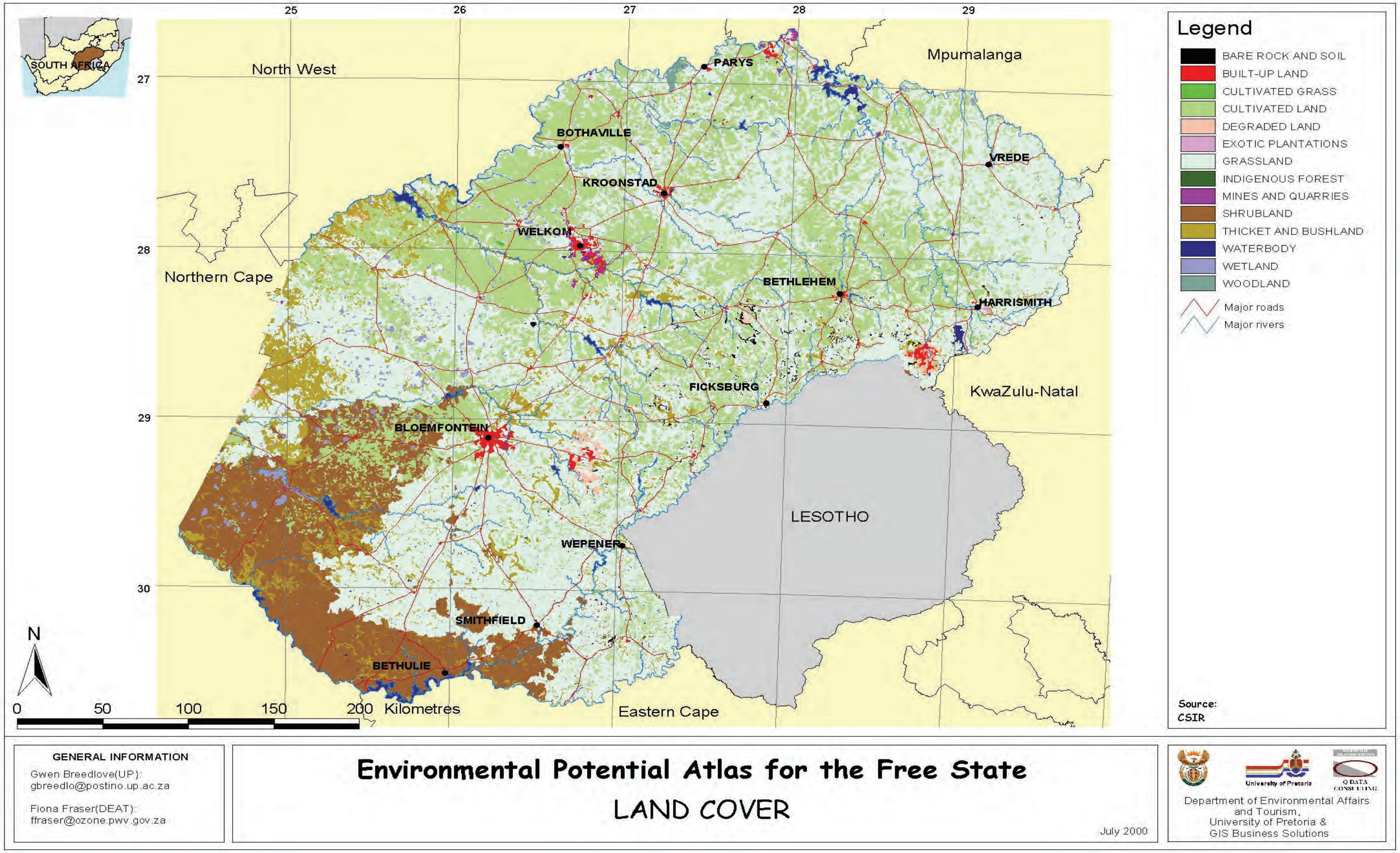
MAP 1: Land use



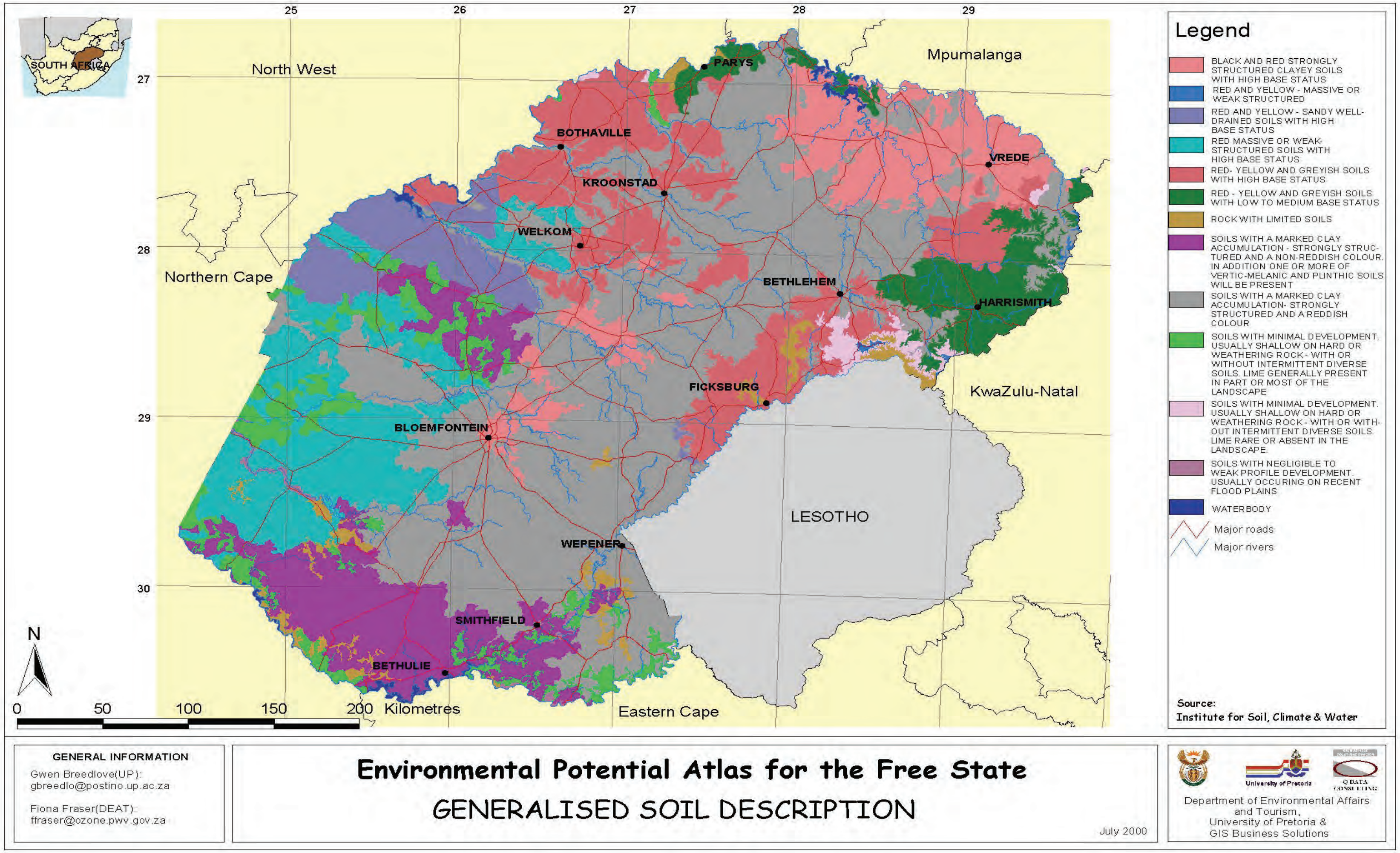
MAP 2: Terrain morphological units



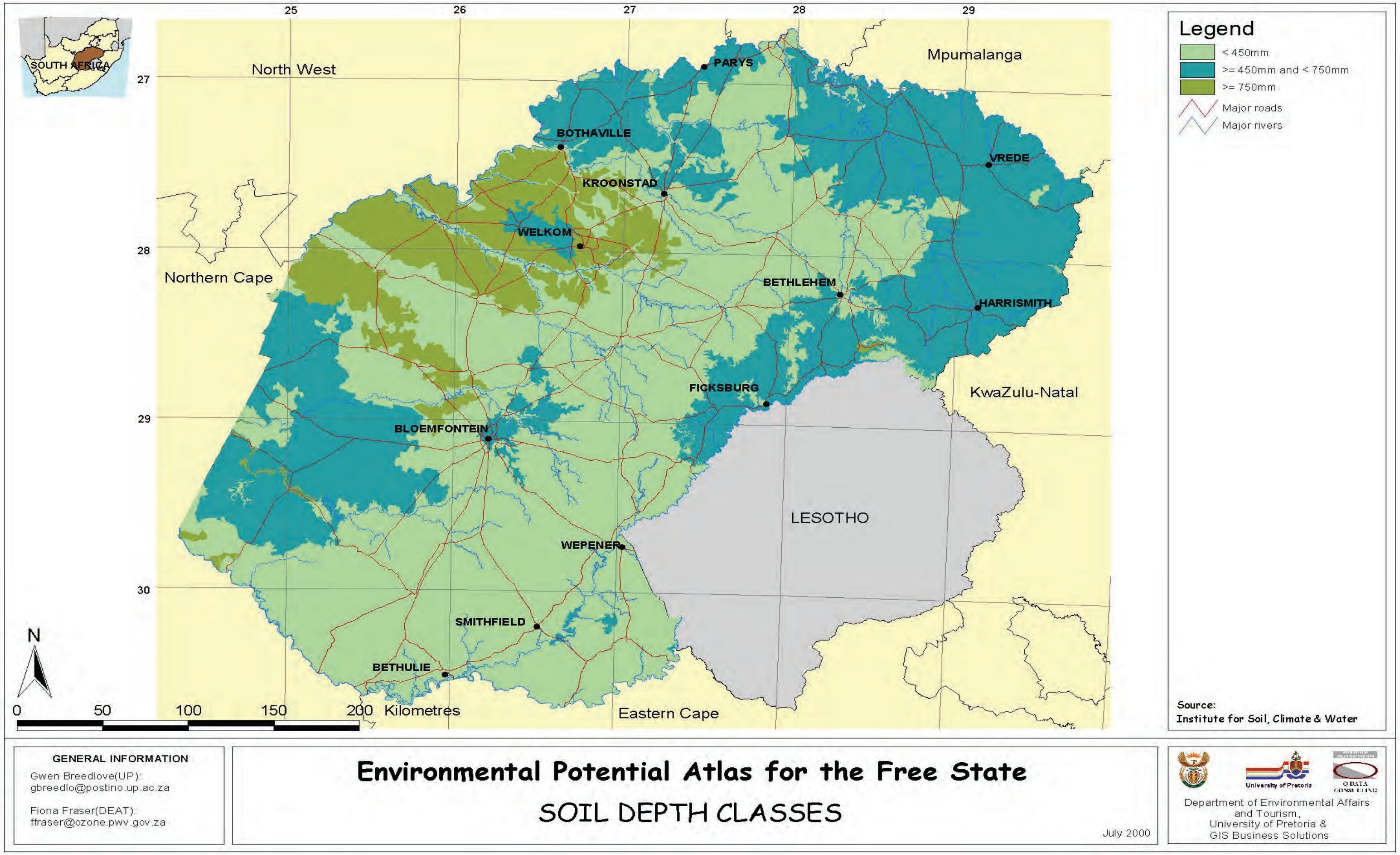
MAP 3: Geology



MAP 4: Land cover



MAP 5: Generalized soil description



MAP 6: Soil depth classes

APPENDIX C - HYDROLOGICAL DATA: MONTHLY PRECIPITATION RECORDS

DEWETSDORP

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1992	32	18	53.6	13.3	0	0	0	29.4	0	96.7	99.4	7
1993	56.3	112.5	46.3	34.2	15.5	2.5	0	26.7	0	118.4	93	37.1
1994	137.4	260.2	52.9	18	0	0.5	1.5	0	1	0.5	26.5	23.7
1995	118.7	14.6	132.7	17.3	0	1.6	0	0	14.3	48.2	59.6	241.2
1996	137.5	172.5	50.5	26	0	1.5	37.6	14	10.5	11.2	136.4	102
1997	66.1	41.8	128.7	31	27.8	29	14	7	8.5	18.7	55.8	23
1998	119.2	267.9	98.5	15.8	1	0	2.3	0	27	77.5	98.5	98
1999	78.3	52.8	47.6	50	0	8.5	0	0	0	0	0	191.2
2000	0	103.5	69.1	80	15.5	2.5	0	15	26	23.5	81.5	79
2001	46.5	76.5	122.5	152	42.7	14.3	0	21	18.5	79.5	213	123.5
2002	109	35.5	21.7	18	101.5	4	4	103.5	10.5	40.4	28.1	75
2003	83	31	127	18	20	0	0	9	25	15.5	53	58
2004	106.5	114.8	58.4	73.5	0	5.5	0	18.5	37.6	13.3	15.7	26
2005	88.5	60	40.5	57	29.5	10.5	0	1	0	92.5	83	43
2006	122.5	157.5	150.5	100	29.2	0	0	79.5	0	79	39.2	45.5
2007	81	39.5	93.1	39.5	3	22	2	13.5	51.5	22.5	74.6	92
2008	79.1	106.9	58.5	22.2	6.5	32	0	4.8	0	21.5	122.5	19
2009	81.2	123.6	15.5	25.7	10.5	21.5	15	0.5	0	140.5	16	27
2010	127.5	63	71.2	34	39.5	20	0	0	0	8.1	81.9	57.8
2011	31.4	49.2	16.5	69	37	75.5	7	0	0	12	42.9	118.5
Total	1701.7	1901.3	1455.3	894.5	379.2	251.4	83.4	343.4	230.4	919.5	1420.6	1487.5

FICKSBURG

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1992	26	62.1	25.2	11.7	0	0	0	87.5	0	31.5	160	33.2
1993	74.2	142	37.3	52.6	0.5	13	0	14.5	3	187	76.1	122.5
1994	90.6	125.7	62.3	60.9	0	0	0	0	4	24	29.5	107.4
1995	96.8	89.3	82.1	0	39	0	0	10	7	89.5	93	144.2
1996	173	133	41.4	75.7	54.8	0	20	16.7	32.7	94.5	157	114.4
1997	113.4	82.9	148.9	129.8	80.7	12.5	31	13.5	25	41	55.4	54
1998	210	97.9	68.5	8	0	0	3	0	20.8	83.8	175	96
1999	91.6	7.5	49.5	17.7	62.5	0	0	4	6	0	0	0
2000	112.1	76.9	140.3	45.5	28.3	0	0	0	47.4	111.6	20.7	151
2001	36.1	60	127.5	84.2	17.6	6.5	1	50.5	25.5	100.3	81.4	167.3
2002	153.5	115	80.3	48	75.1	20.5	0	89.8	49.7	58	43.4	167.7
2003	79	102.1	134.8	38.5	0	0	0	23.2	24	13.3	78	70.4
2004	116.7	71.1	193.3	19.8	0.5	18.5	8.5	25	33	30.2	22	66.8
2005	193.3	133.3	86.8	2.6	0	0	0	11.3	13	89.1	100.1	90.5
2006	236.5	208.3	99.7	77.2	33.5	0	0	109.9	0	86.5	165.9	105.5
2007	63	39.1	59	46.5	0.7	32.7	0	0	36	139.8	52	85.5
2008	139.8	64	86.2	14.5	46	39.9	0	3.7	0	34.2	179.3	91
2009	127	157.5	60.5	9	15.5	55	0	3.5	6.6	104	87.4	31
2010	195.1	65.5	89	67	22.5	9	0	0	0	42.7	204.8	251.1
2011	399.5	58.5	62	135.5	42.5	27.5	10.5	0	4.3	27	14	103
Total	2727.2	1891.7	1734.6	944.7	519.7	235.1	74	463.1	338	1388	1795	2052.5

CLOCOLAN

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2003	138.5	138.6	106.4	58	4	0	0	0	24.5	11.5	66.1	55.5
2004	79.5	92	116	35	0	12	4	14.5	34	44	20.5	115
2005	182.5	169	104	40	29	0	0	24	15	94	133.2	49
2006	229	175	82	49	35	0	0	80	3	83	121	122
2007	31	34.5	16.5	48	4	35	0	0	36	115	92	107
2008	140	60	88	30	55	33	0	10	0	11.5	154.5	61
2009	140	157	53	34	34	83	0	0	1	93	109	73
2010	226	80.5	90	55	7	3	0	0	0	30	137	219
2011	243	53	96	154	52	26	17	0	2	10	39	100
Total	1409.5	959.6	751.9	503	220	192	21	128.5	115.5	492	872.3	901.5

FOURIESBURG

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1992	48.7	35.1	51.2	27.9	0	0	0	79.2	0.4	49.9	198.3	106
1993	95.4	138.9	54.6	49.3	4.7	3.6	0	18.5	12	163	42.7	91.3
1994	146.1	67.4	83.3	66.2	13.5	0	7.5	13.2	14	30.3	31.5	80.7
1995	37.3	78	126.7	19.2	26.5	0.3	0	15.9	19	84.2	112.4	103
1996	119	127.4	65	68.5	26.6	0	57.2	18.3	22.2	135.5	173.2	97.2
1997	105	64.8	145.6	98.7	85	36	30.5	5.4	28	43	71.5	86.6
1998	147.9	164.3	126	33.2	5	0.1	0	20.5	12	34.5	252.4	87.6
1999	118	48	87.6	21	31	0	2.5	0	6.5	79.5	76	0
2000	0	0	0	0	0	0	0	0	0	0	0	0
2001	0	0	0	644	14.5	0	0	65	22.8	124	156	78
2002	167.9	0	51.5	20	32.5	32.5	0	100	37	39.5	22.3	158.5
2003	40.6	186	34.5	45.5	0	1.5	0	17.5	26.5	23.5	108.3	66
2004	112	85.5	182.8	19.5	0	21	0	25.5	18.5	45.5	45.5	92
2005	186	63	98.2	20	23	0	0	12	24	168	145	20
2006	234	120	57	13	39	0	0	114	2	37	122.5	139.5
2007	117	25	54	51	5	29.5	0	0.4	38.5	362	20	100.3
2008	286.5	0	0	0	0	0	0	0	0	14	173.3	112.6
2009	145.5	140.5	69.5	0	28	0	0	21	12.7	68.1	104.1	19
2010	299.8	56	111	72.7	10.4	16.9	0	0	0	29.5	93	100.5
2011	220.1	28.5	98.5	75	19.5	38	10.5	0	0	50	63.8	91.5
Total	2626.8	1428.4	1497	1344.7	364.2	179.4	108.2	526.4	296.1	1581	2011.8	1630.3

WEPENER

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1992	23	25.8	34	7.5	0	0	0	36	7.4	56	68.5	8
1993	51.4	86	52	37.9	6.6	4.5	0	41.6	6.5	110.8	75.5	80.5
1994	224.5	158.9	96	14.6	0.2	0.4	8	0.2	0	1	24.5	12
1995	102	10	134.8	9	28.4	1	0	0.5	16.5	51.5	68.5	135.3
1996	157.1	140.6	58.5	56.9	8.2	0	42.6	11	6.2	47.8	149.4	52
2000	114.6	45.4	88.2	55.4	17.8	3.8	0	0	42.2	33.2	63.6	69
2001	26.4	82.8	78.6	139.6	27	28.4	1	25.2	15.6	67.4	167.7	89
2002	114	30.4	41.2	25.2	72.6	4.8	0	91	22.4	12.4	11.8	59.2
2003	51.4	29.6	86	10.8	13.8	0	0.7	8.8	12	2.6	34.6	63.2
2004	32.8	63	82	0	0.4	0	0	0	0	0.4	0.8	0.4
2005	1	1.8	66.4	38.2	33	11.2	1.4	27	7	62.6	74	11.8
2006	250.6	345.4	162.6	139.4	27.8	0	6.6	65.6	5.2	72.8	124.2	76.2
2007	25	17.4	40.8	72.8	11.4	17.6	1.4	9.8	41.8	36.2	35.4	108.6
2008	131	54	0.6	35.8	14.4	44.6	4	6.8	13	8.4	83.8	68.2
2009	74.2	208.2	10.2	47.8	24.2	36.4	24.2	2.4	0.6	232	23	40.4
2010	257.8	43.8	103.6	65.8	17.8	35.6	0	0	5	68	47.6	116
2011	36.8	110.2	190.8	62.4	33.2	89.8	20.6	0	0.8	66	22.8	97
Total	1673.6	1453.3	1326.3	819.1	336.8	278.1	110.5	325.9	202.2	929.1	1075.7	1086.8

BLOEMFONTEIN

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1993	46.1	43.8	72.8	30.2	7.2	1.4	0	27.7	0	179.6	39	28.1
1994	159.7	168.5	95.6	8.2	0	0.8	1.1	0	0.2	0.4	34.4	18.9
1995	101.9	27.8	77.2	24.2	37.5	0.5	0.1	3.1	7.6	77.3	83.1	145.5
1996	123.2	125	33.5	60.3	0.4	0	33	2.9	19.7	26.8	156	163
1997	88.3	23.9	102.6	35	30.9	18.3	16.6	5.3	14.1	20	18.1	34.4
1998	220.6	172.8	114.5	11.5	2.3	0	5.2	0	21.8	80.4	67.2	43.9
1999	74.3	33.9	25.6	25.8	57.9	0.5	2.6	0.5	0.4	87.1	35	138.1
2000	143	60.4	127	50.5	10.4	2.3	4.1	1	44.3	34.2	77.2	90
2001	16.2	130.4	95.8	109.7	24.8	28.6	0.5	15.9	37.4	45.7	161.1	97.9
2002	112.9	62.5	33.3	41.1	71.8	4.8	0	94.3	9.4	18.6	23.5	76.4
2003	41.5	68.3	147	9.4	13.6	0	0	4.6	20.3	16.2	42.8	45.2
2004	49.2	47.6	151.5	36.9	0	4.4	0	12.4	36.5	10.2	18.5	69.2
2005	94	60.3	41	78.4	24.9	5.6	0	1.6	9	52.1	55.5	12
2006	155.5	147.1	134.7	64.2	10.7	0	0.6	69.1	0.7	30.2	112.4	133.4
2007	67	5.6	32.6	45.3	0.5	23.6	0	0.8	38.8	52.3	83.9	46
2008	45.2	39.7	106.4	17.1	52.3	30.9	0	4.6	0	13.2	144	28.6
2009	108.6	109.3	19.3	7.9	25	28.7	13	2	7.2	98.6	87.5	94
2010	190.2	154.3	68.3	121.8	24.1	8.4	0	0	0	29.5	97.1	89.4
2011	201.2	102.4	71.6	84.8	68	92.8	9	0.6	2	9.6	1.0=	
Total	2038.6	1583.6	1550.3	862.3	462.3	251.6	85.8	246.4	269.4	882	1336.3	1354

CLARENS

Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1992	36	44	33.5	25.6	0	0	0	67.7	10	130	232.9	50
1993	57.5	170.5	20.6	13	13	9	0	15.5	17.5	158	28	92
1994	166	109	58	65	0	0	27	0	0.3	25	58	58.1
1995	31	28	73	0	0	0	0	9.3	18.4	81.6	98.4	115.7
1996	135	136.9	105	108.5	35.8	0	52	28	42.5	103.2	130	81.5
1997	88.6	24	146.2	69.4	95	24.5	37.5	4.5	49	62.1	53.5	82
1998	252.8	91.2	114.8	31.2	0	0	1	0	21.5	52.6	248.1	108.5
1999	62.5	96.1	53	40	13.5	0	0	0	0	0	0	0
2000	168	118	125.5	57	75.9	0	0	0	37.9	156	108.5	168.5
2001	62.1	95.1	99.5	36.5	36	2	0	81	43.5	139	92.5	128.5
2002	199	31	54	28	63	50.5	0	99	46.8	57.5	17.5	167
2003	73	192.4	72.2	23.5	10	4.5	0	10.5	15	21	140	66
2004	81	54.3	122.9	21	0	31.5	7.5	16	10.7	26.5	62	107
2005	183.6	27.5	78.2	36.6	11.2	0	0	11.2	22	69.2	118.7	17
2006	180.8	115.2	37	20	10	0	0	64	4.5	62.5	96.5	162.5
2007	31	37	14.5	31.5	18	21	0	0	50	66.4	51	
2008			63	7	37	0	0	2.5	0	22	167.5	97.1
2009	96	120.9	101	10	15	40.8	0	42	12.3	81.5	119.5	42
2010	163	27.6	89	65.5	11	4	0	0	0	0		162.5
2011	107	29	3	155.7	26.5	26	13	1	1.5	40.4	19	78
TOTAL	**2173.9**	**1547.7**	**1463.9**	**845**	**470.9**	**213.8**	**138**	**452.2**	**403.4**	**1354.5**	**1841.6**	**1783.9**

EXCELLESIOR

Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1984	136.5	12.5	61	36.5	56	0	0.6	26.5	3.5	53.7	23.6	47
1985	63.4	97.9	45	25	0	27	0	0	0	99.6	45.2	118.2
1986	17	31	43	55.5	15.5	18.5	0	36	13	119.8	110.5	23
1987	53	96	28.5	82	0	0	16	34	159	10	114	54
1988	53.5	277	109	113	0	32	0	10	38	112	53	39
1989	142	175	51	15	38	13	0	7	0	32	129	33
1990	114	99	71	115	14	26	4	24	0	13	4	51
1991	172	140	147	0	0	12.5	0	0	58	117	44.5	69.5
1992	6	18	10	10	0	0	0	35	0	45	125	11
1993	43	81	99	25	15	1.5	0	14.5	0	150	47.8	41
1994	77.5	120.5	84.5	12.5	0	0	0	0	0	18	33	64
1995	56.5	15.5	134.5	7.5	46	2	0	0	5	59	60	145
1996	72	202.5	65	83	28.5	0	30	14	11.5	61.9	99	94
1997	80	18	83.5	63.3	49	0	20	11	10	32	54	109
1998	51	102	181	0	0	0	0	0	16	93	75	29
1999	95.5	45	59	3	58	0	0	0	0	0	6	139
2000	28.1	17.5	67	13.5	50	5.5	0	0	70	4.8	142	80.8
2001	47	98	89	67	38.5	10	0	10	3.5	61.2	215	169
2002	85	26	25	38.2	58	18	0	63	20	24.5	11	112.2
2003	0	42	88	30	34.3	0	0	0	0	0	20	24.4
2004	0	0	14	21	0	0	0	22	23	0	0	0
TOTAL	**1393**	**1714.4**	**1555**	**816**	**500.8**	**166**	**70.6**	**307**	**430.5**	**1106.5**	**1411.6**	**1453.1**

THABA PATCHEO

Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1982	0	41.9	46.8	131.5	0	21.8	30.4	0	31	62.9	144.4	52.5
1983	2	49.6	13.2	0	23.7	15.3	32.5	0	6.1	34	92	0
1984	94.7	23.7	47.1	23.2	51.6	0	0	27.8	1.5	41.2	54.2	0
1985	79.1	78.7	26	0	0	56	0	0	0	91.1	66.3	85
1986	44	9	99.5	12.2	0	22.5	0	40	16	89.9	95.9	0
1987	0	76.1	58.1	75	0	0	0	49	176.9	13.2	97.5	68.7
1988	62	303.4	71.5	99	0	22.5	0	0	41.5	84	45.6	78.3
1989	49.4	46.5	111	31	16	18	18	0	0	10	75.4	22.5
1990	45.3	77.3	117.1	129	0	32	0	6.3	0	0	0	21.3
1991	143.1	92.9	0	0	0	0	1.5		0	111	35	62.5
1992	0	0	32	0	0	0	0	0	0	45.3	101.9	0
1993	55.7	41	70.7	54.1	2.5	1.7	0	32.1	8.5	148.9	57.5	17.6
1994	163.2	221	59.6	14.5	0	0	0	0	0	0	35.1	9.9
1995	80.5	67	98	0	40.5	0	0	0	3.5	97	93.7	99.5
1996	154	151.7	80	69	0	0	31	0	0	16.4	86.7	9.1
1997	26.5	23	132.7	13	31	0	19.5	0	0	28	18	4.4
1998	12	215	157	13	0	0	0	0	0	85.2	0	113
1999	0	0	0	0	0	0	0	0	0	87.5	21.5	88
2000	78	0	103	19	0	0	0	0	53	0	0	0
2001	0	0	43.3	152.5	0	0	0	40.8	0	95.5	144	118
2002	96	37	0			23.1	15	50	142	22.4	0	
TOTAL	1185.5	1554.8	1366.6	836	165.3	212.9	147.9	246	480	1163.5	1264.7	850.3

THABA NCHU

Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1992	32.9	133.9	21.3	21.5	0	0	2	21.2	0	39.5	106.6	25.2
1993	47.2	74.7	109.9	45.6	10.8	3	0	19	0	169.1	80.2	40.8
1994	180.2	135.5	76.6	13.6	0	1.1	5.1	0	0	1.5	53	42.6
1995	131.8	57.9	100.2	13.3	62.5	0.1	0	4.8	5.3	63.9	87.7	117.8
1996	100.5	215.3	34.4	68.4	9.5	0	40.5	7.8	14.5	64	158.5	142.5
1997	109.7	32	153	52.1	45.3	8	22.5	17	3.4	24.8	19	34.5
1998	165.4	112.4	159.9	12.8	0	0	7.6	0	30	94.5	125	138.7
1999	83.5	56	42.5	14.8	0	0	0	0	0	0	0	236.7
2000	90	68.9	98	53.5	55	0	2	0	54.5	33.5	117	104.6
2001	76.4	70.5	101.5	190.5	49.8	32	7	22.5	29.5	63	187.2	193.0
2002	182.5	76.8	49	35.5	81.5	4.5	0	86.2	49.5	38.5	19.5	65.5
2003	111.2	94.2	106.5	5.5	7	0	0	6.5	11	14.5	36.5	40.5
2004	126.8	106	85.6	30.1	0	7	0	5	37	15	60	68.5
2005	97	130.2	83.4	82.9	23.1	22	0	6	14	125.5	74.2	19.4
2006	318.4	214.5	137.5	76	25	0	0	97	0	57.5	229.5	63.5
2007	56.8	18.3	20	47.7	3.4	31.6	0	2.5	51.5	98	88.5	104
2008	65.5	127.3	81.5	17	46	34	0	3	0	10.5	166	51.7
2009	96.3	149	19.8	28.5	9.5	31.5	13	5.5	4	122.3	95.2	54
2010	164	114.7	59	100.5	35.5	23	0	0	0	51	41.5	104
2011	284	87	39	119.5	74	60.5	13.5	13.5	0	22	19.4	120.5
Total	2520.1	2075.1	1578.6	838.8	537.9	258.3	113.2	317.5	304.2	1108.6	1764.5	1432.5