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LOCATIONAL MODEL FOR POTENTIAL STORAGE DAM SITE: A KNOWLEDGE-BASED GEOGRAPHIC INFORMATION SYSTEM-APPROACH

by

MING-JANG LIN

THESIS

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SUMMARY

This study is an attempt to do integrated multidisciplinary research about the selection of a dam site/size/type, culminating in a locational model. In order to achieve this aim a knowledge-based geographic information system was developed, which is dependent on human knowledge and input (i.e. the locational model) to solve the problem (the selection and evaluation of a dam site/size/type) for the analyst/decision-maker. This study is also an effort to transfer the models (mankind's knowledge) to computer and automatize the dam site/size/type selection procedures by means of modern computer techniques. The developed Storage Dam Site Selection (SDSS) model can thus be used to incorporate GIS and act as an assistant for analysts and decision makers. The main objectives of this research are as follows:

(i) To develop a locational model for dam site selection at the reconnaissance stage.
(ii) To develop a Geographic Information System (GIS) for the study area.
(iii) To automatize the locational model and implement it in the GIS in order to evaluate potential dam sites in the study area.

The SDSS-model only considers the physical environment factors. The social, economical and ecological factors were not considered due to time and cost constraints on the scope of the study. Also, the SDSS-model is designed for the reconnaissance (first) stage of the planning which assists the analysts/decision-makers in quickly finding and evaluating the locations of potential dam site alternatives. The SDSS-model does not offer the final solution.

The SDSS-model is based on a raster data format to represent spatial phenomena and relationships because of the relatively simple data structure. The pixel size was set at 50 x 50 m owing to the limitation of memory space and speed of the PC/AT-computer used in this study. The SDSS-model is designed as a step-by-step procedure to perform the dam site/size/type selection. The procedure for the SDSS-model is as follows:

(i) Construct DEM.
(ii) Automatically determine the river catchment boundary and the impounded area of the potential reservoir when at full capacity.
(iii) Calculate the area-height-volume relationship at the potential dam site.
(iv) Estimate the areal rainfall from the precipitation records in the study area.
(v) Calculate the Hurst phenomenon index and the stationarity of precipitation records in the study area.
(vi) Select a suitable hydrological model to generate stochastic series of areal rainfall for further stochastic analysis.
(vii) Calculate the relationship between respectively areal rainfall and streamflow, streamflow and sedimentation, as well as pan evaporation records and reservoir evaporation.
(viii) Implement the reservoir yield risk analysis which is based on a stochastic analysis.
(ix) Implement a simulated flood routing through the reservoir.
(x) Perform land evaluation within the impounded area of the potential reservoir which includes up-to-date land use/cover information, land capability classification and land suitability evaluation.
(xi) Find the scope, location and type of mining activities within the
impounded area of the reservoir at full capacity.
(xii) Perform a topographic suitability analysis for the potential dam site.
(xiii) Compute the transportation distance for the construction material from existing quarries and/or material suppliers to the potential dam site.
(xiv) Locate possible local construction material borrow areas.
(xv) Calculate the peak horizontal ground motion according to the specified operating basis earthquake.
(xvi) Roughly estimate the possibility of reservoir induced earthquakes.
(xvii) Estimate the permeability of the bedrock of the potential.
(xviii) Calculate the presumed safe bearing capacity of the potential dam foundation.
(xix) Analyse the rock and soil slope stability around the rim of the potential reservoir.
(xx) Generate computer simulation imagery at the potential dam site.
(xxi) Report on the results of the foregoing outlined steps.

The following are the final conclusions about this study:

(i) The selection and evaluation of a dam site/size/type is a multidisciplinary task and need an integrated research effort between the relevant disciplines.

(ii) A KBGIS is a competent tool to implement integrated research and to enable the handling of various sets of geographical/spatial data.

(iii) Stochastic models can incorporate more types of variables than deterministic models, and are more flexible and less complex.

(iv) The Hurst phenomenon (long term persistence) may possibly exist in the study area while the AutoRegression Moving Average (ARMA) model proved to be suitable for the area.

(v) The Muskingum routing method is an easy and practical method and can be implemented on computer.

(vi) The 'soil and land capability classification for agriculture' which was developed by the Soil and Irrigation Research Institution is a simple and properly defined method. It proved to be also good for the soil surveying and easy to implement on computer.

(vii) Field survey at the potential dam site is very important in order to evaluate the engineering geological conditions.

(viii) The topography at the dam site and the availability of construction materials in the vicinity strongly affect the building costs of a dam and proved to be the main factor for selecting the dam type. An economical model should be incorporated in the future.

(ix) Ground motions could possibly damage the dam structure and should be carefully evaluated, even in South Africa which is relatively earthquake free.

(x) Reservoir induced earthquakes have been reported in South Africa, although it was not serious. The tectonic study at a dam site is necessary for evaluating the safety of a dam.
(xi) The grid-type DEM proved to be successful for complicated geographical/spatial analyses, especially because of its ease of manipulation, compatibility with other raster type data (e.g. satellite information, etc.).

(xii) The catchment boundary detection algorithm could be applied in other regions but is not suitable for topographically flat areas like plains.

(xiii) Remotely sensed imagery with its associated image processing possibilities like automatic classification methods can be used to update the land cover information.

(xiv) Pattern recognition techniques are useful for detecting break points and potential sliding mass movements on slopes as well as identifying potential rock/soil borrow areas.
OPSOMMING:

Hierdie studie is 'n poging om geïntegreerde, multidissiplinêre navorsing oor die keuse van 'n dam se ligging/grootte/tipe te doen, wat sy hoogtepunt in 'n liggingsmodel bereik. In 'n poging om hierdie doel te bereik, is 'n kennisgebaseerde geografiese inligtingstelsel (KGGIS) ontwikkel (KGGIS: 'n GIS gebaseer op die beginsels van kunsmatige intelligensie en datastrukture), wat afhanklik is van menslike kennis en invoer (d.i. die liggingsmodel) om die probleem (die keuse en evaluering van 'n dam se ligging/grootte/tipe) vir die analis/besluitnemer op te los.

Hierdie studie is ook 'n poging om die modelle (menslike kennis) na die rekenaar oor te dra en die kiesprosedure vir die dam se ligging/grootte/tipe te automatiseer, deur middel van moderne rekenaarsteun. Die ontwikkelde Dam-Berging-Ligging-Keusemodel (DBLK) kan dus gebruik word om GIS daarby in te skakel en te dien as 'n hulp vir analiste en besluitnemers.

Die hoof doelwitte van die navorsing is die volgende:

(1) Om 'n liggingsmodel te ontwikkel vir die dam se liggingskeuse tydens die verkenningstadium.

(ii) Om 'n Geografiese Inligtingstelsel (GIS) vir die studiegebied te ontwikkel.

(iii) Om die liggingsmodel te automatiseer en dit in die GIS te implementeer, om sodoende die moontlike (potensieë) damliggings in die studiegebied te evaluer.

Die DBLK-model neem slegs die fisiese omgewingsfaktore in aanmerking. Die sosiale, ekonomiese en ekologiese faktore is nie in aanmerking geneem nie as gevolg van tyd- en kostebeperkings op die omvang van die studie. Die DBLK-model is ook ontwerp vir die verkenningstadium (eerste) van die beplanning, wat die analis/besluitnemers bystaan om die liggings, van moontlike alternatiewe damliggings, vinnig te vind en te evaluer. Die DBLK-model verskaf nie die finale oplossing nie.

Die DBLK-model is op 'n rooster dataformaat gebaseer om die ruimtelike verskynsels en verwantskappe voor te stel, as gevolg van die relatiewe eenvoudige datastruktuur. Die piksel grootte is op 50 x 50 m gestel weens die beperkte geheuespasie en spoed van die persoonlike rekenaar (PR) wat in hierdie studie gebruik is. Die DBLK-model is as 'n stap-vir-stap prosedure ontwerp om die keuse van die dam se ligging/grootte/tipe uit te voer.

Die procedure vir die DBLK-model is die volgende:
(i) Ontwikkel die Syfer-Hoogtemodel (SHM) (Hoogtemodel: hoek tussen die horisontaal en 'n punt op 'n hoër vlak).

(ii) Bepaal automaties die grense van die rivier se opvanggebied en die ingeslote oppervlakte van die moontlike opgaarplek, tydens die bereiking van sy volle kapasiteit.

(iii) Bereken die oppervlakte-hoogte-volumeverwantskap by die moontlike (potensiele) damligging.

(iv) Skat die ruimtelike reënval vanaf die neerslagrekords in die studiegebied.

(v) Bereken die Hurst-verskynselsindeks en die gereeldheid van neerslagrekords in die studiegebied.

(vi) Kies 'n geskikte hidrologiese model om die stogastiese reeksse van die ruimtelike reënval te ontwikkel vir verdere stogastiese analyse.

(vii) Bereken die verwantskap tussen onderskeidelik ruimtelike reënval en stroomvloei, stroomvlloei en sedimentasie, sowel as panverdampingsrekords en die opgaarplek se verdamping.

(viii) Die inwerkingstelling van die opgaarplek se opbrengs-risiko-analise wat op 'n stogastiese analise gebaseer is.

(ix) Die inwerkingstelling van 'n nabootsende (gesimuleerde) vloeiroetebeheer deur die opgaarplek.

(x) Die uitvoering van die grond se waardebepaling (evaluasie) binne die omsluite gebied van die moontlike opgaarplek, wat die huidige inligting oor grondgebruik/-bedekking, die klasifikasie van die grondvermoë en die waardebepaling van die grond se geskiktheid, insluit.

(xi) Vind die omvang, ligging en tipe mynbedrywighede binne die omsluite gebied van die opgaarplek, tydens die bereiking van sy volle kapasiteit.

(xii) Voer 'n analyse uit vir die topografiese geskiktheid van die moontlike damligging.

(xiii) Bereken die vervoerafstand van die boumateriaal (konstruksiemateriaal) vanaf bestaande steengroewe en/of boustofferskaffers na die moontlike dam se ligging.

(xiv) Wys moontlike plaaslike gebiede aan, waarvandaan boumateriaal ontleen kan word.

(xv) Bereken die uiterste van die horisontale
grondbeweging volgens die gespesifiseerde basisaardbeweg wat aan die gang is.

(xvi) Skat rofweg die moontlikheid van aardbewings wat die opgaarplek kan beinvloed.

(xvii) Skat die deurdringbaarheid van die rotsbodem (vaste gesteente) van die moontlike damligging.

(xviii) Bereken die veronderstelde drakapasiteit van die moontlike damfondament (drakapasiteit: die gemiddelde vrag per eenheid oppervlakte voordat 'n ondersteunde grondmassa breek (kg/m²)).

(xix) Analiseer die rots en grond se hangstabiliteit rondom die rand van die moontlike opgaarplek.

(xx) Ontwikkel met behulp van die rekenaar 'n nabootsende afbeelding van die moontlike (potensiele) damligging.

(XXI) Doe verslag oor die resultate van die stappe wat kortliks beskryf is in die voorafgaande.

Die euteindelike gevolgtrekkings van hierdie studie, is die volgende:

(i) Die keuse en waardebepaling (evaluasie) van 'n dam se ligging/grootte/tipe is 'n multidissiplinêre taak en benodig 'n geïntegreerde navorsingspoging tussen die toepaslike dissiplines.

(ii) 'n KGIS is 'n geskikte hulpmiddel om geïntegreerde navorsing inwerking te stel en om die hantering van verskillende stelle geografiese/ruimtelike data moontlik te maak.

(iii) By stogastiese modelle kan meer tipes veranderlikes ingeskakel word, as wat die geval is by deterministiese modelle en dit is ook meer buigbaar en minder ingewikkeld.

(iv) Die Hurst-verskynsel (langtermyn voorkoms) mag moontlik in die studiegebied bestaan, terwyl die Outoregressie-bewegende-gemiddeldmodel (ORBG) bewys gelewer het om geskik te wees vir die gebied.

(v) Die Muskingum-rootebeheermetode is 'n maklike en praktiese methode en kan op rekenaar uitgevoer word.

(vi) Die klassifikasie van die grond en grondvermoë vir die landbou, wat deur die Navorsingsinstituut vir Grond en Besproeiing ontwikkel is, is 'n eenvoudige en behoorlik gedefinieerde metode. Dit het ook bewys dat dit goed is vir grondopmeting en maklik op die rekenaar uitgevoer kan word.

(vii) Veldwerk by die moontlike damligging is baie belangrik
om die ingenieursgeologiese toestande te evalueer.

(viii) Die topografie by die damligging en die beskikbaarheid van boumateriaal in die omgewing, is 'n sterk beinvloedende faktor op die boukoste van die dam - dit lewer bewys om die hoof faktor vir die keuse van die damtype te wees. 'n Ekonomiese model moet in die toekoms ingeskakel word.

(ix) Grondbewegings kan moontlik die damstuktur beskadig en moet versigtig geëvalueer word, selfs in Suid-Afrika wat betreklik vry van aardbewings is.

(x) Aardbewings wat die opgaarplek kan beinvloed is reeds in Suid-Afrika aangemeld, alhoewel dit nie ernstig was nie. Die tektoniese studie by 'n damligging is noodsaklik vir die evaluering van die veiligheid van 'n dam.

(xi) Die ruittipe/roostertipe SHM het bewys gelewer dat dit suksesvol is vir ingewikkelde geografiese/ruimtelike analisies, as gevolg van sy gemaklike bewerking en aanpasbaarheid met ander roostertipe data (bv. satellietinligting, ens.).

(xii) Die opsporingsalgoritme vir die opvanggebied se grens kon in ander gebiede toegepas word, maar is nie geskik vir topografiese plat/gelyk gebiede soos vlaktes nie.

(xiii) Afstandswaargeneemde beelde met hulle geassosieerde beeldverwerkingsmoontlikhede, soos automatiese klassifikasieometodes, kan gebruik word om die inligting oor die grondbedekking tot op datum te bring.

(xiv) Patroonherkenningstegnieke is nuttig vir die opsporing van breekpunte en die moontlike massa skuifbewegings op hange, sowel as vir die aanwyse van moontlike rots/grond ontléningsgebiede.
Chapter 1 Introduction and statement of the problem

1.1 Introduction

1.1.1 Background

This study is a consequence of two visits by the promoter to the National Taiwan University in Taipei during 1983 and 1988 respectively. The visits were sponsored by the Council for Scientific and Industrial Research of South Africa and the National Science Council of the Republic of China. Thereafter the Foundation for Research Development awarded a grant to the author for the Ph.D-study in Geography at the Rand Afrikaans University (R.A.U.). The R.A.U. also awarded a grant to the author while the Department of Water Affairs and Forestry kindly put their considerable GIS-facilities at his disposal.

1.1.2 The context of this study in the field of geography

This study is an attempt to do integrated multidisciplinary research about the selection of a dam site/size/type, culminating in a locational model. In order to achieve this aim a knowledge-based geographic information system was developed, which is dependent on human knowledge and input (i.e. the locational model) to solve the problem (the selection and evaluation of a dam site/size/type) for the analyst/decision-maker.

The selection and evaluation of a dam site/size/type is a multi-disciplinary task, including inter alia the disciplines of hydrology, civil engineering, geology, soil science, hydraulics, regional planning, seismology and geography. The selection factors are as follows [68]:

(i) Project function(s).
(ii) Physical factors.
(iii) Economic factors.
(iv) Environmental considerations.
(v) Social considerations.

The geographer is mainly involved in the environmental considerations and/or social considerations, evaluating the environmental impacts and changes after building a dam, and is seldom involved in the site or size selection task. From the author's personal viewpoint, geography is a management science dealing with the earth's environment. The geographer should thus be able to manipulate and analyse large volumes of spatial data in order to make optimal decisions. The geographer should be involved in the site or size selection task, e.g., as in dam site and size selection. The task of the geographer is to manage, analyse and synthesise relevant data with the aid of modern GIS-technology in locating the "best" dam site which is the least harmful to the environment but the most economical for the society.

A complete discussion of dam site/size/type selection is given by Golzé [68]. Most of the issues concerned are discussed in detail, including hydrological studies, geological & foundation investigations, earthquake hazards, materials suitable for construction, selection of the type of dam and design of dams and reservoirs. The rest of the literature quoted, only deals with one or some of the issues of dam site/size/type selection. These issues and references are as follows,
depending on the relevant dam issue(s) concerned:

(i) Hydrology:

The techniques for establishing the relationship between reservoir capacity and yield can be classified into the following three main categories (126):

a. Critical period techniques, "in which storage size is determined from a sequence (or sequences) of flows during which demand exceeds inflow to storage." (126). The methods in this category are deterministic.

b. Probability matrix methods, in which an integral equation is used for relating inflow to reservoir capacity and releases. The probable state of the reservoir contents at any time can be defined by the integral equation. The probability density function (p.d.f.) for generating a random process is a little too simple; besides the serial correlation is set to zero which is impractical for most of the Southern African subcontinent.

c. Stochastically generated streamflow, in which a stochastic model is used to generate streamflow sequences which have the same statistical properties as those of the historical record. Each of the generated sequences is used to assess the performance of the specified reservoir capacity, thus providing the user with a statistical result for the designed reservoir capacity.

The selection of proper models for research depends mainly on the aim of the research and the nature of the study area. In general, the stochastic models can incorporate more detail than deterministic models, and are more flexible and less complex than deterministic models. On the other hand, deterministic models can be used to find optimal solutions while the stochastic models can only be used to reach approximate solutions.

The National Research Institute for Mathematical Sciences of the CSIR and the Department of Environment Affairs have developed three methods for reservoir yield risk analysis (172), i.e. a variable draft method, a deterministic dynamic programming method and a stochastic dynamic programming method. The variable draft method specifies the water release policy followed during recent historic (observed) inflows and therefore assesses the performance of the specified water release policy, and thereafter employs a trial and error approach. The philosophy of this method is that the best prediction for future inflows is simply a continuation of the sequence observed in the past. The deterministic dynamic programming method is based on the mass balance equation and dynamic programming (in Operations Research), and uses iterative algorithms to find optimal solutions. The stochastic dynamic programming method is based on a probability distribution function (p.d.f.) of historic inflows. A computer-based simulation method is used to generate the random variable for the p.d.f. of historic inflows in order to assess the yield risk of a reservoir by means of the dynamic programming method. These methods are flexible. Unfortunately they cannot be used to deal with the streamflow sequences which have a long-term persistence. Some other methods which were listed in Stephenson and James (177) including the mass flow method, draft-frequency analysis, analytical and synthetic flow records method,
matrix method and queuing theory. These methods cannot be used to process a time series involving long-term persistence either.

When a persistent trend is present in the time series, the synthetic sequences cannot be constructed by sampling values from a probability distribution, because the relationship between each member and its successor in the sequence will not be taken into account. Thus, the AutoRegressive Moving Average (ARMA) model was used for generating sequences when persistence is present. References to this topic can be found in Herald [82], Clarke [39], Bras & Rodriguez-Iturbe [25], Ciriani, Maione & Wallis [53], Haan [75], Lihnart & Zucchini [111], Shaw [164] and Linsley, Kohler & Paulhus [113].

There are two methods for determining flood peak through a reservoir or a natural channel, i.e., a hydraulic and hydrological method respectively [11]. The former is based on the solution of the differential equations of unsteady flow, i.e., the St. Venant equations. This method is quite complex and needs a detailed knowledge of the channel geometry and roughness [11]. In addition to the fact that the channel geometry and roughness may change during the passage of the flood wave, the hydraulic method can be warranted only if all the necessary requirements are reasonably well met [11]. The hydrological method is based on a functional relationship between channel storage and discharge which is developed from observed hydrographs. Knowledge of the channel geometry is not involved in this method [11]. The Muskingum routing method is a widely applied hydrological method because of considerations such as ease of calculation and relatively few parameters necessary in order to do estimations. References about this method can be found in Bauer & Midgley [12], Bauer [11], Op ten Noort & Stephenson [141], Lambourne & Stephenson [107], Kovacs [104] and the HRU report No. 1/72 [50].

Once the inflow to the reservoir is determined by the Muskingum routing method, the outflow from the reservoir can then be calculated by empirically based formulae for the discharge over spillways. The formulae are discussed by e.g., Chow [37], Cassidy & Elder [33], Henderson-Sellers [81].

(ii) Land evaluation:

A land capability classification was developed by the United States Department of Agriculture (USDA) in the early 1960s for evaluating the potential of the land for usage in specified ways. Later on it was adapted and widely applied in other countries [49]. Land suitability evaluation was developed in the 1970's by the Food and Agriculture Organization (FAO) for evaluating specific crops and land utilisation types [49]. "This system differs from that of the USDA in that suitability is not general purpose but is related to a specific form of land use." [64]. The standard land evaluation method for the whole of South Africa is not established yet. The methods applied in this research were adapted from the 'soil and land capability classification for agriculture' which was developed by the Soil and Irrigation Research Institution [160]. Discussion about land capability classification and land suitability evaluation can be found in Dent & Young [49], Vink [196], Simpson [166], Davidson [48], FitzPatrick [64], Jarvis [97], Mather [121] and Olson [140].

(iii) Topography:
The topography of a dam site affects the construction costs of a dam. The construction costs of different types of dams at the same site are usually not the same, hence the dam type with the lowest cost will usually be chosen. There are no strict rules regarding dam types for different topographical features. A brief discussion about this topic can be found in Armstrong [4] and Attewell & Farmer [7].

(iv) Construction Materials:

The most economical type of dam is often the one for which the construction materials can be found in sufficient quantities within a reasonable distance from the site [4]. There is usually no way to locate the materials from maps only. Field survey is therefore essential in this regard. During the reconnaissance stage it is only possible to locate the potential source of materials from the topography-soil relationships (catena) by means of pattern recognition methods. The discussion about suitable materials for dams can be found in the text books on soil/rock mechanics or other dam/civil engineering, e.g., Harboe & Kramer [77], Armstrong [4], Whitlow [206], Attewell & Farmer [7], Bell [14], Bell [15], Goodman [70], Sowers [173], Duncan [55], Zaruba & Mencel [212], Bell [13] and Lo & Cheng [115].

Unfortunately, the topography-soil relationships for engineering purposes have not been established yet. A brief discussion about this topic can be found in Harboe & Kramer [77]. References regarding catena for soil science can be found in Birkeland [18], Brady [22] and Singer & Munns [167].

(v) Seismology:

The seismic risk analysis for this research was based on the studies of Cornell [42] and Smith [170] for calculating the expected peak horizontal ground motions from the seismic records. Another aspect of the seismic risk analysis is the risk of Reservoir Induced Earthquake (RIE). Unfortunately the mechanism of RIE is still not clear. This research deals only superficially with RIE in accordance to guidelines of the United States Committee On Large Dams (USCOLD) [189], instead of estimating the risk of RIE. Relevant studies about RIE can be found in USCOLD [189], Chaplow [35], Dungar [56], Guha, Padale & Gosavi [74], Haws & Reilly [80], Long [117], Ries, Vaidya & Michalopoulos [153], Skipp & Higgins [168], Tosic [186], Willmore [209], Ambraseys & Jackson [3] and Wiegel [207].

(vi) Slopes and Foundation:

The empirical data for reservoir permeability and presumed bearing capacity analyses were adopted from Stagg & Zienkiewicz [176], Goodman [70], Lo & Cheng [115], Bell [14, 15], Spangler & Handy [174], Sowers [173] and Attewell & Farmer [7]. The parameters used in the slope stability analysis were adopted from Hoek & Bray [85], Goodman [70], Duncan [55], Bell [14, 15], Attewell & Farmer [7] and Lo & Cheng [115]. The methods for slope stability analysis including translational slides, rotational slips, plane failure and wedge failure, can be found in most of the soil/rock mechanics text books, e.g., Hoek & Bray [85], Whitlow [206], Goodman [70], Sowers [173], Smith [169], Stagg & Zienkiewicz [176], Bell [13], Bolton [21], Duncan [55], Atkinson [6],
Spangler & Handy [174], Attewell & Farmer [7], Zaruba & Mencl [212], Ramiah & Chickanagappa [151], Simmons & Menzies [165], Veder [195], Capper, Cassie & Geddes [32], Zaruba & Mencl [213], Liu & Evett [114], Wilun & Starzewski [210], Craig [44], Jaeger [94], Huang [87] and Smith [171].

(vii) Computer simulated imagery:

The method for generating computer simulated imagery was based on the ray tracing algorithms in computer graphics. The ray tracing algorithms can be found in most of the books about computer graphics, e.g., Burger & Gillies [28] and Harrington [79].

1.2 Statement of the problem

Fresh water, a precious natural resource, is becoming scarce in many parts of the world. This is especially the case for human consumption and human activities. The shortage may be attributed to the following factors:

(i) Population growth and increasing economic activity.
(ii) Mankind's action is beginning to upset the global climate and the hydrological cycle which may ultimately lead to anomalies in rainfall with resultant effects on drought and flood situations.
(iii) Industrial waste pollutes the surface and underground water.
(iv) Water salinization caused by improper land cultivation practices.

It is very difficult to recover the contaminated "fresh" water at present. Therefore, if we do not try to conserve our precious water resources, the situation may become critical in the near future.

The average annual rainfall of South Africa is about 497 mm which is far less than the world average of 860 mm per year [51]. In addition to the unequal distribution of rainfall, 65% of the country receives less than 500 mm of rain annually. It is therefore very difficult to practise dry-land farming successfully. Consequently water resource management is of critical importance in South Africa.

Water resource management projects usually contain one or more dams as key features. However, in the early days many of the engineers worldwide did not give much attention to dam site investigation. As a result quite a number of dam failures/disasters occurred during the past decades. For example, in 1963 a large landslide at Vaiont Reservoir, Italy, generated a huge water wave which overtopped the crest of the dam causing severe flooding downstream, leaving an estimated 2 500 fatalities in the town of Longarrone [95]. In the same year the Baldwin Hills Reservoir failed in Southern California due to the gradual movement along the Inglewood fault beneath the reservoir, claiming 5 lives and causing approximately $11 million in property damages downstream [100, 95]. These costly and often dangerous experiences illustrated that dam site investigation/evaluation is also an important procedure in the dam building process. Currently dam site studies involve more detailed analyses by the experts from related disciplines than before, e.g. geology, seismology, hydrology, civil engineering, geography, etc. This study is an effort to contribute towards the locational aspects of dam site selection using the latest available techniques and methods.
1.3 The research objectives

The main objectives of this research are as follows:

(i) To develop a locational model for dam site selection at the reconnaissance stage.
(ii) To develop a Geographic Information System (GIS) for the study area.
(iii) To automatize the locational model and implement it in the GIS in order to evaluate potential dam sites in the study area.

The availability of computer technology is paramount to all these research objectives. In general, this study is also an effort to transfer the models ( mankind's knowledge ) to computer and automatize the dam site/size/type selection procedures by means of modern computer techniques. The developed computer programs ( or system ) can thus be used to incorporate GIS and act as an assistant for analysts and decision makers.

1.4 The study area

The study area is the Letsitele river subcatchment area of the Letaba river, situated between 30.0° and 30.45° E and 23.85° and 24.1° S. The Letsitele catchment area is located less than 10 km south of Tzaneen (Figure 1.1). The total catchment area is about 485.16 km². The eastern part is well cultivated land of gentle slope with an altitude of 460 to 600 m. The western part is mountainous with an altitude between approximately 600 to 2050 m. The study area is mostly covered by indigenous bush. In 1985 the population of the Letaba district was 46 599 [34]. The majority of them live in a non-urban area. Most of the inhabitants are farmers. Tzaneen, the largest town in the Letaba district, had 5 795 people [34]. The study area has a well developed transport system, with the R71 and R526 the main roads, connecting Tzaneen with Pietersburg and the Kruger National Park. The R36 connects to the N4 highway. There are railway connections from Tzaneen to the neighbouring towns of Pietersburg, Phalaborwa and Louis Trichardt.

The average annual rainfall in the study area was about 1010 mm over the past 85 years according to the records from the South African Weather Bureau ( SAWB ), occurring mainly during the summer. The mean annual evaporation from an open water surface was about 1 888 mm over the past 32 years according to the records from the Department of Water Affairs and Forestry ( DWAF ). From a climatological perspective the catchment area appears to be suitable for dam construction, inter alia, because of ample rainfall.

The geology of the study area is dominated by its location in the Limpopo Mobile Belt. This belt of intensely folded and faulted rocks exhibits high-grade regional metamorphism. The rock ages vary from 2.7 to 3.7 billion years. The most common rock types are metaquartzites, gneisses, amphibolites, dolomitic marbles, anorthosites and high-grade metamorphic granulites [26]. In general the soil depth is quite shallow. The most common soil types are sandy clay loams, sandy clays, clays and sandy loams [91].

1.5 Data
Data for this study were obtained from the following sources:

(i) Monthly rainfall records; 509 stations (SAWB*, 1903 - 1989).
(ii) Monthly evaporation records (including UK Symons tank and USA class A pan); 2 stations (DWAF* & SAWB, 1967 - 1989).
(v) The locations of the stations mentioned under (i - iv).
(vi) Dips and strikes measured from geological maps.
(vii) Location of local construction material suppliers (Yellow Pages).
(ix) Borehole records (DWAF, without accurate location).
(x) 4 South Africa 1:50,000 sheets (SM*, Map Nos. 2330CC, 2330CD, 2430AA and 2430AB).
(xi) 33 Orthophoto maps (SM, scale 1:10,000, the same area as item x.
(xii) 2 geological maps (SM, scale 1:250,000, Map Nos. 2330 and 2430).
(xiii) 1 geological map (DM*, scale 1:125,000, Map No. 2430A).
(xiv) 2 land type maps (DAWS*, scale 1:250,000, Map Nos. 2330 and 2430).
(xv) 34 large scale airphotos of the study area.

The gauging records (i - ix) were entered into a computer-based database. The maps were digitized, using the ARC/INFO GIS-software package and converted into raster format. Most of the data input and digitizing work was done by Mrs. Yu-Hsueh Yang Lin (the author's wife).

(* SAWB : South Africa Weather Bureau
   DWAF : Department of Water Affairs and Forestry
   SM : Surveys and Mapping
   DM : Department of Mines
   DAWS : Department of Agriculture and Water Supply
   DMEA : Department of Mineral and Energy Affairs)

In general gauging records are not long enough for statistical analyses. The exception is rainfall records. Maps and airphotos are detailed enough for analysis at the reconnaissance stage. Information about geology and soils is also not detailed enough for analysis. More detailed information about geology and soils should be collected at the next stage. The data model and structure for representing these data in a GIS/KBGIS are described in the next chapter.
Chapter 2 Geographic Information Systems (GIS)

2.1 Terminology

Geographic Information System (GIS) : An information system which can manipulate geographic/spatial data.

Knowledge Based Geographic Information System (KBGIS) : A GIS in which domain knowledge is processed as a separate entity and can be used to solve problems according to the facts/data/information in GIS.

The following GIS related terminology was defined by the author or adopted from other sources in order to simplify the description and to unify the concepts throughout this thesis.

Fact : Something that has happened or is accepted as true.

Data : Any values, numbers, characters or symbols that are used to describe/record people, places, things, events, time and abstract concepts.

Information : Any processed data that are meaningful to the user according to the user's purpose.

Knowledge : A set of information, axioms, laws, principles or experiences that can be used to solve problems.

System : Two or more interrelated elements/components that work together to achieve their common purpose.

Model : A simplified, idealized, and organized description of a real world system or phenomenon by means of the qualitative or quantitative methods.

Remote Sensing (RS) : "the acquisition of information about an object without physical contact" [40].

Information System (IS) : A system which can be used to collect/input, display/output, communicate, store, and process data. The main purposes of an IS are information retrieval from data bases and communication of information to various users. The components of an IS include hardware/software, humans, data/information, algorithms and procedures.

(In this text, IS implies computer-based information system.)

Data Base (DB) : "a collection of interrelated data stored together with controlled redundancy to serve one or more applications in an optimal fashion" [143].

Data Base Management System (DBMS) : "a software tool or a software system that is designed to manage and maintain a data base" [143].

Domain : "An area of study or activity" [101].

Domain Knowledge : "Knowledge about the problem domain, e.g., knowledge about geology in an expert system for finding mineral deposits" [204].
Domain Expert: "A person who through years of training and experience has become extremely proficient at problem solving in a particular domain" [204].

Knowledge-Based System: "A program in which the domain knowledge is explicit and separate from the program's other knowledge" [204].

(From the author's viewpoint, it should be a computer system or a very extensive program.)

Knowledge Base (KB): "The portion of a knowledge-based system or expert system that contains the domain knowledge" [204].

Knowledge Base Management System (KBMS): "A computer system whose job is to act as an interface between the physical records in a knowledge base and a program's logical need for knowledge" [101].

Expert System (ES): "A computer program that uses knowledge and inference procedures to solve problems that are difficult enough to require significant human expertise for their solution" (Feigenbaum, 1984, in Ripple and Ulshoefer [155], p. 1431).

Artificial Intelligence (AI): "A field of endeavor whose goal is to devise computational models of intelligent human behavior. It includes such sub-fields and natural language understanding, robotics, expert systems, and automatic programming, as well as intelligent tutoring, design, and manufacturing" [101].

Structured decisions: "Structured decisions are based on clear logic; they are usually quantitative; the factors and the outcomes are well defined; their time horizon is short; usually they are routine and repetitive; they are programmable" [1].

Unstructured decisions: "Unstructured decisions involve heuristics, trial-and-error approach, intuition, and common sense in addition to logic; the relevant factors and outcomes are somewhat vague and tend to be more qualitative than quantitative; decisions are ad hoc and seldom replicate previous decisions; their time horizon is long; they are not programmable" [1].

Decision Support System (DSS): An information system which aids the decision maker collecting information for making decisions.

Computer Simulation: A procedure which converts models into computer programs and implements them in a computer system to attain the models' results without actual experiments.

Geographic Data (GeoData): A kind of data which normally relate to location, time and attributes of geographic/spatial phenomena.

Geographic Data Base (GDB): A data base which can accommodate and manipulate geographic/spatial data.

2.2 An information system as a decision-making tool

The dam site/size/type selection are an extensive as well as a multi-disciplinary task. Many kinds of data need to be collected and
processed. A lot of people will be involved in collecting, processing and analysing the numerous kinds of data. An information system can thus help the analyst and/or decision-maker to improve the efficiency of data processing and analysis as well as communication. The information system can, however, not guarantee a good decision which is made by the decision-maker(s).

2.2.1 Simon's model

H. A. Simon who developed a human decision-making model is considered to be the pioneer in the development of models for human decision-making [1]. His model describes human's decision-making as a three-stage process which can also be used to explain the process of dam site selection:

(i) Stage 1 - Intelligence:

In general, two kinds of motivation might trigger a decision-making process, i.e., problem detection and/or opportunity seeking. The former refers to detecting anything which is deviant. The latter refers to finding some promising circumstances which can increase wealth or upgrade welfare.

For the process of dam site selection, the motivation could be inadequate water supply (problem detection) or development of the local economy (opportunity seeking).

The main tasks at this stage are collection, classification, processing and presentation of the information for the later stages.

The data/information for dam site/size/type selection mainly relate to geographic data/information, i.e. streamflow records, topographic maps, geologic maps, etc. The data/information should be collected as extensively and intensively as possible for a better understanding of the study area. Field surveys are essential for the verification of the collected data/information in the dam site/size/type selection process.

(ii) Stage 2 - Design:

During this stage the decision-makers and assistants outline the possible alternatives. Each alternative should be evaluated by quantitative techniques or other techniques in order to forecast the possible outcomes. Normally, the resources and capabilities of a natural or man-made system are limited. Therefore, every alternative must be considered in view of the restrictions of the system during the evaluation process. If the available information is found to be insufficient or inadequate, the analysts/decision-makers should go back to the previous stage to collect more detailed data/information.

At this stage of dam site selection the analysts/decision-makers and their assistants should carefully consider the situation for each alternative (i.e. possible dam site) and estimate the cost-benefit of each alternative. The locational model (chapter 3) or other methods for dam site evaluation can then be implemented to forecast the possible outcomes of each site by
estimating the cost-benefit.

(iii) Stage 3 - Choice:

At this stage the decision-makers usually face various alternatives. Only one will be the final choice. Sometimes it is quite difficult to make a decision, e.g. because of inability to quantify, incomparability among alternatives, uncertainties and conflicts. It is also possible that there is no satisfactory solution. In this case, going back to the design stage or even intelligence stage may be necessary.

Some of the geographic data/information about alternatives (i.e. possible dam sites) involve some degree of uncertainty. Thus, if the outcomes of the previous analyses cast some doubts, it is necessary to go back to previous stages for verification of the data/information and analysis processes. A decision based on inadequate or inaccurate data/information might in due course cause a disaster, i.e. construction of a dam on a bad site might ultimately cause the abandonment or even the failure of that dam.

2.2.2 Information systems and the decision-making process

Nowadays it is very difficult to imagine the world without computers, for example, regarding the calculation of slope angle and aspect from the digital elevation model (DEM, refer to in paragraph 3.2), the same calculation for a well trained man/woman with a hand calculator will take him/her about 5 years to finish, even without sleep and rest. However, the computer is not as intelligent as the human brain, even introducing artificial intelligence techniques. In the decision-making process the computer cannot help the decision-maker in every aspect. The role of the information system in the decision-making process (based on Simon's model) can be described as follows:

(i) At the intelligence stage (Simon's model) the main purpose is to acquire data of the updated situations in an organization and its environment; then extract information from the data for the decision-maker in order to detect problems or seek opportunities. Information systems play an important part in collecting, processing, storing and displaying data as well as extracting and transmitting information during this stage. All decisions are well structured in the intelligence stage, therefore it can be implemented on the computer without any problems.

(ii) At the design stage all the extracted and other relevant information is already available for analysis. The goal of this stage is to consider all alternatives and forecast the results; therefore domain knowledge is very important for building models and making predictions. An information system is not as important at this stage as during the previous stage. Computer simulation and expert system technology become extreme vital to assist the decision-maker in constructing models for analysis. Usually decisions are unstructured at this stage, thus the use of statistical models to estimate the uncertainty are unavoidable.

(iii) At the choice stage almost all decisions are unstructured. Unstructured decisions such as heuristics, intuition, deduction,
induction, etc., are mostly qualitative based [1]. Most of them are quite difficult or almost impossible to implement on the computer at this moment. Consequently, information systems and other relevant computer technologies play a less important part than during the previous two stages due to the irreplaceability of human intelligence.

2.2.3 An information system as a decision-making tool

On the other hand, the human brain, although a wonderful organ, has the disadvantage of an imprecise memory and slow calculation when compared to the digital computer. These are exactly the strong points of the computer. Obviously, the computer is a complementary tool for the human brain.

Computers can do calculations faster and more accurately than human beings. They also have a more precise memory than human beings. The computer's most important advantage is, however, its ability to do routine and repetitive tasks rapidly without complaint and rest. The cost for a computer in doing routine tasks is thus less than for a human. There is no doubt that computers must be included in most of the decision-making processes in the modern society where an abundance of data/information is usually available.

On the other hand some organizations introduced computer-based information system into their organization, only to find later that they needed more people to run that system. As a result an information system did not improve the efficiency and productivity of such organizations. Information systems are not just a collection of hardware, software, information, data and people. They must above all be designed to fit the needs of the user for better functioning, otherwise the system will not be worthwhile. Also, information systems can assist the decision-maker or analyst as a good tool for selecting the "best" option, if and only if the information system can be well incorporated with the decision-making process or analytical procedure.

In general, the synergism between the decision-maker and the information system is very important for improving efficiency and productivity.

2.3 The components and structure of a GIS

GIS like any management information system (MIS) and other information systems has three main components, i.e., hardware, software, and people. They are in constant interaction with each other. Each of these components has its own sub-components or special parts. The input, processing & analysis, storage, output and data communication are the main parts of a GIS. The following paragraphs list the common parts of a GIS [145, 1, 143, 29, 154, 27].

2.3.1 Input

A. Hardware

* Digitizer (or Tablet)
* Scanner
* Satellite sensor and ground communication station

- 25 -
* Aerial camera and sensor
* Geodesic instruments
* Keyboard

B. Software

* Optic Characters Recognition (OCR)
* Pattern recognition
* Image and photo rectification
* Automatic classification
* Image Processing (IP)

C. People

* Computer operator including digitizer and typist
* Remote sensing/Photogrammetry operator/expert
* Geodesic investigator/expert

2.3.2 Processing and Analysis

A. Hardware

* Processor (main frame, mini- or micro- processor)

B. Software

* Operation System (OS)
* Analytic Model
* Algorithm and Procedure

C. People

* Domain expert
* System and Application programmer
* System analyst
* Artificial intelligence researcher
* Project manager
* System operator
* Knowledge engineer

2.3.3 Storage

A. Hardware

* Disk (floppy, hard or optic)
* Magnetic tape
* Drum
* Memory Integrated Circuit (IC) chip

B. Software

* Data Base Management System (DBMS)
* Knowledge Base Management System (KBMS)
* Data structure

C. People

* Data and Knowledge Base Administrator (DBA and KBA)
2.3.4 Output

A. Hardware

* Printer (dot matrix, ink jet, thermal, drum, or laser printer)
* Plotter (pen or electrostatic plotter)
* Monitor (with monochrome or color CRT)
* Camera
* Film or microfilm recorder
* Video recorder

B. Software

* Computer Aided Cartography (CAC)
* Computer Graphics (CG)
* Computer Aided Design (CAD)

C. People

* Computer operator
* Applications programmer
* Computer engineer

2.3.5 Data communication

A. Hardware

* Modem, transmitter, receiver, electronic switching system, private branch exchange, antenna, or other telecommunication instruments
* Communication mediums (telephone-type twisted wire, radio, satellite, coaxial cable wire, microwave, and optic fiber)

B. Software

* Local Area Network (LAN): e.g. Ethernet and Cambridge ring technique.
* Wide Area Network (WAN): e.g. ARPANET technique.

C. People

* Computer operator
* Application programmer
* Telecommunication engineer

2.4 Data models for GIS

There are two basic types of data models in modern GIS. The first is the vector data model which evolved from maps. The elements of the model are points, lines, polygons and their spatial relationship. The second is raster data model which evolved from pictures, especially from satellite imagery. The elements of the model are picture elements (pixels) of which the spatial relationship is already implied in the data structure. Each of the basic types has variations, some of them quite impractical. The following discussions thus concentrate on the prevailing variation of each of the basic models [29, 38, 145].

- 27 -
2.4.1 The vector data model

The topologic model is currently the most popular and widely used because it retains spatial relationships among the elements. Lines and points are the basic elements and are used to represent all map elements. For example, a polygon (area) is represented by a list of lines which make up the polygon's boundary. Each line is stored as an ordered series of coordinate pairs (e.g. X1,Y1; X2,Y2; X3,Y3; ... etc.). All lines have direction, start from a node (point) and end at another node (point). As implicit in the topological approach, a line has a polygon on its right-hand side and left-hand side respectively [145] (Figure 2.1).

The spatial relationships, coordinates and attributes of data must be stored explicitly in separate data files. Normally, those data files are arranged as a relational data base, the lineage between them is the values of their common item [145] (Figure 2.1).

2.4.2 Raster data model

A regular grid (tessellation) model is currently the most popular in both GIS and remote sensing. The pixel is the basic element of this model, representing a small square or rectangular area. The whole scene is made up by pixels, appearing like a chess board or a fish net. Other geometric forms, e.g. triangular and hexagonal, are also used as pixels. The rectangular grid-like pixel is, however, the most popular because not only the coordinates can be calculated easily but it is also a fact that ALL types of input/output facilities are designed to tessellate format [40, 110].

The raster model can further be divided into two sub-types, i.e., grid cell and grid point (Figure 2.1). The former is used widely in remote sensing imagery; the latter is used mainly in digital elevation or digital terrain model (DEM or DTM). In both cases the attributes of pixels are stored in fixed length data records. The location of records in the data file can be calculated according to its relative position to the origin [40, 110].

2.4.3 Comparison between raster and vector data models

Both raster and vector data models have advantages and disadvantages. Some of the disadvantages can somehow be overcome, but there is "no free lunch". The comparisons are as follows:

(i) Data accuracy

* Vector model: Very accurate; the limitation is mechanical precision during data capturing phase.
* Raster model: Less accurate; it can be improved by reducing the pixel size in the grid, but this will also increase the number of pixels in the grid.

(ii) Storage space (in computer) of simple map features

* Vector model: Small.
* Raster model: Large; it can be significantly reduced by data compression methods, but this needs extra
(iii) Retrieval speed of simple map features

* Vector model: Fast, but in general slower than raster model because of the more complicated data structure.
* Raster model: Fast.

(iv) Storage space (in computer) of complex map features

* Vector model: Very large; data compression methods reduce storage space insignificantly.
* Raster model: Large; data compression methods reduce storage space insignificantly.

(v) Retrieval speed of complex map feature

* Vector model: Very slow; owing to the large volumes of data and complexity of the data structure.
* Raster model: Fast; it does not depend on the complexity of map feature.

(vi) Attributes access time

* Vector model: Same as for items (iii) & (v), sometimes even slower.
* Raster model: Same as for items (iii) & (v).

(vii) Quality of computer graphics

* Vector model: Very good with high accuracy for maps and pictures; needs extra preprocessing time for picture productions.
* Raster model: Excellent for pictures; it is also possible to produce maps, but special smoothing methods are necessary.

(viii) Processing speed of computer graphics

* Vector model: Quite slow.
* Raster model: Fast for pictures, but quite slow for maps.

(ix) Compatibility with remote sensing imagery

* Vector model: Needs vector-raster conversion.
* Raster model: Fully compatible.

(x) Compatibility of DEM (or DTM)

* Vector model: Difficult.
* Raster model: Fully compatible or needs only limited conversion.

(xi) Representation of geographic phenomena

* Vector model: Excellent in all respects.
* Raster model: Not as good as vector model, especially regarding lines.
(xii) Input time

- Vector model: Slow; needs ample human input, especially for complex map features.
- Raster model: Fast; needs only limited human input.

(xiii) Edit and revision time

- Vector model: A lot of time and human input.
- Raster model: Needs some time, depending on the data quality.

(xiv) Potential for automatic input

- Vector model: Low; possible with the aid of a scanner.
- Raster model: High.

(xv) Geometrical characteristics of data

- Vector model: Excellent; easy to convert to another coordinate system (e.g. a projection).
- Raster model: Always needs geometric rectification.

(xvi) Possibility of pattern recognition and automatic classification

- Vector model: Possible, but difficult.
- Raster model: Good, but the accuracy is not very high. It is possible to increase the accuracy by artificial intelligence techniques/texture classification.

(xvii) Spatial operation capability

- Vector model: Very good and accurate in map overlaying, otherwise not as good as raster model.
- Raster model: Very good, especially with relation to DEM/DTM.

2.4.4 The conversion between vector and raster data model

The map/data accuracy is retained after the conversion from raster data to vector data. The contiguous pixels with the same attribute are aggregated together to form a polygon. Because the resolution of the vector data is better than that of the raster data, the location of the features can thus be converted without any error. The problem is that the line will become a zig-zag line (Figure 2.1). Some smoothing methods can be used to smooth the lines, however, the location of the lines will be slightly displaced.

The scanned raster data (either from scanner or satellite) are usually very complex and accompany many 'archipelago' pixels. The file size of the converted vector data will become much larger than the original raster data file in consequence of the 'archipelago' pixels and the complex map/data features. Thus the complex map/data features should be generalized; the 'archipelago' pixels should be eliminated for a faster processing time and a better outcome of the conversion [201, 200, 30].

The map/data accuracy is not retained after the conversion from vector data to raster data due to the poorer resolution of raster data. The usual method for converting the vector data to raster data is to
lay a tessellated fish net on the vector data/map; the attribute of each cell in the fish net can be decided by duplicating either the attribute of the largest/longest or the most important data/map feature in the cell. The location of the data/map features is apt to shift. The location of polygons and the lines tend to shift in the horizontal and vertical direction. In the diagonal direction the lines will become a zig-zag shape. Point features tend to expand to the size of the cell [201, 200].

In conclusion, the shape of the data/map features will be changed after the vector to raster conversion. The resolution of the data/map features will reduce to the half of the cell size/length. It is possible to improve the accuracy of the vector to raster conversion by reducing the size of the cell in the tessellation, but it will also increase the number of cells and consequently increase the data processing time.

(* The scanned imagery includes very detailed and complex features. Thus it may have many isolated pixels which are surrounded by the pixels with a different value/attribute. The scene thus appears like having many islands in the sea. This situation occurs very often after image classification especially by means of a pixel-by-pixel classification method.)

2.4.5 Discussion

Obviously, neither the raster or the vector model is clearly superior to the other. The criteria for data model selection depends mainly on the research objectives. In this study, a raster data model was used to represent geographic phenomena in the GIS which was developed. The reasons are as follows:

(i) More complex spatial operations, e.g. finding the runoff route from a specified point to a river, etc., can be developed easily due to the relatively simple data structure of the raster model.
(ii) Existing pattern recognition and automatic classification methods can be incorporated with spatial operations.
(iii) DEM (grid type) is fully compatible with the raster model because of the same data structure.
(iv) Remote sensing imagery can easily be incorporated for updating the land use/cover information because of the same data structure.
(v) High quality of computer graphics.

2.5 Expert Systems, Remote Sensing, Computer Simulation and GIS

2.5.1 Expert System (ES)

Expert systems is a new technique which can transfer human knowledge or sometime experience into the computer environment by means of specific knowledge representation methods, and in doing so enables it to solve more difficult problems than just data processing. This field is currently growing quite fast owing to intense studies in many disciplines. It was also applied and developed in some earth sciences, e.g. geography, geology, hydrology, etc. The developed ES which were listed in Waterman [204] are as follows:

"DIPMETER ADVISOR infers subsurface geological structure by interpreting dipmeter logs, measurements of the conductivity of rock
in and around a borehole as related to depth below the surface."
"DRILLING ADVISOR assists an oil-rig supervisor in resolving problems related to the drilling mechanism sticking within the borehole during drilling."
"ELAS gives advice on how to control and interpret results from INLAN, a large-scale interactive program for well log analysis and display."
"HYDRO helps a hydrologist use HSPF, a computer program that simulates the physical processes by which precipitation is distributed throughout a watershed."
"LITHO assists geologists in interpreting data from oil-well logs."
"MUD helps engineers maintain optimal drilling fluid properties."
"PROSPECTOR acts as a consultant to aid exploration geologists in their search for ore deposits."
"WILLARD helps meteorologists forecast the likelihood of severe thunderstorms occurring in the central United States."
"PLANT/cd predicts the damage to corn due to the black cutworm."
"PLANT/ds provides consultation on the diagnosis of soybean diseases using knowledge about disease symptoms and plant environment."
"POMME helps farmers manage apple orchards by providing advice on how to improve the apple crop."
"SPERIL-I performs structural damage assessment of existing structures which are subjected to earthquake excitation."

2.5.2 Remote Sensing (RS)

Remote sensing is a well developed technology, which grew out of the invention of photography. In early times people used balloons or airships as platforms. Today aircraft and satellites are used as platforms for sensing devices which greatly enhanced mankind's view, spatially as well as spectrally. In remote and inaccessible areas of the globe where field survey cannot be embarked on, the remotely sensed data thus becomes the most important source for data and information. Also the frequent and economical updating of data sets in a short time period becomes possible, enabling the detection of rapid (and slow) changes in the earth environment. Remote sensing has been used in geography and other earth sciences for quite a few decades.

2.5.3 Computer Simulation (CS)

Most geographical experiments are difficult to perform. For example, it is impossible to generate a real world flood and observe its behaviour when a flood is passing through a dam. Advances in digital computer technology nowadays, however, enables us to create an analytical model simulating such a flood or other real world events and phenomena. This technique is called computer simulation. CS can also be employed as a substitute when the cost of experiments are very high or the time span of experiments are very long. Another merit of CS is that it can be used to verify the outcomes of models for further revision and refinement. CS is thus an extremely powerful tool for the geographer. It also has great potential to be implemented in many aspects of geography or other earth sciences, especially where statistics and mathematics are concerned.

2.5.4 The relationship between ES, RS, CS and GIS

ES, RS and CS play an important role to enhance the capability of GIS (figure 2.2). In the data input phase RS supplements the slow updating capability of GIS by its very fast data capture and processing ability, especially in environmental change monitoring.
In the data processing and analysis phase CS helps the analyst or decision-maker to construct and verify analytical models. It also assists the analyst/decision-maker to gain the simulated outcomes for the evaluation of alternatives. GIS applications can thus be extended by means of CS.

ES can be used to interconnect the domain knowledge, analytic models and geographic information together in a GIS. Because of the combination of domain knowledge with RS, ES and CS, GIS can therefore be used to solve far more difficult problems than before. Generally speaking, incorporation of ES, RS and CS with GIS into an integrated system will greatly upgrade the capability of GIS and effectively increase the system's performance. In the modern dynamic society, an efficient and capable GIS is essential for inter alia the geographer, regional/urban planner and earth scientists.

(* Such a GIS is known as a Knowledge-based GIS which will be explained in paragraph 2.6.)

2.6 Knowledge-Based GIS (KBGIS) : A Spatial Decision Support System

The KBGIS is the combination of ES and GIS, in which the domain knowledge is stored separately from the components of the GIS. The domain knowledge and geographic information (facts) of each environmental zone are stored in a Knowledge Base (KB) and Geographical Data Base (GDB) systematically. In a KBGIS the application model will utilise the data in GDB and KB, and find the relevant domain knowledge and geographic information of the specified zone. Thereafter the application model reads through the whole relevant domain knowledge and geographic information, and registers everything precisely and rapidly. Lastly, the application model starts to analyse, using the gathered information and domain knowledge, and thereafter submits the results and suggestions to the decision-maker.

Owing to the variation of the earth's physical environment, it is impossible to employ a KBGIS which can be implemented all over the world in even a narrow domain of geography. Even in South Africa it is still very difficult to do that. In this research, the application model was the locational model for potential dam sites selection (refer to chapter 3); the domain knowledge and geographic information were stored in separated directories because they were regarded as only one entity, so it was not necessary to develop the GDB and KB. As the system is expanded in future, the GDB and KB should be constructed by means of current GDB, GIS and ES techniques. Figure 2.2 shows the elements of a KBGIS.

It is very important to emphasize that a KBGIS can never replace the human analyst/decision-maker for making unstructured decisions. As mentioned in paragraph 2.4, the unstructured decision is at present still very difficult to implement in the computer environment. A KBGIS is actually a Decision Support System (DSS) which supports the decision-maker in ultimately making unstructured decisions.

2.7 Conclusion

The construction of a KBGIS is a time consuming and costly task. Many people are involved in such an extensive task, e.g. digitizing operators,
domain experts, knowledge engineers, etc. It might take years to fully develop a KBGIS, depending on its volume and complexity. The main difficulty is that the domain experts are not willing to contribute their knowledge to the KBGIS usually because of self-interest. Consequently, the KBGIS may need a longer development time and the knowledge in KBGIS might become outdated or incorrect. The domain experts' attitude is the key of a KBGIS. A KBGIS cannot be compiled successfully without their precise domain knowledge. The domain knowledge used in this study are discussed in the next chapter.
Chapter 3  Locational Model for Potential Storage Dam Sites

3.1 Limitation and methodology of the locational model

Dams are some of the most important man-made hydrological structures related to human activity. The disciplines related to dam engineering include hydrology, hydraulics, climatology, engineering geology, seismology, civil engineering and geography. Therefore an integrated multi-disciplinary model for selecting suitable dam sites/sizes/types is essential. The development of such a model incorporated in a KBGIS for Storage Dam Site/size/type Selection (SDSS) is attempted in this study. The limitations and methodology of the SDSS-model is described next, while the detailed methodology of the SDSS-model is described in paragraphs 3.2 to 3.10.

3.1.1 Limitations

The SDSS-model is designed for the reconnaissance (first) stage of the planning which assists the analysts/decision-makers in quickly finding and evaluating the locations of potential dam site/size/type alternatives. The SDSS-model does not offer the final solution.

Only existing maps and gauging records are necessary for the SDSS-model which will be used as base data for the selection/evaluation of the potential dam site/size/type. After the reconnaissance stage, further field investigation should be embarked on, mainly because of the generalized nature of the data (especially regarding the rock and soil properties) which may possibly results in misleading evaluations. The newly acquired, more accurate data can then again be fed into the SDSS-model for a more detailed and reliable analysis. As regards the design stage of the dam, the SDSS-model is of little or no use.

The SDSS-model only considers the physical environment factors. The social, economical and ecological factors were not considered due to time and cost constraints on the scope of the study.

The SDSS-model is based on the raster model, the pixel size is 50x50 m. It may be necessary to adjust the pixel size for the other relevant applications. By a rule of thumb, pixel sizes between 30 and 80 m should be compatible to the SDSS-model in its present form.

3.1.2 Methodology

The SDSS-model is based on a raster data format to represent spatial phenomena and relationships because of the relatively simple data structure. The pixel size was set at 50 x 50 m owing to the limitation of memory space and speed of the PC/AT-computer used in this study.

The SDSS-model is designed as a step-by-step procedure to perform the dam site/size/type selection. The procedure for the SDSS-model is as follows (the detailed description of each step is given later in this chapter):

(i) Construct DEM (paragraph 3.2).
(ii) Automatically determine the river catchment boundary and the impounded area of the potential reservoir when at full capacity (paragraph 3.3).
(iii) Calculate the area-height-volume relationship at the potential...
(iv) Estimate the areal rainfall from the precipitation records in the study area (paragraph 3.4.4.1).
(v) Calculate the Hurst phenomenon index and the stationarity of precipitation records in the study area (paragraphs 3.4.4.2 & 3.4.4.3).
(vi) Select a suitable hydrological model to generate stochastic series of areal rainfall for further stochastic analysis (paragraph 3.4.4.4).
(vii) Calculate the relationship between respectively areal rainfall and streamflow, streamflow and sedimentation, as well as pan evaporation records and reservoir evaporation (paragraphs 3.4.4.5 to 3.4.4.7).
(viii) Implement the reservoir yield risk analysis which is based on a stochastic analysis (paragraph 3.4.4.10).
(ix) Implement a simulated flood routing through the reservoir (paragraph 3.4.5).
(x) Perform land evaluation within the impounded area of the potential reservoir which includes up-to-date land use/cover information, land capability classification and land suitability evaluation (paragraphs 3.5.1 to 3.5.3).
(xi) Find the scope, location and type of mining activities within the impounded area of the reservoir at full capacity (paragraph 3.5.4).
(xii) Perform a topographic suitability analysis for the potential dam site (paragraph 3.6).
(xiii) Compute the transportation distance for the construction material from existing quarries and/or material suppliers to the potential dam site (paragraphs 3.7.3 to 3.7.5).
(xiv) Locate possible local construction material borrow areas (paragraph 3.7.6).
(xv) Calculate the peak horizontal ground motion according to the specified operating basis earthquake (OBE, paragraph 3.8.2).
(xvi) Roughly estimate the possibility of reservoir induced earthquakes (RIE, paragraph 3.8.3).
(xvii) Estimate the permeability of the bedrock of the potential reservoir (paragraph 3.9.1).
(xviii) Calculate the presumed safe bearing capacity of the potential dam foundation (paragraph 3.9.2).
(xix) Analyse the rock and soil slope stability around the rim of the potential reservoir (paragraph 3.9.3).
(xx) Generate computer simulation imagery at the potential dam site (paragraph 3.10).
(xxi) Report on the results of the foregoing outlined steps (i - xx).

As mentioned in chapter 2, the KBGIS is not going to replace the human analyst/decision-maker. In this research, the results are to be used to aid the analyst/decision-maker in the spatial decision-making process. The SDSS-model was designed for the reconnaissance stage exclusively, as going to the further stage of the dam building project, other models should be developed. That was beyond the scope of this research.

3.2 The Digital Elevation Model and the Geographic Information

3.2.1 The Digital Elevation Model (DEM)

The Digital Elevation Model can be used to represent a continuous 3-D
surface in the digital form. In geography the DEM has been used to represent the topography or geomorphology mainly for demonstration purposes (e.g. 3-D perspective views) and sometimes for visibility analysis (or visual impact analysis). Actually the DEM is a valuable method for the geographer/earth scientist in doing spatial analyses, e.g. deriving the volume-height-area relationship at a potential dam site; finding the least inclined route between a potential dam site and the existing quarries, etc. The DEM plays a very important role in this study because of the spatially related issues studied. Every analysis in this dam site/size/type selection procedure is to a greater or lesser degree based on it. A detailed description of the DEM follows next.

3.2.1.1 Representation methods of the DEM

The representation methods for the DEM include the mathematically defined surfaces method, the point images or the line images as shown in table 3.1 [29].

The mathematically defined surfaces use continuous three dimensional functions to fit the complex surface by means of a global or local method. It always shows a high degree of smoothness when using the global method. Thus the global method is usually not suitable for representing the topography in geographic/spatial analysis due to the imprecise representation. The local method divides the whole study area into many smaller areas (patches). A surface is then generated to "best fit" the sample points at each patch. The local method greatly reduces the degree of smoothness, but the surface usually does not continue on the border between patches. This kind of method is usually used in CAD/CAM [29]. For the representation of topography in geographic/spatial analysis, it needs many patches to represent the complex topography which in turn will complicate the data interpolation. Besides, this method may generate many "sharp" features on the edges of patches which may consequently cause the misinterpretation.

The line image method uses sets of continuous lines which are captured by scanners or digitizers to represent the surface (Figure 3.1). It can be used to plot profiles and contour maps accurately. Unfortunately, this kind of method is not suitable for the calculation of slope angle and aspect and is therefore usually converted to the point image type.

The point image method is widely used in DEM applications. Data for this method can be obtained from photogrammetric measurements or derived from sample points. There are basically two methods, i.e. triangulated irregular network (TIN) and regular rectangular (or tessellated) method (Figure 3.1).

TIN is a vector topological structure which represents the surface by constructing connected triangular facets on a spatially irregular set of sample points. It can efficiently represent the surface and save a lot of storage space in the computer. In general the compilation time for a 3-D surface by TIN is far shorter than for the regular rectangular method. Owing to the many triangular facets (small planes) used to represent the topography in TIN, the detailed topographic features inside each facet will be erased. This makes it useless for more detailed spatial analyses especially when the number
of sample points are insufficient. Its performance can be improved by increasing the number of sample points, but it will also greatly increase the storage space and processing time due to the much more complex data structure (Figure 3.1) in comparison with the regular rectangular method. The complex data structure might also increase the difficulty for implementing the geographic/spatial analyses which may consequently reduce the efficiency of the analytic methods/models. Besides, the final results of TIN retain an imprint of the triangulation which degrade the graphic quality of the images.

The regular rectangular method is based on a raster data structure and represents elevation by means of a set of regularly spaced points. Each point represents, e.g. the altitude at the location of that point. The altitude of points can be calculated by either interpolation from irregularly/regularly spaced sample points or quantitative measurement from stereoscopic aerial photographs using analytic stereo-plotters [29]. The main defect of this method is the large volumes of data which needs long processing time. The other flaw is that the fixed grid size makes the applications less flexible because the grid size should be changed for different levels of applications. But it retains the detailed topographic features of the surface and has a relatively simple data structure which makes the implementation of the more complex geographic/spatial analyses possible. Also, high quality computer graphics methods (e.g. ray tracing) can be incorporated for making fine quality images.

3.2.1.2 Applications of a DEM

In geography and other earth sciences, DEM is a very powerful tool to represent the relief of the earth's surface. A DEM may be applied to the following fields [29, 145, 154]:

(i) Topographic and geomorphic study  
(ii) Planning routes of railways and roads  
(iii) Locating dams, dumps or any other facility related to topography  
(iv) Visibility analysis  
(v) Landscape planning and design  
(vi) Landscape imagery simulation  
(vii) Soil and rock volume calculation  
(viii) Automatic catchment boundary detection  
(ix) Slope, aspect and cross section calculation  
(x) Cartography (e.g. contour maps, profiles, etc.)  
(xi) Flying simulation and pilot training  
(xii) Missile guidance (e.g. cruise missile)

In general, altitude may be substituted by any other attributes, e.g. rainfall distribution, population density, and many other spatial phenomena. The applications of DEM seem numerous in the earth sciences.

3.2.1.3 The DEM of the study area

The regular rectangular method was chosen to represent the topography for the study area due to its relatively simple data structure which can easily be incorporated in the geographic/spatial analyses.

The DEM for the study area was interpolated from the sample points
which were digitized from 1/10 000 orthophoto maps (inside the study area) and the South Africa 1/50 000 map sheet series (outside the study area). In total 401 467 sample points were digitized from the above mentioned maps. The weighted moving averages method was used for interpolating the altitude \( Z(X_j) \) of the interpolated points. The weight function is the inverse of the distance from the nearby sample points to the interpolated point. The formula is as follows:

\[
Z(X_j) = \frac{\sum_{i=1}^{n} Z(X_i) \cdot W_{ij}}{\sum_{i=1}^{n} W_{ij}} \tag{3-1}
\]

where \( W_{ij} = 1 / D_{ij} \)

\( D_{ij} \) : The distance from the interpolated point \( j \) to the sample point \( i \).

The binary search\(^*\) method was used to search the nearest sample point in each octant around the interpolated point. Thus the 8 nearest sample points (in 8 octants, Figure 3.1) were used to estimate the altitude of the interpolated point by the formula 3-1. Figure 3.2 shows the DEM for the topography of the study area.

The main reason for adopting this method is that it can be used to represent continuous and complex surfaces well. The computing procedure is also quite simple and fast, but will become very inaccurate if there are not enough sampling points. For this reason numerous sampling points were digitized for compiling the DEM for the study area.

\(^*\) The binary search method is an algorithm/method for retrieving a specific record from a set of orderly records (i.e. a file) according to user's specification. A full explanation of this method is beyond the scope of this study and the interested reader can refer to Kruse [105] for more information about this algorithm/method.

3.2.1.4 Slopes and aspects

The slope (angle) is the change rate of altitude; the aspect (of a slope) is the projected direction of the change rate of altitude on a horizontal plane\(^*\). In DEM the slopes and aspects can be computed by fitting a plane to the four corners of a pixel. The slope (angle) is the angle between the fitted plane and the horizontal plane; the aspect (of a slope) is the projected direction of the vector normal to the fitted plane on the horizontal plane. The equation of the fitted plane can be calculated by means of multiple linear regression. The equation is as follows:

\[
Z = a + b \cdot X + c \cdot Y \tag{3-2}
\]

The parameters \( a \), \( b \) and \( c \) can be obtained by solving the following three normal equations:
\[ \Sigma Z = a \cdot \Sigma X + b \cdot \Sigma X^2 + c \cdot \Sigma Y \]
\[ \Sigma XZ = a \cdot \Sigma X + b \cdot \Sigma X^2 + c \cdot \Sigma XY \]
\[ \Sigma YZ = a \cdot \Sigma Y + b \cdot \Sigma XY + c \cdot \Sigma Y^2 \]

Thereafter the slope and aspect can be derived from plane equation 3-2 by means of the trigonometrical computation. Figure 3.3 shows the derived slopes for the study area; figure 3.4 shows the derived aspects for the study area.

(* The parameters for the aspect system used in this study are as follows:

North = 0° or 360°
East = 90°
South = 180°
West = 270°)

3.2.2 The geographic information

All the map-type geographic information was digitized as vector type data which was then converted to raster data using the ARC/INFO software package. The land use/cover information could have been obtained from SPOT or Landsat TM images via image processing procedures but due to the high cost of these images, it was decided to use the land use/cover information as available from the relevant South Africa 1/50 000 topographic map sheets. Although this data source is outdated, it should not negatively affect the outcome of the study because of its methodological nature. Gauging records were captured into computer files excluding the precipitation records from the South Africa Weather Bureau (SAWB) which could be read directly into the GIS from magnetic tapes, as it was already stored in ASCII format. It was also possible to read the aforementioned gauging records into computer files by means of a scanner using optical character recognition (OCR) techniques, but owing to the high error rate* and time consuming editing required, the keyboard was used for data entry.

(* The high error rate is mostly caused by the poor print quality which make the printed character not easy to distinguish by scanning. Different symbolisms also cause problems, e.g., most South African reports use the comma (",") as decimal point (".") to express real numbers. In the computer environments the comma is, however, a separator, and will cause confusion when scanning reports of South African origin.)

The following spatial data sets were used in this study:

(i) Precipitation
(ii) Evaporation
(iii) Streamflow
(iv) Sedimentation
(v) Location of gauging stations
(vi) Dips and strikes (of rocks)
(vii) Location of construction material suppliers
(viii) Seismic records
(ix) Borehole records (approximate locations only)
(x) Distances between neighbouring towns
(xi) DEM (Figure 3.2)
(xii) Slope angle (Figure 3.3)
3.3 Detection of the catchment boundary and the impounded area of the reservoir

3.3.1 The overlap method for determining the catchment area

Traditionally geographer/earth scientists determined the watershed of a catchment area with the aid of contour maps and then using this watershed as the boundary of the catchment area. Thereafter this boundary was digitized into a computer file as a base map for further analysis. In general other geographic phenomena usually do not coincide with the catchment area and thus overlapping will occur between different projection/scale maps. In GIS the maps can be easily enlarged or reduced to any scale and the map scale thus plays no role. Instead of the map scale the spatial accuracy of the digitized features from the original maps becomes extremely important when GIS is applied to determine the catchment area. The spatial accuracy of the maps depends on the following factors:

(i) Accuracy due to map scale

The digitized catchment boundary (or other map features) will have a different spatial accuracy, depending on the scale of the original map from which it was derived. The map features digitized from large scale maps will have better spatial accuracy than for the smaller scale maps. It is therefore undesirable to use a catchment boundary derived from a small scale map for large scale analysis due to poor spatial accuracy. It is possible to digitize the watershed boundary from the largest scale maps available for all applications, but the cost consideration might be inhibiting (e.g. approximately 45,800 sheets of 1/10,000 orthophoto maps will have to be digitized to cover the whole of South Africa).

(ii) Map errors

- Surveying error: Every measurement has a certain range of error, due to human and/or instrumental factors. This is unavoidable but can be reduced by more advanced instrumentation and better trained operators.

- Compiling error: Human beings are fallible and controlled by their emotions, thus errors of varying magnitude might occur during the map-compiling process. Sometimes the real world features which are to be mapped are too complex to depict on a single sheet; therefore a certain level of generalization of the map will have to be implemented which also reduces the spatial accuracy.
• The error due to map material: Shrinking and swelling of the map material under various weather conditions also contribute to map errors, especially on paper maps.

(iii) Digitizing errors

Hand digitization by human operators is prone to the same kind of errors already mentioned. Furthermore, digitizing encompasses a limited number of discrete points to express continuous lines and therefore a certain magnitude of error exists in the digitized map features. Digitized features are in digital form and the spatial accuracy will therefore not deteriorate any more.

(iv) Map projection and transformation errors

• Map projection errors: During map compilation features of the real world must be projected from the earth's sphere onto a two-dimensional map by means of a specific map projection. Some extent of geometric distortion will occur during the map projection, i.e., regarding the shape, distance, area and direction of the features. Some of these distortions are unavoidable for any map projection.

• Map transformation errors: Map features depicted by different projections differ in geometric aspects. Maps to be superimposed (overlayed) must thus be transformed to a common map projection of the same map scale. For transformation the locations of the same ground control points* for both the input map and the base map are needed. Thereafter a transformation function is established based on the locations of the ground control point pairs. The transformation functions will not present any error if correct and precise ground control points have been chosen. Errors in the location of ground control points will have a negative influence on the transformation function which in turn will further affect the spatial accuracy of the transformed map.

The above mentioned errors are subject to accumulation during superimposing (overlaying). A more error free method/algorithm may need to be developed for a better spatial representation at lower cost.

(* A ground control point "is a physical feature detectable in a scene, whose location and elevation are known precisely" [40] which can be used as a mark of reference to match two maps at different projections/scales. In some GIS applications, 'tic' is used as denoting a ground control point.)

3.3.2 An algorithm for the automatic detection of a catchment boundary

This algorithm is based on the raster data model*, and is independent of the pixel size. The error in the final result is the error inherent in the DEM during the capturing phase of the sample points from maps. The interpolation method used may also propagate error into the DEM owing to the limited number of sample points. If the DEM is derived by the photogrammetric method, then the error becomes less significant and can be ignored. The boundary detection algorithm developed for this study includes the following three steps:
Step 1: Trace all streams and rivers which can reach the user specified catchment outlet.

Step 2: For each pixel:

(i) Trace the runoff route according to the DEM, slope angle and slope aspect.
(ii) If the runoff route can reach the river, this pixel is inside the catchment.

Step 3: Plot the border of catchment.

(* Actually based on the regular rectangular type of DEM and the surface drainage information of the study area.)

3.3.3 An algorithm for the automatic detection of the impounded area of the reservoir when full

Basically, the algorithm is the same as for the catchment boundary detection, except that the pixels outside of the designed water level* of the reservoir must be excluded. Figure 3.11 shows the detected border of the Letsitele river catchment area, the catchment area of the potential dam site and the impounded area of the potential reservoir.

(* The altitude of the water level when the reservoir is full.)

3.4 Hydrological Analysis of Reservoir Catchment Area

3.4.1 Data sets

Four types of hydrological and meteorological data sets were used, i.e., precipitation, streamflow, evaporation, and sedimentation.

The precipitation records were obtained from the South African Weather Bureau (SAWB) which included the records from 509 stations since 1903. Table 3.2 lists part of the precipitation records, including the station number and monthly precipitation records. For the normal lifetime of a storage dam, the time span of the precipitation records is long enough for statistical analysis.

The streamflow records were obtained from the Department of Water Affairs and Forestry (DWAF). These records include the records from 2 stations in operation since 1959 (table 3.3). The normal lifetime of a storage dam is normally longer than 50 years. The time span of streamflow records is therefore not long enough for a statistical analysis. Consequently an estimated streamflow for the statistical analyses had to be inferred from precipitation by means of simple regression analysis or other more complex models.

The evaporation records were obtained from the SAWB. The time-span is, however, only 9 years and was therefore not used. The evaporation records from the DWAF contained only the records for one nearby station whose measurement was commenced in 1968, using both a Symons's tank and a class A pan (table 3.4).

The sediment records from the DWAF included the records of three stations since 1981. The sediment estimation method adopted the evaporation method from 12 samples in order to reduce possible sampling
3.4.2 Missing values in the gauging records

Most of the gauging records in South Africa have missing values owing to observer absence or breakdown of instruments. In general, the missing values can be estimated from neighbouring stations by linear regression models [214]. The use of a regression model to estimate the missing values will, however, reduce the inherent variance of the gauging records. It is therefore strongly recommended that only the genuine observed gauging records should be used to generate the stochastical time series for analysis.

3.4.3 The volume-elevation-area relationship at the dam site

In the natural environment the topography can be treated as a continuous three-dimensional surface, therefore the elevation of reservoir proportion to the square root of the reservoir's impounded area at that elevation. Similarly, the elevation of a reservoir proportion to the cube root of reservoir's volume at that elevation. In general the natural topography is quite complex and it is very difficult to express it by means of a mathematic model. Numerical methods can thus be used to estimate the relations between the aforementioned variables from a DEM. It is fast and accurate enough for this study, e.g. the correlation coefficient between these variables was estimated to be both higher than 0.99 (Figure 3.12 & 3.13) which is good enough for most applications.

3.4.4 Reservoir yield risk analysis

3.4.4.1 Estimated areal rainfall

The areal rainfall is the total rainfall over an area during a specific time span, i.e., a day or a month. The areal rainfall can be estimated from the point measurement records. There are many methods to estimate the areal rainfall, including arithmetic mean, Thiessen polygons, isohyetal, hypsometric and multiquadric method [164].

The arithmetic mean is not accurate enough for most applications, while the isohyetal and hypsometric methods are more suitable for manual operations and therefore not used in this study.

The multiquadric method employs the three dimensional rainfall surface compiled with the aid of a mathematical model. The mathematical model is inferred from the precipitation records of the measuring stations by either polynomial equations, Fourier series, or multiquadric methods. Unfortunately, the measurement records have many missing values, making them inadequate for estimating the rainfall surface by means of the methods described. The weighted moving averages method was thus used to estimate the rainfall surface from the measurement records which have missing values.

The Thiessen polygons and weighted moving averages method (equation 3-1) were adopted for this research. The weight function of the latter method was used, based on the inverse of the distance and the inverse of the squared distance respectively, i.e.,
\[ W_{ij} = \frac{1}{D_{ij}} \text{ or } W_{ij} = \frac{1}{(D_{ij})^2} \]

Table 3.6 shows the areal rainfall records of the study area which were derived from the point precipitation records of 509 gauging stations.

3.4.4.2 The Hurst phenomenon

Hurst is considered the first person who discovered the long-term persistence of natural phenomena. He tested about 800 time series of natural phenomena (e.g. streamflow, precipitation, temperature, etc), using the following equation (Figure 3.14) [113, 25, 139].

\[ R_m = \sigma_m \left( \frac{m}{2} \right)^n \]

where \( \sigma_m \) is the standard deviation
\( m \) is the length of the series
\( n \) is the Hurst coefficient
\( R_m \) is the difference between the greatest cumulative excess above the mean and the greatest cumulative deficiency below the mean.

He found that \( 0.5 < n < 1 \), with a mean value of 0.73 and a standard deviation of 0.09 [113]. For a random series, \( n \) should be equal to 0.5. If the time series exhibits a Hurst coefficient greater than 0.5, the Markov process is unable to express the time series, and the AutoRegressive-Moving-Average (ARMA) model is more proper to represent long-term persistence than a Markov process. Explanations of the Hurst phenomenon are given by O'Connell [139] and Bras & Rodríguez-Iturbe [25] and deals with:

(i) transience
(ii) non-stationarity
(iii) stationary processes with a very large memory

An explanation of the Hurst phenomenon is beyond the scope of this research, but in conclusion the following: "Statistically, it cannot be proved that any of the above explanations for the Hurst phenomenon is the correct one. Operationally, though, hydrologists are able to handle only the third argument" [25]. Table 3.7 (left-hand part) shows the Hurst indices for the study area.

3.4.4.3 Stationary time series

A stationary time series is one in which the properties of the series do not change with time [75]. For a stationary time series, the probability density function \( p(x; t_1) \) must be equal to \( p(x; t_2) \) where \( t_1 \) and \( t_2 \) represent any two different time instants in the possible range of time (Figure 3.15). For most of the climatological or hydrological phenomena, it is almost impossible to find the probability density function at any specific time. Statistically, it is very difficult to prove the stationarity of a hydrological or climatological time series. Operationally, a substitutional method can be used to test a non-stationary time series. This method incorporates the chronological regression analysis of the time series. If the slope of regression line is, say, greater than 5°, the time series will be treated as non-stationary. It should be borne in mind that the slope of regression line less than 5° does not
mean stationarity of the time series, but only the POSSIBILITY of a stationarity of time series. Table 3.7 shows the percentage of the non-stationarity point rainfall series in study area.

3.4.4.4 Generating stochastic series for the areal rainfall

The aim of generating a stochastic time series is to produce a set of traces which are statistically indistinguishable from historical data. Monte Carlo simulation was used to generate such a series.

The areal rainfall series for the study area was found to be persistent and stationary. The ARMA(1,1) model could therefore be used to generate a stochastic series of areal rainfall in the catchment area of the potential dam site [139, 39, 25]. Owing to limited man power and time, only ARMA(1,1) was used in this research. It might be necessary to apply another suitable method for another catchment area.

The parameters of ARMA(1,1) can be computed by the following formula [39] :

\[ R(t) = \mu + \beta (R(t-1) - \mu) + c(t) - \alpha c(t-1) \]  
\[ \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (3-5) \]

where 
- \( R(t) \) is the areal rainfall in year \( t \)
- \( \mu \) is the mean annual areal rainfall series
- \( c(t) \) is the random noise of year \( t \)
- \( \alpha, \beta \) can be estimated by the following two equations :

\[ r_1 = \frac{(\beta - \alpha)(1 - \alpha \beta)}{1 - 2\alpha \beta + \alpha^2} \]  
\[ \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (3-6) \]

\[ r_2 = r_1 \beta \]  
\[ \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (3-7) \]

where 
- \( r_1 \) is the serial correlation of lag one.
- \( r_2 \) is the serial correlation of lag two.

According to Herald's research [82] "..., due to the long period of data required before it becomes representative of the long-term streamflow regime and because of the frequent occurrence of zero data values which present problems when normalizing the data series, ARMA models are not recommended for simulating monthly streamflows within semi-arid environments. Alternative approaches that may prove more successful include the disaggregation of annual series that should prove easier to model using ARMA models and the generation of monthly rainfall series which may be converted to flow series using deterministic rainfall-runoff models." The latter method is adopted in this study, because the streamflow record in the study area is only about 30 years. This is not long enough to generate a stochastic series for more than the 50 years which is the normal lifetime of dams. Due to the periodicity component of monthly data, the monthly series of the areal rainfall will become non-stationary and more complex for analysis. It is more proper to generate the annual rainfall series and then convert it to an annual streamflow series by means of the rainfall-runoff models. The annual streamflow is then disaggregated into monthly streamflow according to the ratio of average monthly streamflow to average annual streamflow (Figure 3.16).
3.4.4.5 Areal rainfall and streamflow

The correlation between the annual areal rainfall and streamflow is very high for the study area (r > 0.9, Figure 3.17). Linsley, Kohler & Paulhus [113], also stated that "A simple plotting of annual precipitation versus annual runoff will often display good correlation." The areal rainfall-runoff model can thus be implemented using a log linear regression model.

3.4.4.6 Evaporation records and reservoir evaporation

The evaporation record for the study area spans about 20 years which is far less than the normal lifetime of dams. The evaporation process is also very complex and difficult to estimate using other meteorological data. The monthly evaporation is thus treated as a random variable which fits a particular distribution. The random variable from particular distribution can easily be generated by means of a computer simulation method. The appropriate Chi-squared test indicated that the evaporation record for the study area conforms to the log-normal distribution. The random variable of the log normal distribution* and the random noise ε(t) (paragraph 3.4.4.4) were generated by the Box-Muller method which makes use of one of the following two equations [130]:

\[ N_1 = \left( -2 \cdot \ln(U_1) \right) \cdot \cos(2\pi \cdot U_2) \quad \text{(3-8)} \]

\[ N_2 = \left( -2 \cdot \ln(U_1) \right) \cdot \sin(2\pi \cdot U_2) \quad \text{(3-9)} \]

where U_1 and U_2 are two independent uniform distributions for U(0,1) random variables. N_1 and N_2 will be the independent random variables of N(0,1).

(* if the records fit another type of distribution then other methods must be used to generate that type of independent random variable.)

The pan evaporation records required adjustment by pan factors for the estimation of evaporation from the reservoir. The pan factors for this study was established according to the HRU report No. 2/73 [147], resulting in pan factors of 1.0 for November to June and 0.8 for July to October. The SDSS-model adjusts these factors automatically.

The pan factors are only suitable for Symon's tank records. The class A pan records must be converted to Symon's tank records, thereafter adjusted by the pan factors, and then converted to estimated class A pan records. The conversion can be attained by the following formula [126]:

\[ E_s = 0.625 \cdot E_a + 280 \text{ (mm)} \quad \text{(3-10)} \]

where E_s is the Symon's tank evaporation record

E_a is the class A pan evaporation record

3.4.4.7 Sediments and streamflow
The sediment yield of a catchment is dependent on many factors such as wind, rainfall and rainfall intensity, vegetation, landuse pattern, etc., making the modelling difficult. Added to this is the fact that adequate data are not always easily obtainable or even existent. It is thus difficult to find the relationship between sediment quantity and relevant factors by means of deterministic models.

From Fleming's study (Fleming, 1969, in [113]), the mean annual suspended load \( (Q_s) \) was found to be a function of the mean annual discharge \( (Q) \):

\[
Q_s = \alpha \cdot Q^n \tag{3-11}
\]

where \( \alpha \) and \( n \) are empirical coefficients which depend on the characteristics and circumstances of the catchment area.

The correlation coefficient between the monthly suspended load and the monthly discharge was determined at nearly 0.9 for the study area (Figure 3.18). The inferred monthly suspended load from the monthly discharge (or streamflow) using the above formula is thus acceptable.

The bed load in the river is even more difficult to measure than the suspended load, but according to the HRU report No. 10/81 [126], the bed load is seldom likely to exceed 10% of the total silt load. The total monthly sediments were thus set to 110% of the suspended load, representing a worse case situation.

3.4.4.8 Trap efficiency of the reservoir

Brune derived a relationship between reservoir trap efficiency and the ratio of reservoir capacity to annual inflow, which is widely used nowadays [113]. The relationship is as follows:

\[
Y = 100 \cdot \left( 1 - \frac{1}{1 + \alpha X} \right)^n \tag{3-12}
\]

where \( Y \) is sediments trap efficiency (\%), \( X \) is the ratio of reservoir capacity to annual inflow, \( \alpha \), \( n \) are coefficients, determined by means of 3 types of Brune curves -

- for the mean curve \( \alpha = 100, n = 1.5 \)
- enveloping curve \( \alpha = 130, n = 1.0 \) (upper curve)
- reasonable minimum curve \( \alpha = 65, n = 2.0 \) (lower curve)

(Note: These curves apply to the total sediment load which includes suspended load and bed load.)

The Brune curve has been validated by sediment surveys for the Hendrik Verwoerd and Welbedacht dams (Roberts, 1980, in [126]). In the same report they mentioned that "Rooseboom (1978) in his study of the silting of South African reservoirs has found that generally under South African conditions the Brune curve would be reasonably acceptable for storage reservoirs of a capacity greater than 75% MAR\(^1\). For diversion weirs or reservoirs of an average capacity of say 10% MAR, work by Coetzee (1980) indicates that for South African..."
conditions the Churchill curve would be the more readily applicable."
In conclusion, the Churchill curve would be more suitable for weirs and smaller size reservoirs, the Brune curve would be more suitable for larger size reservoirs.

(* Mean Annual Runoff.)

3.4.4.9 Volume of sediments

In order to compute the volume of sediments at a specified time, the specific weight must be calculated first, using the following formula to obtain the volume of sediments (V).

\[ V = \frac{M}{W} \] (3-13)

where \( M \) is the mass of sediments
\( W \) is the specific weight of sediments

The specific weight (W) can be calculated by the following formula [113].

\[ W_t = W_1 + K \cdot \log(t) \] (3-14)

where \( W_t \) is the specific weight at year \( t \)
\( W_1 \) is the initial specific weight
\( K \) is a coefficient

(Note: The \( W_1 \) and \( K \) value are listed in table 3.7)

The volume can now be computed by the foregoing formulas (3-11 to 3-14).

As time goes by the reservoir will be silted up by sediments, resulting in a diminishing capacity. The reservoir's trap efficiency will also decrease and adjustment of the trap efficiency will be necessary at certain time intervals. For example, in the SDSS-model used for this study, the reservoir's trap efficiency will be adjusted every year.

3.4.4.10 Reservoir yield risk analysis

The risk analysis was based on the Monte Carlo method which employs the random variables in a simulated model. The random numbers are generated by computer using congruential pseudo-random number methods, using the following formula [130]:

\[ X(n+1) = (a \cdot X(n) + \beta) \mod m; \text{ for } n \geq 0 \] (3-15)

where \( a \), \( \beta \), and \( m \) are suitably chosen fixed integer constants.
\( X(0) \) is the seed which can be set by the user.
\( \mod \) is an arithmetical operator, the result of this operation is the remainder, e.g. 5 \( \mod 3 = 2 \); 2 \( \mod 3 = 2 \).

A monthly time interval was chosen for this analysis. Every month the SDSS-model checks the water balance via a budgetary method. The equation is as follows:

\[ S(n+1) = S(n) + I(n) - Y(n) - (E(n) \cdot A(n)) \] (3-16)
where $S(n)$ is storage at the beginning of the month $n$.
$I(n)$ is the inflow of month $n$.
$Y(n)$ is the yield of month $n$.
$E(n)$ is the evaporation of month $n$.
$A(n)$ is the impounded area of the reservoir at month $n$.

The water inflow is mainly from the monthly streamflow which can be derived from the areal rainfall-streamflow relationship (log linear regression model). The stochastic series of monthly areal rainfall can be generated by the method described in paragraph 3.4.4.4. The water consumption is mainly due to the monthly evaporation from the reservoir which can be estimated from the evaporation records and the reservoir area at that time. The random noise based on the statistical distribution of evaporation in the study area should be added to the monthly evaporation from the reservoir because of variance. The sediment is also calculated every month and then converted to volume. The effective storage is also computed for every month, but the trap efficiency is only revised at the beginning of each year and then used throughout the year.

The underground water is excluded in this analysis for lack of adequate information. The leakage of the dam is ignored, because it is very difficult to estimate and may vary from dam to dam, and thus can only be measured after construction.

The yield from the reservoir per month was assumed to be the same for every month. Actually, this is not correct because the monthly water demands are different, but no firm information could be found for the study area. As soon as such information becomes available, the monthly water demand model/distribution can easily be incorporated in the SDSS-model for this study.

There are four output indicators of the analysis which are as follows.

1. Reservoir yield risk:

   risk = No. of failure series / total stochastic series ...(3-17)

   where a failure series is defined as three or more consecutive yield deficient months in the series.

   (Note: Experience showed that the total stochastic series must exceed 1000 series for a reliable result.)

2. Overflow probability (OP):

   OP = No. of overflow month / total simulated month ........(3-18)

   where an overflow month is one where there is a water surplus which must be released.

3. Expected residual capacity (ERC):

   ERC(%) = (residual capacity / initial capacity) • 100 ........(3-19)

4. Expected fullness of dam: which is the average fullness of the
reservoir in the simulation period.

The above indicators are used as indices for adjustment to the designed dam size. For example, if the yield risk is too high then enlargement of the dam size or another more suitable site will be necessary. If the overflow probability is too high then the dam size must be set larger. If the residual capacity is too low then another site may be the only choice because of the usually very high sediments yield in the catchment.

The adjusted dam size can be input to the SDSS-model for an updating/recalculation of the risk analysis. The analysis could be iterated until the results satisfy the expectations of the user. Figure 3.19 shows the process of the reservoir yield risk analysis and the results.

3.4.5 Flood routing through reservoirs

3.4.5.1 The Intensity Duration Frequency (IDF) formulae

The IDF curves for Southern Africa are widely used for applications, but these type of curves are not easy to program for computer analysis. The IDF formulae which were developed and reported in the HRU report No. 2/1982 [141] were adopted for analysis in the study area. The formulae which are as follows, yield practically the same result as that of the IDF curves and are as accurate:

\[
\begin{align*}
\text{Inland region: } i &= \frac{0.3}{(7.5 + 0.034 \times \text{MAP}) \times R} \quad \ldots \ldots (3-20) \\
\text{Coastal region: } i &= \frac{0.3}{(3.4 + 0.023 \times \text{MAP}) \times R} \quad \ldots \ldots (3-21)
\end{align*}
\]

where \(i\) is point rainfall intensity in mm/h.
\(\text{MAP}\) is mean annual precipitation in mm.
\(\text{td}\) is storm duration in hours.
\(R\) is recurrence interval in years.

3.4.5.2 Areal reduction factor

During a storm the distribution and the intensity of rainfall usually is not equal in a catchment everywhere, especially for a large catchment area. Besides, the duration of rainfall over the whole catchment area is subject to inequalities due to variations in the storm path. Thus the point rainfall intensity (derived from the IDF formulae) cannot be used to estimate the total precipitation in the study area during a storm. The areal reduction factor has to be calculated to estimate the areal rainfall from the point rainfall intensity. The following formula was obtained from the HRU report No. 2/1982 [141] for calculating the areal reduction factor:
0.02 \cdot A^n
\begin{equation}
Ra = (1.04 - 0.08 \cdot \ln(A)) \cdot (td) \quad \ldots \ldots (3-22)
\end{equation}

where Ra is the areal reduction factor to be applied to the point rainfall intensity.
A is the size of catchment area in km².
td is the storm duration in hours.
n is a constant which equals 0.28 for this formula.

3.4.5.3 Mean storm loss reduction factor

During the storm, part of the rainfall may be stored on the vegetal cover (interception) and in the surface puddles or pools. Some of the rainfall evaporates back to the air or infiltrates into the ground. Only a certain part of the rainfall will be drained. It is necessary to adjust the actual rainfall contribution to the surface runoff by the mean storm loss reduction factor. The following formulae were obtained from the HRD report No. 2/1982 [141] which were based on the curves presented in the HRU report No. 3/69 and 1/72 [50].

For veld-type zones 1, 3, 8, and 9:
\begin{equation}
Rs = (0.012 - 0.028 \cdot 10^n \cdot A) \cdot (i \cdot Ra \cdot td) \quad \ldots \ldots (3-23)
\end{equation}

For veld-type zones 2:
\begin{equation}
Rs = (0.054 - 1.600 \cdot 10^n \cdot A) \cdot (i \cdot Ra \cdot td) \quad \ldots \ldots (3-24)
\end{equation}

For veld-type zones 4, 5, 6, and 7:
\begin{equation}
Rs = (0.019 - 0.047 \cdot 10^n \cdot A) \cdot (i \cdot Ra \cdot td) \quad \ldots \ldots (3-24)
\end{equation}

where Rs is mean storm loss factor.
A is the size of catchment area in km².
n is a constant, which is equal to -5 for these formulae.
i is point rainfall intensity in mm/h.
Ra is the areal reduction factor.
td is storm duration in hours.

3.4.5.4 Muskingum flood routing

According to Bauer & Midgley [12] "Those who have had some experience of determining design storms and synthesizing flood hydrographs will appreciate that the methods proposed in the Hydrological Research Unit Reports can be rather cumbersome and time-consuming. ....... It was found that unitgraphs could be satisfactorily synthesized by routing excess rain through storage employing Muskingum routing procedures as modified by Nash. ....... The value of K in the routing equation was found to be strongly dependent on size of catchment and vegetal cover but relatively independent of catchment shape, provided of course the shape was not too unusual."

Muskingum flood routing is a very simple procedure to determine the direct runoff from uniformly distributed rain, and it can easily be implemented on computer. For ungauged catchments the values of K
(the routing constant) can be estimated simply from another catchment area with similar size and vegetal cover.

In Muskingum routing the change rate of storage is based on the following continuity equation [11, 12, 113, 37]:

\[
I - O = \frac{dS}{dt} \quad \text{(3-26)}
\]

or in finite differential form

\[
\frac{I_1 + I_2}{2} - \frac{O_1 + O_2}{2} = \frac{S_2 - S_1}{t_2 - t_1} = \frac{dS}{dt} \quad \text{(3-27)}
\]

where \( I \) is the inflow rate to the reach
\( O \) is the outflow rate to the reach
\( S \) is the storage within the reach
\( t \) is time from an arbitrary origin
subscript 1 is the beginning of the time step \( dt \)
subscript 2 is the end of the time step \( dt \).

The stage-discharge and stage-storage relations can be expressed as the exponential functions of stage \( y \).

\[
Q = a \cdot y \quad \text{(3-28)}
\]

\[
S = b \cdot y \quad \text{(3-29)}
\]

where \( Q \) is discharge from reach.
\( S \) is storage of reach.
\( y \) is the stage of flow.

From (3-27), the following two equations can be derived

\[
I = a \cdot y \quad \text{(3-30)}
\]

\[
O = a \cdot y \quad \text{(3-31)}
\]

From (3-28), (3-29) and (3-30), the following two equations can be derived.

\[
S_i = b \cdot \left( \frac{I}{a} \right) \quad \text{(3-32)}
\]

\[
S_o = b \cdot \left( \frac{O}{a} \right) \quad \text{(3-33)}
\]

The Muskingum routing assumes that the inflow rate is not equal to the outflow rate during the passage of a flood wave. The actual storage in the reach during a flood could therefore be assumed to be a weighted means of \( S_i \) and \( S_o \).
\[ S = x \cdot S_1 + (1 - x) \cdot S_0 \] \hspace{1cm} (3-34)

Substitution of (3-32) and (3-33) in (3-34) yields the following equation:

\[ S = \frac{b}{a^n} \cdot \left[ x \cdot I^n + (1 - x) \cdot O^n \right] \] \hspace{1cm} (3-35)

where \( n = i/j \)

The Muskingum routing assumes that \( i/j \approx 1 \) for a natural channel, and takes \( b/a \) as a substitute for \( K \). The equation (3-35) becomes the Muskingum storage equation:

\[ S = K \cdot \left[ x \cdot I + (1 - x) \cdot O \right] \] \hspace{1cm} (3-36)

Substitution of (3-35) in (3-26) yields the final equation:

\[ O_2 = C_0 \cdot I_2 + C_1 \cdot I_1 + C_2 \cdot O_1 \] \hspace{1cm} (3-37)

where

\[ C_0 = -\frac{K \cdot x - 0.5 \cdot t}{K - K \cdot x + 0.5 \cdot t} \]

\[ C_1 = \frac{K \cdot x + 0.5 \cdot t}{K - K \cdot x + 0.5 \cdot t} \]

\[ C_2 = \frac{K \cdot x - 0.5 \cdot t}{K - K \cdot x + 0.5 \cdot t} \]

\[ C_0 + C_1 + C_2 = 1 \]

For \( x = 0 \) storage is a function of the outflow (reservoir routing) and for \( x = 0.5 \) storage is a function of both inflow and outflow (channel routing). In this simulation the catchment is represented by a series of reservoir-type storages (\( x = 0 \)). The inflow to each storage is the excess rainfall on this storage and the outflow from the upstream storage \([12]\).

According to the HRU report No. 1/74 \([12]\), the \( K \) value for the study area is 3.583 and the surface area of study area is 254 km\(^2\). The actual area of the study area was calculated to be 485.16 km\(^2\). The difference is quite big, so the area was manually checked. The result confirmed that the latter is correct. The \( K \) value was therefore overestimated due to underestimation of the catchment area. It was necessary to adjust the area by the revisional factor when estimating the areal rainfall for any subcatchment inside the study area. The revisional factor is 0.523539 (\( = 254 / 485.16 \)) for the study area.

3.4.5.5 Water flow over spillways or crests of dams

The discharge over a sharp-crested weir or the simplest form of overflow spillway can be expressed in the following general form \([37, 33]\):

\[-54-\]
\[ Q = C \cdot L \cdot H \]  \hspace{1cm} \text{(3-38)}

where \( L' = L' - (0.1\cdot N \cdot H) \)

\[ C = 3.27 + 0.40 \cdot \frac{H}{h} \]

\( Q \) is discharge.
\( L' \) is the effective length of the crest.
\( H \) is the measured head above the crest.
\( h \) is the height of weir or spillway.
\( N \) is the number of contractions.
For two end contractions, \( N = 2 \).
For one end contraction, \( N = 1 \).
When no contractions are present at the two ends, \( N = 0 \).

(Note: The above hydraulic formula is only applicable for sharp-crested weirs or the simplest overflow spillways. The designed spillway may be different to the aforementioned simple type, the hydraulic formula must then be revised for the designed type of spillway.)

3.4.5.6 Computer simulation

This simulation procedure for flood routing through a reservoir includes the following steps.

(i) Calculate the point rainfall intensity by the MAP, storm duration, and recurrence interval.

(ii) Estimate the areal reduction factor (Ra) and the mean storm losses reduction factor (Rs).

(iii) Compute the actual areal rainfall (AAR) by the following equation.

\[ \text{AAR} = i \cdot A \cdot \text{Ra} \cdot \text{Rs} \] \hspace{1cm} \text{(3-39)}

(Note: the catchment area (A) needs to be adjusted - see paragraph 3.4.5.4.)

(iv) Implement the Muskingum flood routing to calculate the direct runoff (inflow) to the potential reservoir.

(v) Calculate the discharge (outflow) from the potential reservoir by the hydraulic formula in (paragraph 3.4.5.5) according to the initial condition (fullness) of the potential reservoir and the inflow to the potential reservoir.

Figure 3.20 shows the simulated inflow and outflow hydrographs of the designed flood routing through reservoir.

3.5 Land evaluation in the impounded area of the potential reservoir

The purpose of land evaluation is to evaluate the present and potential land use within the impounded area of the reservoir. In South Africa,
the impounded area at full supply level of reservoirs range normally from tens of thousands of hectares to only a few hectares. The land within the impounded area of reservoir cannot be used any more after the dam starts to store water. It is thus important to carefully evaluate the land within the impounded area of the potential reservoir before beginning the building of a dam.

3.5.1 Land use/cover at present

The existent land use/cover within the impounded area of the potential reservoir cannot be used after the reservoir starts to store water. For example, the roads, bridges, and other public facilities must be moved or rebuilt. The residents and their homes must also be moved to other places. The more intensive the human activity within the impounded area of the potential reservoir, the more expensive it will be to resettle elsewhere. The cost of dam building will thus increase to the extent of the resettlement costs.

The following land use/cover patterns were checked in the impounded area of the potential reservoir when full (the result is shown in Figure 3.21):

(i) Railways, railway stations, bridges, and roads
(ii) Power lines and telephone lines
(iii) Post offices, police stations, stores, hotels, schools, and churches
(iv) Lighthouses and marine beacons
(v) Magnetic stations and ground signs
(vi) Residential area (rural and urban)
(vii) Monuments
(viii) Dipping tanks
(ix) Windmills
(x) Walls
(xi) Anti-erosion walls
(xii) Perennial and non-perennial rivers
(xiii) Canals and pipelines
(xiv) Marshes and swamps
(xv) Lakes and reservoirs
(xvi) Cultivated lands
(xvii) Orchards and vineyards
(xviii) Bush and dense bush
(xix) Trees and forests

These land use/cover patterns were digitized from South Africa 1:50 000 sheets (2330CC, 2330CD, 2430AA & 2430AB). Some land use types in the catchment area (upstream of reservoir) must be strictly forbidden to avoid increasing sedimentation and reduce the lifetime of the dam ("forbidden land-use boundary decision" within the context of the SDSS-model).

The land cover information could also be derived from remotely sensed imagery (e.g. Landsat or SPOT) or for updating the land use/cover information which was captured from the outdated maps [110]. The remotely sensed imagery is fully compatible with the developed SDSS-model because both of them are based on the raster data model.

3.5.2 Land capability classification
The land capability classification was first developed by the United States Department of Agriculture (USDA) in the early 1960s for evaluating "the potential of the land for use in specified ways, or with specified management practices" [49]. An assumed sequence of uses is built into the classification system. They are as follows in descending sequence of assumed desirability [49]:

(a) Arable use for any crops and economic plants without soil conservation practices.
(b) Arable use for choice crops and economic plants and/or with soil conservation practices.
(c) Improved pastures for grazing.
(d) Natural pastures for grazing or woodland.
(e) Recreation, wildlife conservation, water catchments and aesthetic purposes.

Land capability classification is based on the permanent limitations of the land which affect the land use pattern of that land [49, 64]. Permanent limitations are the land characteristics which cannot be easily modified, e.g. slope, soil depth, rainfall, flood risk, etc. On the other hand, the temporary limitations of the land can be modified and improved by proper management, e.g. the soil nutrient content of the land can be improved by soil fertilization [49].

There is still no standard land capability classification system for use in South Africa yet. The method which was adopted for this research was developed by the Departments of Agriculture and Environment Affairs [160]. This system includes the soil and the land capability classification*. The objectives and assumptions of the classification are discussed in the following paragraph (3.5.2.1). The structure and categories of the system are described in paragraph 3.5.2.2 and the definitions and criteria of the soil and land capability classes are listed in paragraph 3.5.2.3 and 3.5.2.4.

(* The land capability classification includes the assessment of the soil factors, terrain factors and climatic factors while the soil capability classification only includes the soil factors and terrain factors.)

3.5.2.1 The objectives and assumptions of the classification

"The prime objective of the system for assessing soils and land capability is the systematic arrangement of different kinds of land to show their most intensive longterm use for agriculture, and at the same time indicate the permanent hazards attached to the use of each class" [160]. The soil and land capability classification system was developed to help the landowners and the planners in South Africa to make rational choices between various land use options.

A number of assumptions have been made for applying the system in land evaluation practice. The assumptions are listed as follows [160]:

(i) "Land capability is determined mainly by the collective effects of soil and terrain features and climate"

(ii) "The land capability system has pedological significance since
it is derived from soil units defined and mapped in terms of soil classification. It is assumed that the capability classification will be preceded by an appropriate soil survey and that the information will then be appropriately interpreted taking account of specified criteria.

(iii) "Soil/land will be classified according to its present limitations in use even though it may be feasible to remove the limitation (e.g. prevention of flooding, removal of stones or boulders). Despite economic consequences low nutrient status is not considered a limitation since it is assumed that inherent nutrient deficiencies/toxicities will be rectified by appropriate liming and/or fertilization. Similarly, the rise and fall of fertility status within the topsoil over time is assumed to be non-restrictive for capability assessments"

(iv) "The capability classification system will be applied to rainfed agriculture. Where irrigation is envisaged or possible, a separate irrigation suitability assessment should be made"

(v) "Economic considerations such as proximity to markets and capital resources of the farmer will influence final land-use recommendations but are not criteria for soil/land capability assessments. Availability of capital to provide necessary inputs (e.g. fertilizer) is assumed"

(vi) "Soils suited to crop production are also suited to other less intensive uses such as pasture, natural grazing, forestry and wildlife. Intensity of use refers primarily to the degree of cultivation"

(vii) "Modern farming methods and good management are assumed. This implies the construction and maintenance of necessary soil conservation works and the availability of machinery required to timeously complete mechanical operations"

3.5.2.2 The structure and categories of the classification system

The soil/land capability classification has four categories*: land capability units, subclasses, classes and order (Table 3.8). The categories are described as follows [160]:

(i) Land capability order: "The land capability order is a grouping of capability classes reflecting a very general assessment of arability and agricultural potential". They are as follows:

"Order A: Arable land - high potential land with few limitations (Classes I and II)"
"Order B: Arable land - moderate to severe limitations (Classes III and IV)"
"Order C: Grazing and Forestry Land (Classes V, VI and VII)"
"Order D: Non-agricultural land (Class VIII)"

(ii) Land capability classes: "This level is the category of the most used for assessment purposes and places all land in eight capability classes. By convention these classes are designated by Roman numerals and comprise groups of capability units or subclasses that have the same relative degree of limitation or
potential". Class I to IV are generally suited for cultivation. Class V to VI are not suited for cultivation, but some smaller intensity land use patterns are permitted, e.g. pasture, forestry, etc. Class VII can be used only for afforestation. Class VIII cannot be used for any kind of commercial production. The detailed definitions of the land capability classes will be described in the next paragraph.

(iii) Land capability subclasses: "Land capability subclasses comprise capability units with the same kind of limitation or problem. Six major kinds of limitations are recognized at the subclass level and are applied when a specific hazard is the dominant problem affecting land-use". These limitations and their suffix notations are as follows:

"erosion hazard (e)"
"excess wetness (w)"
"excess flooding (f)"
"root zone limitations (d)"
"mechanical limitations (m)"
"climatic limitations (c)"

For example, the subclass Ile consists of the class II land but it has soil erosion hazard limitation.

(iv) Land capability units: "Land capability units comprise one or more soil mapping units with similar agricultural potential and limitations". The land use/cover pattern with the unit is nearly uniform. Units are expressed by arabic numbers, e.g. I1w-2, Ile-3.

The land which is allocated to any particular soil/land capability class (or order) can also be used for the specified land use pattern(s) in that class and for all classes below it. Table 3.9 shows the relationship between land capability classes, orders and intensity of use.

(* There are only three categories of the USDA system, i.e. capability classes, capability subclasses and capability units [64, 49, 48].)

3.5.2.3 The definitions of the soil/land capability classes

The definitions of the soil/land capability classes are listed as follows [160]:

Class I: "Land in Class I has few permanent limitations that restrict its use and has a very high potential for intensive crop production"

Class II: "Land in Class II has some permanent limitations that reduce the degree of intensity of crop production but is nevertheless of high potential"

Class III: "Land in Class III has severe permanent limitations that restrict the choice of alternative uses and the intensity of crop production and is of moderate potential"

Class IV: "Land in Class IV has very severe permanent limitations that greatly restrict the choice of alternative uses and the potential for crop production"

Class V: "Land in Class V is unsuitable for the cultivation of annual
crops, but has very slight erosion hazard under natural veld, established pastures, forestry or special crops"

Class VI: "Land in Class VI has permanent limitations that make it unsuited to cultivation and limit its use to natural grazing, veld reinforcement, afforestation or wildlife"

Class VII: "Land in Class VII has very severe permanent limitations that render it unsuitable for cultivation or intensification and restrict its use to natural grazing, afforestation or wildlife"

Class VIII: "Land in Class VIII has permanent limitations that preclude its use for commercial agricultural production and restrict its use to wildlife, recreation, water supply or aesthetic needs"

3.5.2.4 The criteria for determining the soil/land capability classes

Eight factors must be considered for determining the land capability classes (only seven factors for soil capability classes). However, some of the factors in the classifications must be obtained by field investigation. It was therefore not possible to implement the entire classification in this study due to insufficient data. In order to obtain all the relevant data, extensive and expensive field investigation had to be undertaken. Because this part of the study is of secondary importance to the total study, it was decided to make do with a simplified classification method.

The following simplified factors/criteria which are based on the soil and land capability classification for South Africa were adopted for this study. The method classifies the land capability for each pixel within the impounded area of reservoir into one of eight classes. Class I - IV are arable land and V - VIII non-arable land. The classification criteria include erosion hazard, flood hazard, effective soil depth, top soil texture, mechanical limitations, and climatic factors. The simplified elimination key for determining soil/land capability classes is shown in Table 3.10. The simplified classification factors/criteria used in this study are described in the following section. It should be kept in mind that field investigation is imperative if a more detailed analysis is required. Figure 3.22 shows the result of the classification.

(i) Erosion hazard (terrain factor)

The soils are firstly divided into one of four groups which are as follows:

Group 1: Soils are ferrallitic and have a K-value generally less than 0.15.
Group 2: Soils are non-ferrallitic and non-duplex without an E horizon or a clay increase in the B horizon (or luvic) horizon. The K-value is generally less than 0.35.
Group 3: Soils are the same as for group 2, but the K-value is generally less than 0.45.
Group 4: Soils are duplex, B-horizon soils. The K-value is generally greater than 0.45.

Explanation of terminology:

• K-value (soil erodability factor) can be obtained by using the
nomograph proposed by Wischmeier & Smith (Wischmeier & Smith, 1978, in [160]).

• Ferrallitic soils: "highly weathered red and yellow, porous, friable, acid loams and clays of the high rainfall areas" [160].
• Clay increase in the B horizon or luvic horizon: "a B horizon with the following properties:
  (a) when any part of the A1 horizon has less than 15% clay then the B21 horizon must contain at least 5% more clay; or
  (b) when the A1 has 15% or more clay the ratio of clay in the A1 to that in the B21 must be 1:1.3 or more" [160],
• Duplex soil: "soils with a relatively permeable topsoil abruptly overlying a very slowly permeable diagnostic horizon which is not a hardpan" [119].

The erosion hazard can thus be determined according to the soil groups and slope angle (Table 3.11).

(ii) Flood hazard (terrain factor)

The flood hazard was modified and can be estimated by the method described in 3.4.5, including the following steps:

Step 1: Calculate the flood hydrographs from the return period.
  For F1: 100 years return period,
  F2: 40 years return period,
  F3: 4 years return period,
  F4: 2 years return period,
  F5: the land is usually covered by water (or river bank, lake bank).

Step 2: Compute the maximum stage of flood for F1 to F4 from the flood hydrographs (step 1).

Step 3: Evaluate the flood hazard.
  For each pixel within the impounded area of reservoir.
  (a) Retrieve the height (altitude) of the pixel from DEM.
  (b) If the height of the pixel is higher than the maximum stage of F1, it is regarded as F1*.
  If the height of the pixel is higher than the maximum stage of F2 and less than F1, it is regarded as F2.
  The rest may be inferred by analogy.

(* That is, the land in this pixel will not be immersed by water during the flood with 100 years return period.)

(iii) Effective soil depth (soil factor)

"Effective soil depth is the limit to soil material that plant roots can penetrate to obtain water, air, and nutrients" [160]. It is an important property affecting moisture supply to crops and plants. The criteria for the effective depth are as follows:

    D1: soil depth > 1 000 mm
    D2: soil depth between 600 - 1 000 mm
    D3: soil depth between 400 - 600 mm
    D4: soil depth between 250 - 400 mm
    D5: soil depth < 250 mm

(iv) Soil texture (soil factor)
Soil texture influences mainly the moisture content and erodability of soils. The criteria are as follows:

Group 1: T3 class, sand.
   T2 class, loamy sand (contain ≥ 80% sand).
   T1 class, the rest.

Group 2: T3 class, sand.
   T2 class, clay and loamy sand (contain ≥ 80% sand).
   T1 class, the rest.

Group 3: T3 class, sand.
   T2 class, clay and loamy sand.
   T1 class, the rest.

Group 4: T3 class, sand and clay.
   T2 class, loamy sand.
   T1 class, the rest.

(v) Mechanical limitations (soil factor)

For this study only stoniness and/or shallowness were considered. The information was extracted from the "Land types of the maps (2330 Tzaneen & 2430 Pilgrim's Rest)" [91] which includes the following five classes:

"MBO - no mechanical limitations"
"MB1 - many stones, but ploughable"
"MB2 - large stones and boulders, unploughable"
"MB3 - very shallow soils on rock"
"MB4 - lack of soil"

(vi) Climatic factors

The following climatic measurements were used for determining the soil/land capability classes:

(a) The average monthly precipitation and evaporation as estimated from records of the nearest gauging station.
(b) The average maximum and minimum monthly average temperatures obtained from the "Land types of the maps (2330 Tzaneen & 2430 Pilgrim's Rest)" [91].

The temperature required for the growth of crops was assumed to be 30°C for the upper range and 15°C for the lower range in the growing season. The criteria can thus be modified from the original one for easier quantitative computation. The frost hazard was not taken into account due to insufficient information - it is also commonly known that the study area is largely frostfree. The criteria are as follows:

C1 - Average monthly rainfall records > 1/2 A pan evaporation records. Maximum monthly average temperature ≤ 30°C and minimum monthly average temperature ≥ 15°C.
C2 - Average monthly rainfall records > 1/2 A pan evaporation records. Maximum monthly average temperature > 30°C or minimum monthly average temperature < 15°C.
C3 - Average monthly rainfall records > 1/3 A pan evaporation records. Maximum monthly average temperature ≤ 30°C and minimum monthly average temperature ≥ 15°C.
C4 - Average monthly rainfall records > 1/3 A pan evaporation records. Maximum monthly average temperature > 30°C or
minimum monthly average temperature < 15°C.

C5 - Average monthly rainfall records ≤ 1/3 A pan evaporation records. Maximum monthly average temperature ≤ 30°C and minimum monthly average temperature ≥ 15°C.

C6 - Average monthly rainfall records ≤ 1/3 A pan evaporation records. Maximum monthly average temperature > 30°C or minimum monthly average temperature < 15°C.

3.5.3 Land suitability evaluation

Land suitability evaluation was developed in the 1970s by the Food and Agriculture Organization (FAO) of the U.N. for evaluating "the suitability of land for specified kinds of use" [49]. In general, land suitability evaluation is the process of assessing the suitable land for a specific use, e.g. forestry, irrigated rice production, etc. Therefore it cannot be used as a fully developed scheme [64]. On the other hand, the main disadvantage of the land capability classification is "the failure to classify land adequately for uses other than arable" [49]. The land suitability evaluation seems to have a great potential for using in land use planning schemes at regional or even national levels because it goes beyond broad generalities.

3.5.3.1 The structure and definitions of the evaluation system

The land suitability evaluation has four categories, i.e. land suitability orders, classes, subclasses and units (Table 3.12). These categories are as follows [49, 64] :

(i) Land suitability orders : "These indicate whether the land is suitable or not suitable for a specific use" [64]. There are three main reasons that the land may be classified as not suitable, i.e. technically impracticable, environmentally undesirable and economically unprofitable [49]. The definition of the orders are as follows [64, 49] :

- Order S suitable : "Land on which sustained use of the kind under consideration is expected to yield benefits which justify the inputs, without unacceptable risk of damage to land resources"
- Order N not suitable : "Land which has qualities that appear to preclude sustained use of the kind under consideration"

(ii) Land suitability classes : "Any number of classes may be distinguished and may indicate the extent to which the land is suitable for the defined use and are indicated by Arabic numbers" Normally three classes for Order S and two classes for Order N are presented which are described as follows [64, 49] :

- S1 Highly suitable : "Land having no significant limitations to the sustained application of the defined use"
- S2 Moderately suitable : "Land having limitations which will reduce production levels and/or increase costs but which is physically and economically suitable for the defined use"
- S3 Marginally suitable : "Land having limitations which will reduce production levels and/or increase costs making it economically marginal for the defined use"
- N1 Currently not suitable : "Land having limitations which may be surmountable in time but which cannot be corrected with
existing knowledge at presently acceptable costs and which preclude successful sustained use in the defined manner"

• N2 Permanently not suitable: "Land having limitations so severe as to prevent any possibility of successful sustained use in the defined manner"

(iii) Land suitability subclasses: These are "divisions of the classes based on the nature of the limitation" [64]. They are expressed by the lower-case letters as follows:

n : for soil nutrient deficiency.
m : for moisture deficiency.
e : for erosion hazard.
t : for topographic limitation.

The lower-case letters are placed after the class symbol, e.g. S2m, S2t. There is no restriction for the numbers of the subclasses nor the indicated symbols at present. There are no subclasses in S1 due to its definition.

(iv) Land suitability units: "These are divisions of subclasses that differ from each other in detailed aspects of their production characteristics or management requirements" They are indicated by successive Arabic numbers following a hyphen, e.g. S2e-1, S2e-2, S2e-3, etc.

In conclusion, the land capability classification is designed for generalised purpose land evaluation while the land suitability evaluation is related to a specific form of land use [49, 64].

3.5.3.2 The criteria for determining the land suitability classes

In this study only land suitability orders and classes were used for determining the land suitability classes due to the lack of field survey data as mentioned in paragraph 3.5.2.4. A simple example for evaluating suitable land for a playing field (or sports ground) was presented in this study. The following orders and classes were used in the evaluation process.

Order S (suitable)
  Class S1 (highly suitable)
  Class S2 (Moderately suitable)
  Class S3 (Marginally suitable)
Order N (not suitable)
  Class N1 (Currently not suitable)
  Class N2 (Permanently not suitable)

The elimination key for determining land suitability classes is shown in Table 3.13. The result of the land suitability evaluation for the playing field is shown in Figure 3.23. The factors/criteria for the evaluation are as follows:

(i) Terrain factor

For the terrain factor only the slope of the pixel was considered. The slope criteria are as follows:

S1 - slope < 5°
(ii) Flood hazard

The flood hazard criteria are exactly the same as described in the paragraph 3.5.2.4.

(iii) Soil effective depth

The soil effective depth criteria are exactly the same as described in the paragraph 3.5.2.4 because the playing fields usually need vegetation cover.

(iv) Soil texture

The soil of a playing field must be able to drain water quickly away from the soil surface after rainfall. Walking on moist clay may be slippery, therefore top soil which contains too much clay will not be suitable for a playing field. Since the playing field is always covered by grass, gravel will not be suitable for the playing field either. The criteria are as follows:

- $T_1$ - SW,SM,SC (unified soil classification, refer to paragraph 3.7)
- $T_2$ - ML,SP
- $T_3$ - CL
- $T_4$ - the rest

(v) Mechanical limitations

The criteria of mechanical limitations are the same as described in paragraph 3.5.2.4.

(vi) Climatic factors

Since the playing field is for outdoor recreation, too much rain may not be suitable for the playing field and also increases the maintenance costs due to the fast growing grass. Too little rain may also increase the maintenance costs, because the grass will need irrigation. The criteria for the climatic factors are as follows (the source of precipitation and temperature data are the same as described in paragraph 3.5.2.4).

- $C_1$ - Average monthly rainfall between 500 - 1500 mm.
  Maximum monthly average temperature $\leq 30^\circ$C and minimum monthly average temperature $\geq 10^\circ$C.
- $C_2$ - Average monthly rainfall between 200 - 1500 mm.
  Maximum monthly average temperature $\leq 30^\circ$C or minimum monthly average temperature $\geq 10^\circ$C.
- $C_3$ - Average monthly rainfall between 0 - 1500 mm.
  Maximum monthly average temperature $\leq 30^\circ$C or minimum monthly average temperature $\geq 10^\circ$C.
- $C_4$ - The rest.

3.5.4 Mines
In this study the following kinds of mines were located in the impounded area of the potential reservoir:

(i) Working mines  
(ii) Abandoned mines  
(iii) Location of mineral occurrences (potential mines)  

Inundated working mines will have total production loss. The cost of the dam building project will soar due to the compensation for the mine owners. If prospecting indicated that there are large economic deposits of minerals in the impounded area of the potential reservoir, another dam site may have to be considered, depending on the value/scarcity of the mineral. Abandoned and working mines may also cause leaking from the reservoir. It may also cause undue settlement of the dam wall and foundation due to the heavy water load. In general, working mines should not be inundated within the reservoir mainly because of economic considerations. Abandoned mines and mineral occurrences may need further investigation, if inundation by water will occur. Figure 3.24 shows the result of analysis.

3.6 Topographic suitability analysis

The topography of the potential dam site has an important influence on the cost of dam building. The cost of different dam types at the same site are usually not the same, hence the type which can be built at the lowest cost will usually be chosen at that site*. There are no strict rules to decide which type of dam should be fitted into which kind of topography and vice versa. This part of the SDSS-model thus only suggests the possible dam type(s) at the potential dam site according to the geometric shape of the site. The process for selecting a dam type is based on the topography - dam type decision table (Table 3.14) which was compiled from relevant literature about this issue [4, 7, 8, 13, 14, 15, 55, 86, 108, 115, 212]. The following geometric shapes of the potential dam site can be determined automatically from the DEM, slope angle and aspect at the site:

(i) Topographic limitation of the dam height: The maximum height of abutments (both right and left abutment) is the topographic limitation of the dam height.

(ii) The axis of the dam wall: The axis is taken to be the perpendicular direction of the dam wall (Figure 3.25). The axis is denoted from the aspect (refer to paragraph 3.2.1.4).

(iii) Average slope of the right/left abutment: The average slope of the abutment along the profile of the potential dam site can be calculated by the least square method. It is an indicator for the valley shape (Figure 3.25).

(v) Width - height ratio: The ratio is the width of the valley to the height of the valley (Figure 3.25). The smaller the width - height ratio, the narrower the valley. It is an important indicator for selecting the dam type, e.g. arch dams usually need a narrow valley with a width - height ratio less than 3.0 [4].

(vi) Relief: The relief is the maximum difference of altitude in the vicinity of the potential dam site. It is an indicator for distinguishing the land feature, e.g. plain, hilly area,
mountainous area, etc.

(vii) Valley shape: This relates to the geometric form of the valley, e.g. V-shape or U-shape valley, broad or steep valley, etc. It is also an important indicator for dam type selection, e.g. arch dams need a steep and V-shape (or U-shape) valley [4].

(viii) Width of valley bottom: The width of the valley bottom where the slope is nearly flat. Some dams like earthfill dams and gravity dams are suitable in a wide valley with a flat floor, because the cost for those dam types are much lower than for most of the other dam types in this kind of valley [4, 7].

(ix) Valley symmetry: The geometric shape and characteristic of both the left and right part of the valley are nearly the same. Only an arch dam needs a symmetric valley but it is not a controlling factor [4].

The detailed cost estimation of each dam type at a specific dam site should be embarked for selecting the proper dam type at the design stage. A cost analysis submodel may be more suitable than this topographic suitability analysis in the dam type selection phase. Figure 3.26 shows the result of the analysis.

(* Other factors must also be considered for deciding on a suitable dam type, e.g. dam foundation, etc.)

3.7 Construction materials in the vicinity, suitable for dam building

"... Without the use of a classification system, published information or recommendations on design and construction based on the type of material are likely to be misleading, and it will be difficult to apply experience gained to future design. Furthermore, unless a system of conventional nomenclature is adopted, conflicting interpretations of the terms used may lead to confusion, rendering the process of communication ineffective" [206]. Thus a proper rock/soil classification system needs to be chosen or developed before any inventory concerning rocks/soils available in the vicinity are undertaken.

3.7.1 Soil classification

A soil classification system involves grouping the different soil patterns into categories which possess similar properties. Since there are so many properties in natural soil, it is impossible to develop a universal system for soil classification. Most of the soil classification systems are based on those soil properties which are the most important for their particular applications. For dam building a soil classification system will be more concerned about the engineering properties of soil. The Casagrande system represents one of the first comprehensive engineering classifications of soil [14, 15]. In this system the particle size of grained soils is used to classify soils. The Unified Soil Classification (USC) and British Soil Classification (BSC) are outgrowths of the Casagrande-system. In South Africa soil classification systems were mainly developed for agriculture purposes and a soil classification system for engineering purposes has not been established yet. The USC was thus adopted in this study because it was widely used in dam building operations. Sower [173] stated that "The Unified System has proved very useful in classifying soils for many
different purposes such as highway and airfield construction, earth dams, embankment, and even for foundations". The USC catalogues soils into 15 classes which are as follows [173, 174]:

(i) GW : well-graded gravels, sandy gravels.
(ii) GP : gap-graded or uniform gravels, sandy gravels.
(iii) GM : silty gravels, silty sandy gravels.
(iv) GC : clayey gravels, clayey sandy gravels.
(v) SW : well-graded sands, gravelly sands.
(vi) SP : gap-graded or uniform sands, gravelly sands.
(vii) SM : silty sands, silty gravelly sands.
(viii) SC : clayey sands, clayey gravelly sands.
(ix) ML : silts, very fine sands, silty or clayey fine sands, micaceous silts.
(x) CL : Low plasticity clays, sandy or silty clays.
(xi) OL : Organic silts and clays of low plasticity.
(xii) MH : Micaceous silts, diatomaceous silts, volcanic ash.
(xiii) CH : Highly plastic clays and sandy clays.
(xiv) OH : Organic silts and clays of high plasticity.
(xv) Pt : Peat, sandy peats, and clayey peat.

The soil classes of USC for this study were interpreted from the 1/250 000 land type map series. Some classes, however, may have been misinterpreted because the field investigation and soil classification for this series of maps were for agricultural purposes. Furthermore, as Sower [173] stated about USC that "Many soils can be grouped visually, and only tests for grain size and plasticity are necessary for accurate classification. It must be kept in mind, however, that no classification is a substitute for tests of the soil's properties and engineering analysis of the results". Field investigation is essential for the further stages in any dam building operation.

3.7.2 Rock classification

Two types of rock classification systems have been developed [14, 15]. One is based on some selected properties of the intact rock, the other based on the properties of the rock mass, i.e., the natural discontinuities inside the rock mass. The latter is more suitable for engineering purposes. Since there were no any engineering geological maps available nor any intensive field surveying undertaken for the study area, it is impracticable to employ a rock classification system for this study. Thus the rock type was interpreted from the 1/250 000 geological map series and as mentioned in paragraph 3.7.1, some rock types might also have been misinterpreted. The in situ test for rock mass should be embarked on at a later stage.

3.7.3 The transport distance of construction materials

The most economical type of dam is often the one of which the construction materials can be found in sufficient amount within a reasonable transport distance from the potential dam site [4]. The transport distance strongly affects the construction costs of a dam and depends on the location of a potential dam site relative to the sources of materials, i.e., existing quarries, material suppliers and potential local borrow areas for construction materials. It is possible to estimate the transportation cost to a specific dam site. Due to a severe time constraint, only the transport distance was calculated for this study. However, the model for estimating the transportation cost can
easily be incorporated at a later stage.

3.7.4 The transport route and distance from dam site to existing quarries

In this study, the following weighted score function was used in the SDSS-model to find the least inclined route to existing quarries:

\[ S(i) = W_d \cdot |dD(i)| + W_a \cdot |dA(i)| + W_t \cdot Nt(i) + W_s \cdot Is(i) \quad (3-40) \]

where

- \( S(i) \) is the score (or value) of the route \( i \).
- \( dD(i) \) is a direction indicator, i.e. the aspect difference in angle between the direction of the destination and route \( i \).
- \( dA(i) \) is a relief indicator, i.e. the altitude difference between the position of the junction (or cross) and route \( i \).
- \( Nt(i) \) is an urban indicator, i.e. the number of pixels which contain build-up area (or urban, town) along route \( i \).
- \( Is(i) \) is an undulation indicator.

\( W_d, W_a, W_t, W_s \) are weights which can be adjusted by the user.

This function (equation 3-40) will be evoked to decide the route when the SDSS-model reaches a junction or cross. The SDSS-model first computes the value of those indicators, then calculates the score of each possible route by summing the products of those indicators and their weight. The route with the highest score will be chosen as the transport route for trucks to transport the construction materials. The function will be evoked again when the SDSS-model reaches another junction or cross. The SDSS-model will stop after arriving at the destination. The total transportation distance is the total length of pixels crossed. The weight of the indicator can be adjusted to suit different topographic areas, e.g. in a mountainous area the undulation indicator is more important than the direction and urban indicators; the weight of the undulation indicator should therefore be increased. Figure 3.27 shows the traced transportation routes for construction materials from existing quarries to the potential dam site.

3.7.5 The shortest distance from the potential dam site to construction material suppliers

The shortest distance from the dam site to construction material suppliers can be calculated by means of a network model [41, 98]. The location of suppliers, the potential dam site and end point of roads* (Figure 3.28) were taken to be nodes. The distance between the potential dam site and the end point of roads can be measured by the SDSS-model itself using the method described in paragraph 3.7.4 (Figure 3.29). The distance between the suppliers outside the study area and the end point of roads was measured manually. Thereafter the network model was used to solve the shortest distance problem. The algorithm is very simple and can be described as follows [41]:

(i) Find the nearest node to the origin (i.e. the potential dam site) by searching every node which is connected to the origin by road.
(ii) Find the next-nearest node to the origin, and then find the next-next-nearest node to the origin and so on.
(Note : If there is no existing road from the potential dam site to nodes the SDSS-model will search the smoothest route and calculate the distance.)

The algorithm will stop after reaching the destination. During the
process, any route that is obviously not the shortest route will be eliminated in order to simplify the calculation. Table 3.15 to 3.18 shows the shortest distance to the various construction material suppliers.

(* The end point of roads are the road ends at the boundary of the study area, i.e. from where onwards no digitization was done.)

3.7.6 Potential local borrow areas for construction materials

3.7.6.1 Suitable construction materials for dam building

The construction materials for dam building may include one (or more) of the following items [77]:

(i) Permeable soils
(ii) Impermeable soils
(iii) Rocks
(iv) Aggregates

The criteria for suitable soils for dam building were adopted from Lo & Chen [115], Sowers [173] and Bell [15] which used USC as the soil classification system and adopted it for dam building purposes (Table 3.19). Harboe & Kramer [77] stated about rock materials for dams that "Preference should be given to locating igneous rock, second choice is massive metamorphics, the well-cemented sandstone or limestone. Desirability of a material decreases with increased weathering and alteration. Sedimentary rocks containing clay should be suspected of weakness". Thus the igneous and metamorphic rocks were considered as suitable construction materials for dams and the well-cemented sedimentary rocks (i.e. conglomerate, limestone, sandstone; etc.) were considered as the second choice materials in this study.

3.7.6.2 Recognizing the terrain features

The sources of construction materials can possibly be recognized by means of pattern recognition methods. The potential sources are as follows [77]:

(i) Alluvial cones
(ii) Alluvial fans
(iii) Flood plain
(iv) River terrace
(v) Lacustrine deposits
(vi) Glacial deposits
(vii) Morainal deposits
(viii) Glacial outwash
(ix) Sand dunes
(x) Loess
(xi) Rock outcrop/cliff
(xii) Talus

In the study area only (i) - (iv) and (xi) were found from the topographic maps and airphotos. These terrain features can possibly be recognized by means of the edge enhancement (Laplacian filter) technique [124]. In this study a 3 x 3 window was used for spatial filtering (or convolution). The Laplacian edge enhancement coefficients were set as follows:
0 -1 0
-1 4 -1
0 -1 0

Figure 3.30 shows the distribution of the potential borrow areas for the construction materials.

3.8 Seismic Risk Analysis

3.8.1 Earthquake recurrence

When designing a dam, the designer may want to know the largest earthquake that may occur near the site under consideration. The recurrence of major earthquakes may be assessed from the historical data. From the research of Allen, St Amand, Richter and Nordquist (in Smith, [170]), the earthquake recurrence can be expressed by the following equation:

\[ \log N = a - b \cdot M \] (3-41)

where \( M \) is Richter scale magnitude.
\( N \) is the annual frequency of earthquakes exceeding magnitude \( M \) within a specified region.
\( a, b \) are constants.

The magnitude of major earthquakes at a specified recurrent interval can be estimated by equation 3-41. Figure 3.31 shows the earthquake recurrence in the study area. Figure 3.32 shows the relationship between the magnitude of body waves (\( M_b \)) and surface waves (\( M_s \)) in the study area which was derived by means of linear regression analysis.

3.8.2 Seismic risk

3.8.2.1 Operating basis earthquake (OBE)

The OBE is the magnitude of the earthquake which will be expected to occur once in the lifetime of structures [170]. A dam should be designed to withstand such an earthquake without serious damage. The OBE can be estimated from historical records by equation 3-41.

3.8.2.2 The peak horizontal ground motion

The peak horizontal ground motion can be estimated by the following equation [42, 170]:

\[ Y = b_1 \cdot e^{b_2M} \cdot b_3 \cdot R \] (3-42)

where \( M \) is the magnitude of earthquake.
\( R \) is the focal distance = \( \sqrt{r^2 + h^2 + 20^2} \).
\( r \) is the epicentral distance.
\( h \) is the depth to hypocentre.
\( 20 \) is the correction factor.
\( b_1, b_2, b_3 \) are constants whose values are as follows:

(i) When \( Y \) is acceleration, \( b_1 = 2000, b_2 = 0.8, b_3 = 2.0 \).
(ii) When \( Y \) is velocity, \( b_1 = 16, b_2 = 1.0, b_3 = 1.7 \).
(iii) When Y is displacement, \( b_1 = 7, b_2 = 1.2, b_3 = 1.6. \)

This equation can be used to estimate the peak horizontal ground motion resulting from a specified magnitude and focal distance of an earthquake.

### 3.8.2.3 Evaluation of seismic risk at the potential dam site

The seismic risk analysis in this study was based on the research of Cornell [42] and Smith [170]. In their research, earthquakes are assumed to occur randomly as independent events. Thus earthquake events follow a Poisson distribution, the probability of exactly \( n \) earthquakes in excess of magnitude \( M_0 \) occurring in any one year can be estimated by the following equation:

\[
P(n) = \frac{-N_0}{n!} \cdot e^{N_0} \quad \text{........................................ (3-43)}
\]

where \( N_0 \) is the average annual frequency of earthquakes greater than the smallest magnitude of interest (\( M_0 \)).

Given that an earthquake occurs at a focal distance (\( R \)), the probability density function of its magnitude (\( f(M) \)) is thus a diminishing function (Figure 3.33). The probability between the magnitude \( M_0 \) and \( M \) can be calculated by

\[
F(M) = \int_{M_0}^{M} f(M) \, dM \quad \text{........................................ (3-44)}
\]

From the research of Epstein and Lomnitz (in Smith, [170]), the following formula can be used to represent the cumulative distribution function (c.d.f.) of large earthquakes:

\[
F(M) = 1 - e^{-\beta (M - M_0)} \quad \text{........................................ (3-45)}
\]

Where \( \beta = b \cdot \ln 10, \ M > M_0. \)

Substituting 3-45 in 3-44:

\[
f(M) = \beta \cdot e^{-\beta (M - M_0)} \quad \text{........................................ (3-46)}
\]

The probability that there are exactly \( n \) earthquakes and all of them are less than \( M \) may be calculated by means of the product law of conditional properties.

\[
P(n \mid \text{mag} < M) = \frac{-N_0}{n!} \cdot e^{-\beta (M - M_0)} \cdot \left(1 - e^{-\beta (M - M_0)}\right)^n \quad \text{........................................ (3-47)}
\]

Thus the probability that no earthquakes in any one year will exceed \( M \) can be given by the summation of equation 3-47.
The probability of the annual maximum ground motion which will exceed a specified value (Y) at a focal distance (R) can be derived by equations 3-42 and 3-48. Hence

\[ P(Y_{\text{max}} > Y) = P(M_{\text{max}} > M) = 1 - e^{-\beta(M - M_0)} \]

From equation 3-42, \( M = (1/b_2) \cdot \ln(Y/b_1) \cdot R \).

Substituting \( M \) in equation 3-49 by 3-50.

\[ P(Y_{\text{max}} > Y) = 1 - e^{-\beta/b_2 - \Gamma} \]

where \( \Gamma = \beta b_3/b_2 \).

In the case of large earthquake magnitudes, the power of equation 3-51 will approach 0. Therefore, equation 3-51 can be simplified to the following equation:

\[ P(Y_{\text{max}} > Y) = N_0 \cdot C \cdot Y \cdot R \]

Equation 3-52 gives the probability of the peak horizontal ground motion exceeding a specific value in any one year. The inverse will be the recurrence interval of the peak horizontal ground motion.

In this study the historical records inside the 500 km radius from the potential dam site were used to evaluate the seismic risk at the potential dam site. The circle was divided into a number of annular areas, then each annular was subdivided into a number of sectors. Earthquakes are assumed to have an equal chance to occur anywhere within a sector of an annular (Figure 3.33). The equation 3-52 can thus be modified to the following equations:

\[ dP(Y_{\text{max}} > Y) = (N_0 \cdot C \cdot Y \cdot R) \cdot e^{-\beta/b_2 - \Gamma} \]

Hence, \( xdx = RdR \), the equation can be derived as follows:
\[
P(Y_{\text{max}} > Y) = N \cdot C \cdot \theta \cdot Y \cdot \int_{R_i}^{R_o} \frac{-(\Gamma - 1)}{R} dR - \frac{\beta/b2}{N \cdot C \cdot G \cdot Y} = \frac{\theta}{n \cdot R_i^n} \cdot \left[ 1 - \left( \frac{R_i}{R_o} \right)^n \right]
\]
\[
\text{where } \theta = \frac{\theta}{n \cdot R_i^n} \cdot \left[ 1 - \left( \frac{R_i}{R_o} \right)^n \right]
\]

The seismic risk at the potential dam site can be calculated by summing the peak horizontal ground motion of all sectors using equation 3-54. Figure 3.34 shows the expected peak horizontal ground motions at the potential dam site.

3.8.3 Reservoir induced earthquakes (RIE)

The mechanism of RIE is still not clear and a satisfactory procedure for evaluating the potential risk of RIE has not been developed [168]. It is also difficult to distinguish between natural earthquakes and induced earthquakes. In general, most induced earthquakes have a shallow focus. Possible explanations for RIE have been attributed by Meade [125], Guha et al. [74], Skipp & Higgins [168], Haws & Reilly [80], Willmore [209] to the following:

(i) "The weight of the water on the crust may have caused movement on a fault" [125].
(ii) "The change in pore pressure may have triggered slip on a fault" [125].
(iii) "The crust beneath the reservoir must be critically stressed by tectonic forces and the reservoir merely adds a small perturbation to the state of stress and triggers failure" [125].
(iv) "Physical interaction between the molecules of water and of the crustal rocks (say quartz as observed in laboratory studies) leads to fatigue and weakening to give rise to seismogenic yield of the material. This could be expected to occur generally in silicate rocks" [74].

Instead of the tectonical analysis for estimating the risk of RIE, the following suggested indicators for a potential induced earthquake were used in this study to evaluate the risk of RIE:

(i) Dams higher than 91 m (300 ft) [189].
(ii) The capacity of reservoir greater than 617 million cubic meter (500 000 arce-ft) [189].
(iii) Dam sites located in tectonically sensitive areas [189].
(iv) Faults (including concealed faults) beneath reservoir or inside catchment area [125].

Figure 3.35 shows the result of the RIE evaluation. Further tectonic studies at the potential dam site are essential for the next stage, especially for a large dam construction projects.

3.9 Slope and foundation analyses
3.9.1 Permeability evaluation within the impounded area of reservoir

Leakage from reservoirs has up to now not usually been given attention to the same level as for other factors. In fact the water tightness of a reservoir is very important and should be carefully investigated before building a dam, because it is very expensive and sometimes very difficult to seal the underlying strata of reservoirs. For example, the abandonment of the Jerome Reservoir in Idaho and of the Hondo Reservoir in New Mexico, USA, as a result of uncontrollable leakage from reservoirs which occurred after the dams had been built, amounted to a huge financial loss [108]. Another example mentioned by Legget & Karrow [108] stated that "There is standing today in the northeastern part of North America a fine, buttress-type, reinforced-concrete dam about 12 m (40 ft) high and 540 m (1/3 mi) long, constructed in 1910 and still in good condition, even though it has never retained water. It was built by an owner who spurned professional advice. ... and one complete side of the intended reservoir, consisted of a glacial moraine made up of small boulders. As could have been foretold, the reservoir leaked like a sieve as soon as impounding of the water commenced. Not willing to be beaten by geology, the owner had a vast area paved with an asphalt-coated, reinforced-concrete slab; later he had a cutoff wall, in places taken to a depth of 24 m (80 ft) below ground level, carried up the valley from the dam. All to no avail; the reservoir still leaked to such an extent ... The dam stands today in mute testimony to what the neglect of geology can do".

The structural geology of the dam site and reservoir plays a very important part in evaluation of leakage from reservoirs. A fault or excessive fissuring in the underlying strata of reservoirs may cause serious leakage from reservoirs. Permeable strata and working/abandoned mines are also the causes of leakage from reservoirs. Strata deposited by water soluble rocks like limestones, rock salt, etc., should be carefully investigated, because caverns might be developed in strata.

Since there was not any engineering geological maps nor field surveying for the study area, an assumption for strata must be made that the rocks in the underlying strata of reservoir are intact, and the empiricals value about the coefficients of permeability of intact rocks were adopted in this study (Table 3.20). Table 3.21 shows the typical coefficients of permeability of soils (USC). The in situ test for determining the coefficients of permeability of rocks/soils at the potential dam site should be embarked on during a follow-up study. In comparison with rocks, information about the permeability of soils are more reliable in this study due to a proper soil classification system.

The permeability evaluation of this study simply uses the rock and soil patterns within the impounded area of the potential reservoir from the soil and geological maps. Thereafter the permeability of the underlying strata and surface soils within the potential reservoir was evaluated according to the permeability decision table (Table 3.22). Figure 3.36 shows the statistics about the permeability of the underlying strata and surface soils within the potential reservoir after the permeability evaluation.

3.9.2 Presumed safe bearing capacity of the dam foundation

Half of the failure of dams was caused by foundation failure or uneven
settlement [13]. For example, the Malpasset Dam in southern France collapsed after several days of unusually severe rain; 344 people were killed. The French Ministry of Agriculture came to the conclusion that "the principal cause of the catastrophe was a rupture of the rock below the foundations, a rupture that induced substantial displacement, notably of the abutment, and so the destruction of the dam" [108]. It is thus extremely important to investigate the potential dam foundation before constructing a dam. Any suspicions related to the geology at the potential dam foundation should be carefully studied until all suspicions have been solved.

The dam foundation is the supporting part of a dam and provides a critical interface between a dam and the ground beneath it. The function of the dam foundation is to transfer the loads transmitted from the dam to the supporting rocks or soils [206, 173]:

The definitions of bearing capacity are taken from the British Standard Code of Practice CP 2004: 1972 [206]:

(i) "Ultimate bearing capacity: The value of the net loading intensity at which the ground fails in shear"

(ii) "Net loading intensity: The value of the additional loading intensity imposed by the new structure or other work"

(iii) "Presumed bearing value: The value of loading intensity considered appropriate to a particular type of ground for preliminary design purposes (Table 3.23)"

The presumed bearing values are based on the assumption that the rocks of the foundation are sound unweathered rocks or carried down to unweathered rocks, the width of foundation (B) > 1 meter; and ground water table > B meters below the base of foundation [206, 173]. In fact the majority of soil deposits tend to be non-homogeneous, the rock strata tend to be weathered and sometimes impossible to carry down to unweathered rocks because of the huge volume. An in situ bearing test should thus be embarked on for providing a better estimation about the allowable values of bearing capacity at the potential dam site. Many different kinds of in situ tests may be implemented for a more reliable result.

The foundation analysis of this study includes the following steps:

(i) Retrieves the underlying rock type and surface soil pattern at the potential dam site from geological and soil maps.
(ii) Assigns the presumed bearing value to the potential dam site according to the British Standard Code of Practice CP 2004: 1972.
(iii) Suggests the possible dam types at this site according to the empirical bearing capacity decision table (Table 3.24).

Figure 3.37 shows the result of the foundation analysis at the potential dam site.

3.9.3 Slope stability analysis around the rim of the reservoir

3.9.3.1 Recognizing the break point & possible slide mass of the slope

The break points are the discontinuous points of the slope profile, e.g. a breakneck slope toe, a man-cut slope, etc. The slope failures
would more likely occur at the break point than at other flatter or continuous points. The possible slide mass is the convex part of the slope which is located above the break point. The method described in paragraph 3.7.6.2 can be used to recognize the break point and the possible slide mass. The recognized break point and possible slide mass in each slope profile will be shown in the figures of the slope stability analyses (Figure 3.42).

3.9.3.2 Failures of the soil/rock slopes

The rock/soil slope slides around the rim of reservoirs accelerate the silting up of reservoirs and sometimes even cause disaster (landslide at Vaiont Reservoir mentioned in paragraph 1.2). The day-to-day operations of a reservoir change the water level rapidly, resulting in relatively rapid changes in pore pressure on slopes which may result in triggering rock/soil slope slides.

The causes of instability in natural soil slopes are listed as follows [173, 195, 206, 44]:

(i) Excessive inclination of a natural or man-made slope.
(ii) Increased stresses in/on slope.
   - External loads on slope, e.g. man-made structures, water/snow.
   - Increment of unit weight in slope, e.g. increased water content.
   - Removal of part of slope by man-made or natural excavation.
   - Undermining of slope which is caused by tunnelling, collapse of underground caverns, seepage erosion, etc.
   - Shock which is caused by either earthquake or blasting.
   - Developed tension cracks in slope.
   - Water pressure in tension cracks.
(iii) Decreased strength in/on slope.
   - Swelling of clays which is caused by absorption of water.
   - Increasing the pore water pressure (neutral stress) in slope which is caused by heavy rainfall, flood, reservoir operation, etc.
   - Breakdown of the soil structure with shock, vibration or seismic activity.
   - Crack developing which is caused by alternate swelling and shrinking or by tension inside the slope.
   - Melting of frozen soil.
   - Loss of capillary tension especially in cohesionless soil on drying.
   - Chemical or biochemical weathering.
   - Deterioration of cementing material in soil which may be caused by the above mentioned reason(s).

In general gravity and water are the main causes of instability in natural soil slopes. The most common types of soil slope failure are illustrated in Figure 3.38 [206]. A short description of these failures are as follows [206, 210, 44]:

- Falls are usually characterised by the movement of soil mass away from existing tension cracks, e.g. fissures, joints, steeply-inclined bedding planes, faults, etc. The failure of falls may be assisted or precipitated by the water or ice pressure in these tension cracks.

- Translational slides usually occur along a plane where a weak layer (or stratum) lies at a relatively shallow depth below the surface. of
the slope. The failure surface tends to be approximately parallel to the slope surface.

Rotational slips occur characteristically in homogeneous cohesive soils. The failure surface is a circular arc and usually deep seated. In a non-homogeneous soil slope the failure surface may be a non-circular arc. The slipping mass slumps down at the top of the slope and heaves up near the toe of the slope.

Flows usually occur in weak saturated soils when the pore pressure has increased sufficiently during a heavy rainfall or other causes. Soil will lose its shear strength and then become liquid to flow down to a lower place under its own weight.

The mechanism of flows is very complex and there is still no proper mathematical model to describe it. The analysis of falls needs detailed data about the dip and strike of tension cracks which are not available for the study area at this stage. Thus only the translational slip and rotational slide were included in this study. Detailed descriptions about these two analyses are listed in paragraphs 3.9.3.3 and 3.9.3.4.

In comparison with soil slopes, rocks slopes are usually very stable, especially igneous or metamorphic rock slopes [70]. The failure of a rock slope is possible only if discontinuities exist in the rock mass in which the discrete rock mass can be easily moved under gravity (sometimes accompanied with the effects of seepage force). The stability of a rock slope mainly depends on the inclination of discontinuity surfaces within the rock mass, such as bedding planes, faults, joints, etc,. When the angle of these discontinuities is approximately vertical or horizontal, the slope appears quite stable. When the discontinuity surfaces are dipping towards the slope face and the angle with the horizontal is between 30° and 70°, slope slides may occur [85]. The most common types of rock slope failure are illustrated in Figure 3.39 [88]. A short description of these failures is as follows [88, 85, 70, 94]:

A plane slide occurs on a plane surface where it daylights in the slope face. The following geometrical conditions must be satisfied to form a sliding rock mass [85]:

(i) The strike of the failure plane must be nearly parallel (± 20°) to the strike of the slope face.
(ii) The failure plane of the sliding rock mass must 'daylight' in the slope face, i.e. the dip of the failure plane must be smaller than the dip of the slope face (Figure 3.40).
(iii) "The dip of the failure plane must be greater than the angle of friction of this plane" (Figure 3.40).
(iv) Released surfaces (Figure 3.40) provide negligible resistance (or the failure surface passes through the convex nose of a slope where no released surfaces are present).

Some analysts/engineers treat the plane failure as a special case of the wedge failure [85].

Wedge failures occur along the intersecting line of two discontinuity planes where a wedge (tetrahedral rock block) was formed. The dip of the intersected line must be greater than the angle of friction of the
Toppling failures involve overturning of rock columns/blocks downhill. In those cases the dip of rock strata is nearly vertical. This type of failure commonly occurs in slates, schists and thin-bedded sediments [70].

Flexural topping occurs in a rock mass with continuous columns which are separated by well developed, steeply dipping discontinuities. When the rock mass bends forward the columns break in flexure. Undermining or erosion of the toe of the slope starts the toppling process and it retrogresses backward into the rock mass [85].

Block toppling occurs in a rock mass with continuous columns when individual columns are divided by widely spaced orthogonal joints. The blocks forming the toe of the slope are pushed forward by the longer overturning columns/blocks behind them. The sliding of the toe allows further topping to develop in the higher area of the slope [85].

The analysis for the toppling failure is always very complex and only suitable in some special cases, besides that geometrical shape as well as dip of blocks/columns must be precisely described for analysis. Also, the geometrical conditions to form a toppling failure are unusual in South Africa, hence toppling failure was not included in this study. A detailed description about plane failure and wedge failure analyses are listed in paragraph 3.9.3.5 and 3.9.3.6. The parameters of rocks/soils used in the slope stability analysis were adopted from Hoek & Bray [85], Goodman [70], Duncan [55], Bell [14, 15], Attewell & Farmer [7] and Lo & Cheng [115] (Table 3.25 for rocks, Table 3.26 for soils).

3.9.3.3 Translational slide analysis

The method used for translational slide analysis in this study was based on work by Whitlow [206] and Craig [44]. This method considers a section in a long slope which tends to fail along a failure plane nearly parallel to the slope surface (Figure 3.41). This section of slope can then be divided into numbers of elements in which the length of each element is the unit length. The forces acting on an element are as follows:

Weight of the section, \( W = r \cdot z \cdot b \cdot \cos \beta \) \hspace{1cm} (3-55)

Normal force on the failure plane, \( N = W \cdot \cos \beta \) \hspace{1cm} (3-56)

Tangential force on the failure plane, \( T = W \cdot \sin \beta \) \hspace{1cm} (3-57)

The forces \( E_1 \) and \( E_2 \) acting on the sides of an element are assumed to be equal and can be cancelled. The shear strength of a cohesionless soil is given by the following equation:

\[ \tau = \sigma \cdot \tan \phi \] \hspace{1cm} (3-58)

where \( \tau \) = shear strength,
\( \sigma \) = total normal stress,
\( \phi \) = angle of shearing resistance in terms of total stress.

Resolving along the failure plane gives:
Thus

\[ T = N \cdot \tan \theta \] ........................................ (3-61)

Substituting (3-56) and (3-57) into (3-61) gives:

\[ W \cdot \sin \beta = W \cdot \sin \beta \cdot \tan \theta \] .................................. (3-62)

Hence

\[ \tan \beta = \tan \theta \] ....................................... (3-63)

A safe factor (F) for slope stability may therefore be defined as follows:

\[ F = \tan \frac{\theta}{\tan \beta} \] ........................................ (3-64)

or in terms of effective stress:

\[ F = \tan \frac{\theta'}{\tan \beta} \] .................................. (3-65)

where \( \theta' = \) angle of shearing resistance in terms of effective stress.

In most natural soils, the water can pass through soils and so seepage forces need to be considered. Thus, at the base of the element:

Effective normal force, \( N' = W \cdot \cos \beta \)
\[ = (r \cdot z \cdot b \cdot \cos \beta - rw \cdot h \cdot b \cdot \cos \beta) \cdot \cos \beta \]
\[ = (r \cdot z - rw \cdot h) \cdot b \cdot \cos^2 \beta \] ............. (3-66)

Tangential force, \( T = W \cdot \sin \beta \)
\[ = r \cdot z \cdot b \cdot \cos \beta \cdot \sin \beta \] ............. (3-67)

where \( r = \) bulk unit weight,
\( rw = \) unit weight of water,
\( z = \) height of water above failure plane,
\( h = \) height of the soil element above failure plane,
\( b = \) unit length of the soil elements,
\( \beta = \) the inclination angle of the slope face.

The safe factor can now be defined as the ratio of the shear strength to shear stresses along the failure plane.

\[ F = \frac{N' \cdot \tan \theta'}{T} = \frac{(r \cdot z - rw \cdot h) \cdot b \cdot \cos^2 \beta \cdot \tan \theta'}{r \cdot z \cdot b \cdot \sin \beta \cdot \cos \beta} \]
\[ = \left( 1 - \frac{rw \cdot h}{r \cdot z} \right) \cdot \frac{\tan \theta'}{\tan \beta} \] ........................................ (3-68)
The shear strength of a cohesive soil is given by the following equation:

\[ \tau = c' + \sigma' \tan \theta' \] ..............................(3-69)

where \( \tau \) = shear strength.
\( c' \) = apparent cohesion in terms of effective stress.
\( \sigma' \) = effective normal stress.
\( \theta' \) = angle of shearing resistance in terms of effective stress.

The safe factor for cohesive soils becomes:

\[ F = \frac{c' \cdot b + N' \cdot \tan \theta'}{T} \]

\[ = \frac{c' + (r \cdot z - r \cdot w \cdot h) \cdot \cos^2 \beta \cdot \tan \theta'}{r \cdot z \cdot \sin \beta \cdot \cos \beta} \] ..............................(3-70)

For a waterlogged slope, the ground water level rises to the soil surface which gives \( h = z \). If the ground water level is located at the failure surface, \( h = 0 \). Figure 3.42 shows the minimum safe factors of the profiles.

3.9.3.4 Rotational slip analysis

The method for rotational slip analysis in this study was based on Bishop's simplified method for estimating the long-term stability of slopes. In this method, a trial slip surface is selected and the slip mass is considered as a series of slices because of the different stresses along the trial slip surface (Figure 3.43). This method assumes that the pore pressure ratio is nearly constant throughout the slope. It is also assumed that the resultant forces on the sides of the slices are horizontal forces only (i.e. \( X_1 = X_2 \), \( E_1 \parallel E_2 \), see figure 3.43). For equilibrium along the base of any slice:

\[ W \cdot \sin \alpha - \frac{\tau}{F} \cdot l = W \cdot \sin \alpha \cdot \frac{c' \cdot l + N' \cdot \tan \theta'}{F} = 0 \] ..............................(3-71)

Summing all slices gives:

\[ F = \frac{\Sigma (c' \cdot l + N' \cdot \tan \theta')}{\Sigma W \cdot \sin \alpha} \] ..............................(3-72)

where \( W \) = weight of the slice.
\( \alpha \) = inclination angle at the base of slice.
\( \tau \) = shear strength.
\( c' \) = effective cohesion.
\( N' \) = effective normal force.
\( \theta' \) = angle of shearing resistance in terms of effective stress.
\( l \) = chord at the base of slice.
\( F \) = safe factor.

For equilibrium in the vertical direction of any slice:
\[ W - N' \cos \alpha - u \cdot l \cdot \cos \alpha - l \cdot \sin \alpha = \mathcal{F} \]
\[ = W - N' \cos \alpha - u \cdot l \cdot \cos \alpha - \frac{c'}{l} \cdot \sin \alpha - \frac{N' \cdot \tan \phi'}{F} \cdot \sin \alpha \] ... (3-73)

Hence
\[ W - \frac{c'}{l} \cdot \sin \alpha - u \cdot \cos \alpha \]
\[ N' = \frac{\tan \phi'}{\cos \alpha + \frac{\sin \alpha}{F}} \] ................. (3-74)

Substituting \( l = b \cdot \sec \alpha \) and \( N' \) gives:
\[ F = \frac{l}{\cos \alpha + \frac{\tan \alpha \cdot \tan \phi'}{F}} \]
\[ = \frac{1}{l} \left( \frac{c' \cdot b + (W - u \cdot b) \cdot \tan \phi'}{W \cdot \sin \alpha} \right) \]
\[ = \frac{\tan \alpha \cdot \tan \phi'}{1} \] ............... (3-74)

where \( u \) = pore pressure.
\( b \) = unit length of slice.

The calculating procedure is started by assuming a trial value for \( F \) in equation 3-74 and then using an iterative process to converge on the true value of \( F \). The safe factors calculated by this method may be slight under-estimates, but with errors \( \leq 3\% \) [206]. Figure 3.44 shows the minimum safe factors of the profiles.

3.9.3.5 Plane failure analysis

The method for plane failure analysis in this study was based on the method developed by Hoek & Bray [85] in which the following assumptions are made:

(i) The strike of the sliding surface and tension crack are nearly parallel to the strike of the slope surface.
(ii) The tension crack is nearly vertical and locates at the slope face or the top of the slope. The tension crack is filled with water to a depth \( Zw \) (Figure 3.40).
(iii) Water can enter the sliding surface along the base of the tension crack and seeps into the sliding surface. Water can also flow in the sliding surface and then escapes from the sliding surface. The pressure distribution induced by the horizontal water force \( V \) and uplift water force \( U \) is illustrated in Figure 3.40.
(iv) The weight of the sliding mass \( W \), \( U \), and \( V \) all act through the centroid of the sliding mass. That is, there are no moments which could cause rotation of the mass and hence the slope failure occurs by means of sliding only.
(v) The shear strength of the sliding surface is defined by the following equation:
\[ \tau = c + c' \cdot \tan \phi \] ......................... (3-75)
where \( \tau \) = shear strength.
\( c \) = cohesion.
\( \sigma \) = normal stress.
\( \varphi \) = friction angle.

(vi) The release surfaces are present and there is no or very little resistance at the release surfaces, or there are no release surfaces.

The safe factor of the slope can be calculated by means of the following equation:

\[
F = \frac{c \cdot A + (W \cdot \cos \varphi - U - V \cdot \sin \varphi) \cdot \tan \varphi}{W \cdot \sin \varphi + V \cdot \cos \varphi}
\]

\[ \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 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\[ F = \frac{m_2 \cdot \tan \theta_2 + c_2}{1^2 \cdot b_y^2 + k \cdot p^2 \cdot u_1^2 + 2 \cdot (r \cdot b_z - a_z) \cdot p \cdot u_1} \]  

\[ \text{(3-79)} \]

(iv) If \( m_1 < 0 \) and \( m_2 < 0 \), there is no contact on both planes and the safe factor should be set to zero.

where \((a_x, a_y, a_z) = (\sin \theta_1 \sin (\alpha_1 - \alpha_2), \sin \theta_1 \cos (\alpha_1 - \alpha_2), \cos \theta_1)\)

\((f_x, f_y, f_z) = (\sin \theta_4 \sin (\alpha_4 - \alpha_2), \sin \theta_4 \cos (\alpha_4 - \alpha_2), \cos \theta_4)\)

\(u_1 = u_2 = rw \cdot H / 6\)

\(b_z = \cos \theta_2\)

\(i = a_x \cdot b_y\)

\(g_z = f_x \cdot a_y - f_y \cdot a_x\)

\(q = b_y \cdot (f_z \cdot a_x - f_x \cdot a_z) + b_z \cdot g_z\)

\(R = a_y \cdot b_y + a_z \cdot b_z\)

\(k = 1 - R^2\)

\(l = (r \cdot H \cdot q) / (3 \cdot g_z)\)

\(p = -b_y \cdot f_x / g_z\)

\(n_1 = \{ (1 / k) \cdot (a_z - r \cdot b_z) - p \cdot u_1 \} \cdot p / |p|\)

\(n_2 = \{ (1 / k) \cdot (b_z - r \cdot a_z) - u_2 \} \cdot p / |p|\)

\(m_1 = \{ l \cdot a_z - r \cdot u_2 - p \cdot u_1 \} \cdot p / |p|\)

\(m_2 = \{ l \cdot b_z - r \cdot p \cdot u_1 - u_2 \} \cdot p / |p|\)

\(r = \) unit weight of the rock wedge.

\(r_2 = \) unit weight of water.

\(H = \) height of the wedge.

\(c_1, c_2 = \) cohesion of the failure plane 1 and 2.

\(\theta_1, \theta_2 = \) friction angle of the failure plane 1 and 2.

This method is quite simple and can only be used to estimate the safe factor of wedge failure with the following conditions [85]:

(a) A wedge with a horizontal slope crest and without tension cracks.
(b) Each plane may have a different friction angle and cohesion.
(c) The water pressure on each plane is included in this method.
(d) The external forces (e.g., installation of rock bolts) are excluded in this method.

If other types of wedge failure need to be analysed, e.g., a wedge with tension crack on its slope surface, this method cannot be used and other methods should be used for estimating the safe factors of these slopes. Figure 3.47 shows the minimum safe factors for the profiles.

3.9.3.7 The distribution of sensitive slopes

In this study the safe factors of the slopes in every profile around the rim of the reservoir were estimated by means of the mentioned failure analyses (paragraphs 3.9.3.3 - 3.9.3.6) in the following two situations:

(i) Dry slopes in which it is assumed that the ground water table will rise to half the height of the slope face when the reservoir starts to impound water and consequently raises the ground water table.
(ii) Waterlogged slopes in which it is assumed that the ground water table will raise to the slope face during heavy rainfall.
If the safe factors (which were estimated by the mentioned failure analyses) of a slope profile are all below 1.0, this slope profile will be treated as a sensitive slope profile. On the other hand, if the safe factors of a slope profile are all above 1.0, this slope profile will be treated as a very stable slope profile. Figure 3.48 shows the distribution of the sensitive slopes.

3.10 Computer-simulated imagery

The ray tracing is one of the most popular graphics techniques for generating realistic scenes nowadays. This method is quite suitable for the regular rectangular (grid-type) DEM developed for this study. It is thus used in this study to generate the simulated imagery for the area including the potential dam site and reservoir for demonstration purposes and to get a better "feeling" for the terrain and natural/cultural landscape of the study area. The elements of ray tracing are as follows:

(i) Light source, i.e. the sun, is a uniform light source.
(ii) Objects, i.e. a mountain or a tree, is an object.
(iii) Incident ray, the ray emitted from the light source to the object.
(iv) Reflected ray, the ray reflected from the object to space.
(v) Viewing ray, the ray reflected from the object to the viewer's eyes.

In this study the light source is the sun; the landscape in the study area is the object. The user specified date and time will decide the position of the light source (sun). The incident ray and the reflected ray at a point on the object can thus be calculated by the position of the light source and the geometric shape of object (i.e. DEM, slope angles and aspects). The intensity of that point can be calculated by means of the Lambert's cosine law which is as follows:

\[ I_r = I_i \cdot R \cdot \cos^n(\theta) \] .......................... (3-80)

where

- \( I_r \) = the intensity of the reflected ray.
- \( I_i \) = the intensity of the incident ray.
- \( R \) = the reflectivity for diffuse or specular reflection.
- \( \theta \) = the angle between the reflected ray and viewing ray.
- \( n \) = a parameter.

For more detail description about ray tracing, refer to Burger & Gillies [28] or Harrington [79]. Figure 3.49 shows the computer-simulated imagery in the morning (10:00) and figure 3.50 shows the imagery in the afternoon (14:00) both on the twenty-first of September.

3.11 Conclusion

The SDSS-model was designed as a step-by-step procedure which is flexible for further expansion and modification. The replacement or modification of some sub-models may be necessary before applying it to other study areas. This can easily be done by replacing the modified sub-model into the SDSS-model. A detailed assessment, including the advantages and constraints of the SDSS-model, are discussed in the next chapter.
Chapter 4 Discussion and Conclusion

4.1 Assessment of the SDSS-model

4.1.1 Overview

The earth's environment is very complex and unique and therefore also difficult to model scientifically. Scientific analytical models should thus be designed to be as flexible as possible, including different kinds of submodels/methods for different types of environments and situations. In this study a locational model (SDSS-model) for dam site/size/type selection at the reconnaissance stage was designed as a step-by-step procedure. Each step generates some information for the next step. Various approaches were followed for different types of situations.

The SDSS-model for this study was developed for a reconnaissance stage and only considered the factors regarding the physical environment. Other factors, e.g. project function(s), economic factors, environmental impact considerations and social considerations, should be included for a more detailed analysis in the next stage. Since the dam site selection process is very complex, it is quite difficult to implement the whole SDSS-model automatically on computer. The model was thus designed as a spatial decision support system which acts as an (artificially) intelligent assistant for the user.

4.1.2 Submodels/method assessments

The assessments of the submodels/methods are as follows:

(i) DEM: The data structure of the sampling points is a sorted list from ARC/INFO exported files. The binary search method was used to access the sampling points in the sampling point file. Because of the limited system memory of a PC, the file had to be stored on hard disks. The input/output (I/O) operations were thus very frequent and consequently the searching speed was very slow. For such a large and complex analysis, a workstation or mini-computer would be the better choice.

The weighted moving average method was used for interpolating the data points in the DEM. The inverse of the distance between the sampling points and data point was used as the weight function. This method is easy to compute but will slightly smooth the spatial surface through the data points in the DEM.

The multiple linear regression method was used to calculate the slope angle and aspect for each pixel. This method fits a plane through the four corners of a pixel by the least squared method, thus smoothing of the spatial surface is unavoidable.

(ii) Geographical information: The gauging records have some missing values which might bias the result from the statistical analysis. Another flaw is the short observation period in some cases which makes some statistical inferences less confident. Some maps which were compiled and printed in the 1970's may not represent the current situation.

(iii) Hydrological analysis: Regression analysis was adopted for estimating the rainfall-runoff relationship due to the high correlation between areal rainfall and streamflow. For the area without high
correlation between those two factors, other methods or models should be used for better estimation. The sedimentation yield from the catchment area is underestimated which may have been caused by the short span or the bias of observed values*. The ground water flow and leakage were not taken into account in the reservoir yield risk analysis which may tend to overestimate the performance of the reservoir.

The intensity duration frequency (IDF) formula for the inland region is not very precise everywhere in the region because it is based on only one formula to represent quite an extensive area. The IDF for smaller areas should be developed for a more detailed analysis. The parameters of the Muskingum routing in this study were adopted from the HRU report No. 1/74, in which the estimated area of the catchment used for estimating the K parameter is nearly half that of the actual catchment area. The underestimation of the catchment area will lead to overestimation of the K parameter. This overestimation was adjusted to avoid too much bias in this study. All the K parameters in the HRU report may need to be adjusted before applying it to other catchment areas.

(* The bias of observed value might be caused by the absence of sedimentation records during floods which contribute most of the total annual sediments.)

(iv) Land evaluation: Some land use/cover patterns and the location of some mines might be not correct due to the outdated maps. Field survey or remote sensing imagery should be incorporated for updating the data. The land capability classification and the land suitability classification were simplified due to the insufficient data. Field surveys should be implemented at a next stage and the updated classification could thus be better used for evaluating the land in the impounded area of the reservoir.

(v) Catchment boundary detection and topographic suitability analysis: These two submodels depend on the precision of the DEM. The more accurate the DEM the more useful the results. The decision table of the topographic suitability analysis for suggesting the suitable dam type at the potential dam site was derived from papers and books mainly published in the USA and the UK. However the situation in South Africa might be quite different from those countries and a further modification may be necessary before application in South Africa.

(vi) Construction materials: The weighted function was used to decide the route from the potential dam site to existing quarries and material suppliers. The coefficients of the weighted function depend on the area and can only be decided by means of a trial and error method which is quite time consuming. Other methods may need to be developed for area independent coefficients which can be calculated rapidly. The edge detection technique was used in this study to detect local rock/soil borrow areas. The newly developed texture classification in remote sensing and artificial intelligence techniques can be incorporated for better outcome, e.g. the detection of the topographical features (i.e. alluvial fans, sand dunes, etc.).

(vii) Seismic risk analysis: The method for estimating the peak horizontal ground motions was developed in USA where the western coast is the earthquake active zone. South Africa is not on the earthquake
active zone and the historical records of earthquakes may not be sufficient to derive prediction curves for larger magnitudes, as the record may not include any data about powerful earthquakes. Consequently the peak horizontal ground motions may be underestimated due to the short span of the historical records.

The mechanism of the reservoir induced earthquakes (RIE) is still not clear at this moment. For an important dam building project, the detailed tectonic structure at the dam site should be investigated and analysed for estimating the RIE.

(viii) Slope and foundation analysis: The main shortcoming of this submodel is insufficient data at this stage. Thus the results should be treated as a preliminary analysis due to the absence of in situ test data. As soon as a detailed in situ test has been done, the estimated rock/soil properties and dip/strike of discontinuities can be input to this submodel to yield better results.

(ix) Computer-simulated imagery: The ray tracing technique in computer graphics is one of the most popular graphics techniques nowadays. In this study only the satellite imagery-like images were generated. For demonstrating purposes and to get a better "feeling" for the terrain and land use, three dimensional perspective pictures may possibly give a better impression to the viewer than the satellite imagery-like images.

4.1.3 Assessment of the potential dam site

Based on the results (Table 3.27) rendered by the various submodels of the SDSS-model as applied to the specific site (Magoboya's location; long. 30°10'23"; lat. 24°1'37".) evaluated in this study. From the summary provided by table 3.27, it can be concluded that the specific site is most probably a suitable site for dam building.

4.1.4 Conclusions about assessment

In conclusion, the SDSS-model is an integral model which evaluates the potential dam sites in many aspects to give more useful information to analysts/decision-makers. It is also very flexible for modifying the procedure to apply to other study areas and to incorporate new sub-models/methods. This type of model may be the solution for integrated multidisciplinary research.

4.2 Recommendations for further research

During the study period, the author found that specialised research as well as suitable/useful data/information in this field in South Africa need more attention and effort in the future. The following need to be addressed specifically:

(i) The national DEM of South Africa: The national DEM of South Africa is based on a 500 x 500 m grid. This is not good enough for most applications even at the reconnaissance stage. Thus a grid size of 50 m or less should be compiled to satisfy most of the users. An automatic procedure for estimating the height at a specific point from stereo airphoto pairs should be the key to the construction of such a higher resolution national DEM.
(ii) The digital map series: The conventional way of map production can be improved by digitization and computer-aided plotting techniques, making these maps, basically available in digital form, easier to duplicate and manipulate and thus easier to update. The national standard of digital map format must be set as a computer communication protocol.

(iii) The data and knowledge base of river catchments: Studies about catchments in South Africa are usually done by research units, local authorities and/or municipalities. The disadvantage is that the research methods, surveying techniques, etc., may be inconsistent and incompatible. A standard procedure for constructing the basic data base as well as standardising the parameters should be designed and enforced at the national level.

(iv) The national land evaluation system: The land evaluation systems in South Africa are mainly tailored for agricultural purposes and there is still no standard system in South Africa. A national land evaluation system for agriculture and other applications, e.g. hydrology, forestry, etc., should be implemented. Such a national system should be beneficial for national and regional development schemes.

(v) Models for the economic factors (e.g. estimated cost of dams), environmental and social considerations should be developed and incorporated into dam building projects.

(vi) More study should be undertaken about the soil-topography relationship for engineering purposes.

(vii) A national engineering geology map series should be compiled.

(viii) An engineering soil map series should be compiled.

(ix) Standardised formats for geographical information such as gauging records, seismic records, rock/soil information, borehole records, etc., should be introduced.

(x) Research about the synergism between GIS, remote sensing and expert system/artificial intelligence techniques should receive more attention, especially at a national level.

(xi) Regarding the SDSS-model developed for this study, the following aspects need further development/improvement:

- The data structure of the sampling points (e.g. binary tree).
- The interpolating method for the DEM (e.g. the regional variable theory technique (Kriging)).
- The rainfall-runoff model in the study area.
- The sedimentation yield calibration in the study area.
- The IDF formula in the study area.
- The land evaluation system.
- The decision table for topographic suitability analysis.
- The route searching algorithm for calculating transportation distance.
- The pattern recognition algorithm for detecting the potential rock/soil borrow areas.
- Earthquake recurrence adjustment for southern Africa.
- Tectonic study for estimating the RIE.
- The incorporation of in situ test data in the slope and foundation
• 3-D perspective simulated imagery.

4.3 Toward integral multi-disciplinary research

In the past scientific studies about the earth focused mainly on some narrow fields because the earth's environment is very complex. Gradually it became apparent that inter- or multi-disciplinary studies were necessary in order to better understand these complexities. This trend of multi-disciplinary studies became increasingly apparent recently and helped earth scientists to better understand spatial problems, as well as to come to better solutions to global and regional problems. The invention of the computer, and based on that the progress of the GIS technology, made integrated research possible, offering better ways for cooperation between different disciplines.

The KGBGIS is a combination of GIS and expert systems which may be the key to future integral researches in geography and other earth sciences. The construction of the KGBGIS is a big task, many people will be involved, e.g. the domain expert (geographer, hydrologist, etc.), the knowledge engineer, the digitizer, the system analyst, etc. The most important element in a KGBGIS is the knowledge (coming from many different disciplines) which is stored in a knowledge base by means of a specific knowledge representation method. The knowledge can be updated and expanded by the domain experts from different disciplines. It is very convenient to integrate the knowledge from different domain experts from knowledge bases by means of expert system technology. An integrated research can thus be implemented for offering the better solution regarding environmental problems.

4.4 Conclusion

Fresh water is a recyclable and LIMITED resource; the vital resource for life on earth and becoming scarce in many countries of the world. Better utilization as well as development of existing and future water resources are thus of the utmost urgency, especially in those countries experiencing water scarcity for agricultural, industrial and household uses. Dams are currently still the key features in the water resources development projects because of economical considerations. Dams should be well planned and constructed in order to operate efficiently and harmoniously with the environment and society. The dam site/size/type selection is thus one of the most important steps in a water resource development project. "There is no simple formula for deciding upon an optimum acceptable plan which consists of the most satisfactory combination of economic, social and environmental values" [68]. An integrated research approach, aided by a KGBGIS is vitally important for this issue.

The following are the final conclusions about this study:

(i) The selection and evaluation of a dam site/size/type is a multi-disciplinary task and needs an integrated research effort between the relevant disciplines.

(ii) A KGBGIS is a competent tool to implement integrated research and to enable the handling of various sets of geographical/spatial data.

(iii) Stochastic models can incorporate more types of variables than deterministic models, and are more flexible and less complex.
(iv) The Hurst phenomenon (long term persistence) may possibly exist in the study area while the AutoRegression Moving Average (ARMA) model proved to be suitable for the area.

(v) The Muskingum routing method is an easy and practical method and can be implemented on computer.

(vi) The 'soil and land capability classification for agriculture' which was developed by the Soil and Irrigation Research Institution is a simple and properly defined method. It proved to be good for the soil surveying as well as easy to implement on computer.

(vii) Field survey at the potential dam site is very important in order to evaluate the engineering geological conditions.

(viii) The topography at the dam site and the availability of construction materials in the vicinity strongly affect the building costs of a dam and proved to be the main factor for selecting the dam type. An economical model should be incorporated in future.

(ix) Ground motions could possibly damage the dam structure and should be carefully evaluated, even in South Africa which is relatively earthquake free.

(x) Reservoir induced earthquakes have been reported in South Africa, although they were not serious. The tectonic study at a dam site is necessary for evaluating the safety of a dam.

(xi) The grid-type DEM proved to be successful for complicated geographical/spatial analyses, especially because of its ease of manipulation, compatibility with other raster type data (e.g. remotely sensed imagery, etc.).

(xii) The catchment boundary detection algorithm could be applied in other regions but is not suitable for topographically flat areas like plains.

(xiii) Remotely sensed imagery with its associated image processing possibilities like automatic classification methods can be used to update the land cover information.

(xiv) Pattern recognition techniques are useful for detecting break points and potential sliding mass movements on slopes as well as identifying potential rock/soil borrow areas.

(xv) The results of the SDSS-model (table 3.27) are instructive and easily interpretable by analysts/decision-makers in order to evaluate and make comparisons between alternatives.

The end of this study is the beginning of a never ending story, a story about human-earth relationship. This study needs to be expanded both in the locational model (SDSS-model) and KBGIS technology, thus becoming ultimately a small contribution to mankind's welfare. There is no limitation for the progress of KBGIS, expert systems and artificial intelligence technologies.

According to Robinson, et al. [157], "Lessons learned in building these smaller systems will in turn be transportable and expandable to later more
advanced system. By developing more than one prototype addressing the same problem but using different methods, we can begin to conduct comparative analyses that can support more informed decisions concerning the development of expert systems for GIS.

The following viewpoint of DWAF [51] is fully supported by this study and may serve as a final thought for this study: "Effective legislation should be framed to promote the efficient and equitable use and protection of water and water-related ecosystems. Pricing and other economic incentives should be used to promote the efficient and equitable use of water. National mechanisms for the management of water resource should apply the best measures to improve the existing systems and the best available techniques for planning and design of conservation and distribution systems in the most efficient way and should equally attend to proper maintenance, control at the regional, national and farm level and operation of delivery systems to increase efficiency."


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