NATIONAL FLOOD NOWCASTING SYSTEM: TOWARDS AN INTEGRATED MITIGATION STRATEGY

G Pegram • S Sinclair • M Parak •
D Sakulski • N Nxumalo

WRC Report No. 1429/1/06

Water Research Commission

National Flood Nowcasting System:

Towards an integrated mitigation strategy

by

Geoff Pegram, Scott Sinclair, Mohamed Parak, Dusan Sakulski and Ntokozo Nxumalo

University of KwaZulu-Natal

Report to the Water Research Commission on the project

"A National Flood Nowcasting System: Towards an integrated mitigation strategy"

WRC Report No: 1429/1/06
ISBN No: 1-77005-512-6

January 2007

Executive summary

1 The background to the study

Floods cannot be prevented. Through appropriate planning and management strategies, the devastating effects of floods can be reduced or mitigated. Loss of life and damage to infrastructure can be minimized but never completely eliminated. With large increases in population and increasing urbanization (largely driven by poverty) there are more people living in informal settlements (near cities). These settlements often encroach on floodplains, as this is the only undeveloped land, which remains available. The people living in these settlements are those who are most at risk, not only due to their geographical location in the floodplain, but also because (without access to insurance policies) they do not have the financial resources to recover from damage caused by flooding. In addition many formal developments already exist in areas that are susceptible to flooding. When the nature of the development is such that significant damage would result from flooding and mitigation steps could be employed, early warning systems can provide a means of reducing the risk to acceptable levels.

The recently promulgated Disaster Management Act (Act 57 of 2002) advocates a paradigm shift from the current "bucket and blanket brigade" response-based mindset to one where disaster prevention or mitigation are preferred. It is in the context of mitigating the effects of flood events that the development and implementation of reliable flood forecasting systems has major significance. In the case of flash floods, even a small amount of lead-time (a few hours) can allow disaster managers to take steps, which may significantly reduce loss of life and damage to property.

Two previous WRC contracts (Pegram and Sinclair, 2002; Sinclair and Pegram 2004), focused firstly, on developing a computationally efficient rainfall runoff model incorporating radar estimates of rainfall and secondly, implementing that model in a pilot study to provide efficient flood nowcasting in the Umgeni catchment. The focus was to provide timeous warning for those most vulnerable and least protected against flooding (informal settlements in flood-prone areas near rivers) as well as strategically important industries.

An extension (Mkwananzi and Pegram, 2004) to the flood nowcasting contract provided the important link between flood flows and inundation levels. The lessons learned are that the flood nowcasting methodology is feasible but needs more work to:

1. Ensure that the Disaster Managers are well trained in the implications of the flood forecasting information available to them.
2. Improve the method of dissemination of information by making the data streams dependable and sustainable once the WRC contracts have been completed.
3. Extend the ideas to other flood prone areas in Southern Africa.

In this project, the tasks were divided amongst those most skilled in the different facets of the work. Its thrust has been to seek collaboration between several different organizations: the South African Weather Service (SAWS), department of Civil Engineering at the University of KwaZulu-Natal, the National Disaster Management Centre (NDMC) and the Department of Water Affairs and Forestry (DWAF) Hydrology Unit. SAWS scientists led by Dr Deon Terblanche continued to collect and provide best estimates of rainfall from satellite, radar and gauges. UKZN was to improve and adapt models for rainfall runoff conversion to more catchments countrywide and assist SAWS in improving rainfall estimations (Pegram et al., 2006).

To efficiently disburse, archive and quality control the data stream, the IT division of NDMC was to be used. The intention was to remove much of the busy work from researchers, allowing them to spend more time doing the science and engineering to sustain the system. Crucial to this project is to have enabled the technological knowledge transfer to those doing the job on the ground - the Disaster Managers and Municipal Engineers - and to build their capability to cope with flooding disasters. In addition to exposing them to the ideas, it was felt that there was a need to motivate, educate and train them in flood forecasting using simulation tools developed under other WRC contracts, particularly the String of Beads stochastic rainfall field model (Pegram and Clothier, 1999; Clothier and Pegram, 2002).

2 Stated Aims

This project, building on previous research and development, aimed to:

1. Put an effective, efficient, available national flood-forecasting system in place.
2. Use this system to forecast flood inundation levels routinely.
3. Use these forecast inundation levels to alert vulnerable people, industry, Disaster Managers in order to mitigate the effects of floods.
4. Have recent information (satellite, radar and gauge estimation of rainfall) distributed from the NDMC/DWAF:PSU (National Disaster Management Centre/Department of Water Affairs & Forestry: Public Safety Unit) to the regions.
5. Provide flood nowcasts/forecasts (with horizons of 1/2, 1, 2, 4, 8 hour etc.) to sensitive regions in as much detail as required.
6. Interact and work with local Disaster Managers (DMs) and Local Authorities to convert flows to inundation levels.
7. Provide training initiatives (annual courses, presentations and software) for local DMs using simulated weather systems to augment training on historical events.

3 Approach to Project

In order to achieve these aims, a number of deliverables were initially scheduled for completion during the course of this project. These consisted mainly of establishing links (comprising inter-organisational, interpersonal and physical communication) between the various role players, effecting necessary training and technology transfer and developing a strategy for catchment modelling. The purpose of this interconnected activity was to be able to extend warning systems to ungauged catchments and generally provide the relevant authorities and disaster managers with knowledge resources supporting a sound perspective on flood risks and their possible mitigation in South Africa.

Soon after the inception of the project, it became clear that the objectives as listed (despite initial enthusiastic acceptance by role-players) were excessively over-ambitious in the light of (i) the lack of clear definition of the roles (as well as changing roles) of various institutions involved in flood warning and management, and (ii) the severe lack of institutional capacity required to roll out the national flood nowcasting system as envisaged.

Consequently, it was necessary to take a step back, adapt the approach and modify deliverables (see Appendix A1 to main report) in an effort to prepare the ground as best as possible for the eventual institution of the national flood nowcasting system.

A very large and important part of the project was consequently devoted to formal and informal consultation and interaction with role-players, and presentations at meetings with national leaders and decision-makers in SAWS, NDMC and DWAF, extending to the Metros. This activity was undertaken in order to create awareness of the needs for, and potential benefits of, a national flood nowcasting system, provide the necessary background knowledge and to clarify optimal institutional arrangements. The technical issues of determining areas at risk, establishing physical communication links and developing appropriate catchment models continued to receive attention.

4 Outcomes of the Project

There are three major outcomes from the project, setting the stage for further development:

- new insights into the existing and desired capacities, roles and responsibilities of institutions
- new flood-related knowledge resources generated and made more widely available
- technical advances and adaptations such as a hazard atlas and distributed catchment modelling

4.1 New Institutional Insights

SAWS claimed the responsibility for Flash Flood Forecasting at a meeting in Bethlehem on May 10, 2005. The repercussions of this decision were profound and include:

- the need within SAWS for hydrological modelling of the rainfall-runoff relationship in catchments where people and property are vulnerable
- the need for information on the wetness of the surface of the catchments concerned.

The first consequence is that weather forecasters will be the channels of warning to local Metros and regional DMs, not only for severe weather which they do now, but also for flash floods. The SAWS forecasting office is going ahead with this.

The second consequence is that SAWS has decided to deploy soil moisture probes at selected sites to telemeter information on a daily basis to their data-base. This will allow ground validation of remote sensing of soil moisture indicators by satellites, a task built into a new WRC project K5/1683: Soil Moisture from Satellites: Daily Maps over RSA.

DWAF will continue to work with large rivers and dam releases to issue flood warnings and monitor their progress. The “division of labour” between the two institutions depends on the response time of the catchments of interest. Flash Floods in the South African context are to be (somewhat arbitrarily) considered as those which occur in catchments with response times less than 6 hours. Predicting these floods will be the responsibility of SAWS. Predicting floods in catchments with response times greater than 6 hours are to remain the responsibility of DWAF who will work through the National Disaster management Centre (NDMC).

4.2 New Flood-related Knowledge Resources

With rare exceptions, current practice in Metros is to limit flood studies to static flood assessments, designed for zoning and risk assessment. Much work has gone into defining flood-lines. Only recently have a series of flood forecasting related WRC projects:

1. Pegram GGS and DS Sinclair, 2002. A Linear Catchment Model for Real Time Flood Forecasting. *WRC Report No*. 1005/1/02, Water Research Commission, Pretoria.
2. Sinclair DS and GGS Pegram, 2004. A Flood Nowcasting System for the eThekwini Metro, Volume 1: Umgeni Flood Nowcasting Using Radar - an Integrated Pilot Study. *Water Research Commission Report* WRC 1217/1/04.
3. Mkwananzi N and GGS Pegram, 2004. A Flood Nowcasting System for the eThekwini Metro, Volume 2: Modelling Flood Inundation in the Mlazi River under Uncertainty. *Water Research Commission Report* WRC 1217/2/04.

led to local practitioners being exposed to the possibility that there is data available which can assist in anticipating a flood rather than waiting for it to happen. Not only local knowledge, but international practice gleaned by the Project Leader (PL) from involvement with EU funded flood projects in Europe, have been the message behind several presentations. These were to the CEO of SAWS, the Director of NDMC, the Regional DM of the Cape, combined meetings (some unprecedented and organised by the PL) of Metro DMs and city Engineers of Cape Town Metro, Mandela Metro, Buffalo City, eThekwini Metro and Tshwane Metro. In addition a presentation was made to the 2003 Disaster Management Institute of South Africa Symposium. This has led to a proposal from Mandela Metro to the WRC for Flood Forecasting involving key players.

4.3 Technical Advances

Previous work for the WRC, on the measurement and modelling of rainfall using gauges, radars and satellites, together with the forecasting in real time of where rain is likely to fall in the next hour, has provided tools to assist buying time in Flash Flood Forecasting. This knowledge and capability is an essential ingredient in the overall flood forecasting thrust.

What is also required is to know where to put one's limited resources to have most effect. It was decided to conduct a survey of historic floods and areas which have been most vulnerable to loss of life and property damage. This study forms the core of information for future work and appears as an Atlas, hosted on the DWAF web-site.

To do flood forecasting and particularly flash flood forecasting, a knowledge of soil moisture is vital. One way of doing this is to use a distributed catchment model to estimate the wetness of each pixel, which when subject to rainfall, produces runoff which, combined over the catchment, turns into estimated flow. This calculated flow is compared with the measured flow and selected soil parameters are adjusted until the estimated and measured flows match. There are few generic distributed models (with pixel scales of the order of 1 km square) that are computationally efficient. The one selected here is the **TOP**ographic **K**inematic **AP**proximation **I**ntegration (TOPKAPI) model of Prof. Ezio Todini. This has been implemented from the theory as derived in his publications rather than using his (and his students') code. The model is now well understood and tested to ensure its integrity and is ready for implementation in practice.

In addition, the knowledge gained in two associated WRC contracts has been particularly valuable for determining, with greater precision and confidence, the amount of rain that actually falls where there are no raingauges. Two reports which are helpful here are:

- Pegram GGS, 2004. Spatial interpolation and Mapping of rainfall: 3. Optimal integration of Rain Gauge, Radar and Satellite-derived data in the production of daily rainfall maps, *Water Research Commission Report* WRC 1273/1/02.
- Pegram GGS, DS Sinclair and SM Wesson, 2006. Daily Rainfall Mapping over South Africa: Modelling, *Water Research Commission Report* WRC 1425/1/06

5 Recommendations

Based on the above project outcomes, the following is presented as a **proposed blueprint** for a national flood nowcasting system. This is drawn from the minutes of a recent meeting (19 June 2006) involving senior members of SAWS: Dr Deon Terblanche and Mr Eugene Poolman; the key person in DWAF's flood forecasting office: Mr Brink du Plessis; and Professor Geoff Pegram.

The meeting decided that it is important to give input to the NDMC's Coordinator of the Water Sector Working Group regarding procedures of flood and flash flood management by disaster management structures. The following areas were identified:

1) The definition of large flood events versus flash floods, with the relevant guidelines associated with each class of event and responsible institution for issuing warnings.

2) Procedures regarding the communication process of warnings for each class of event to the national, provincial and municipal disaster management centres need to be outlined.

3) Since data are critical for effective warnings, municipal and provincial disaster management centres (and CMAs) need to be encouraged to also collect weather and stream flow information where data collection networks of SAWS and DWAF are insufficient for local purposes. Guidelines are needed to set standard criteria and coordination mechanisms with SAWS and DWAF to ensure quality and compatibility of the infrastructure.

4) To effectively implement warning systems for areas vulnerable to flooding, it is important that vulnerability assessments by municipal and provincial disaster management centres be provided via the NDMC to SAWS and DWAF.

5) To avoid confusing warnings from more than one source, flood and flash flood warning systems developed by municipal and provincial disaster management centres for their own use must be coordinated with the systems put into place by DWAF and SAWS. Guidelines are needed on the coordination of warnings issued by SAWS or DWAF with those of the local system, responsibility for warnings issued, and operational running of the local systems.

6) Procedures are needed for warnings of flood events in river basins shared with neighbouring countries.
7) A need was identified for a committee to meet routinely between SAWS, DWAF and NDMC to discuss the entire warning system.

The following are two figures presented to the above-mentioned meeting by Mr Eugene Poolman of SAWS. They are self-explanatory and are offered as initial proposals for a national framework for the issuing of flood warnings.

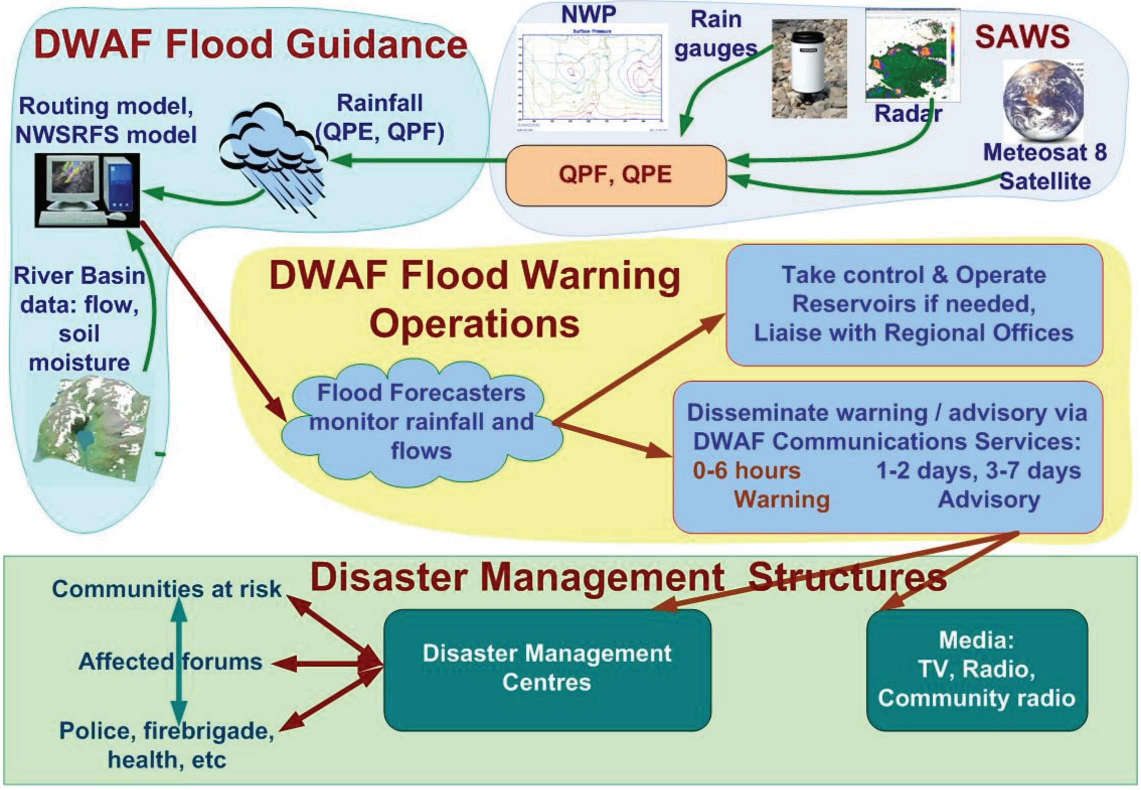


Figure 1. DWAF: Flood warning system: schematic diagram describing the end-to-end warning process from the data input to dissemination of warnings by flood forecasters to disaster management centres, DWAF regional offices and affected communities.

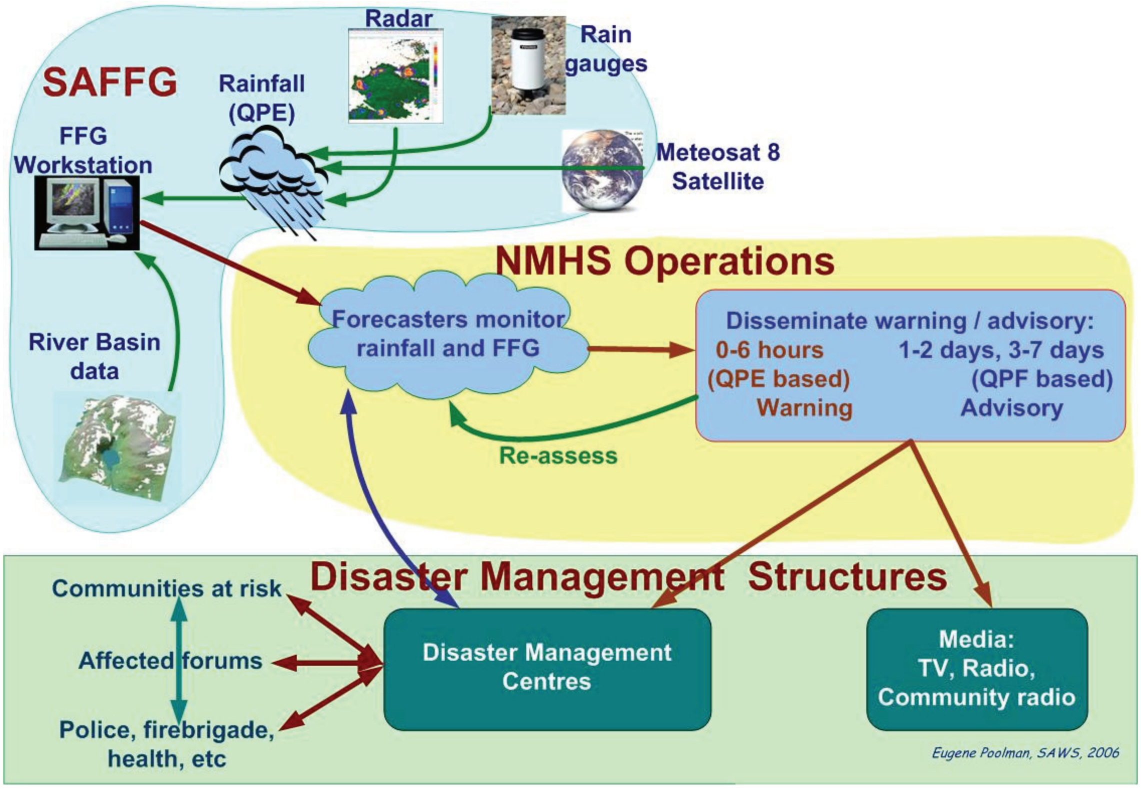


Figure 2. SAWS: Flash Flood warning system: schematic diagram describing the end-to-end warning process from the data input to dissemination of warnings by disaster management centres to their structures and affected communities.

The SAFFG noted in Figure 2 is the Southern African Flash Flood Guidance system offered to SAWS by the University of San Diego California through the WMO. Mr Poolman attended the WMO Workshop in Costa Rica in March 2006 to form the necessary links. SAFFG is a system which integrates rainfall, soil moisture, topography, vegetation, soil type and ground cover at the pixel (1 km) scale through chosen distributed or semi-distributed models of the catchment to provide visual warnings of impending floods over the subcontinent. The work of the present project will benefit from being imbedded in the SAFFG shell, acquired through a SAWS initiative and for which SAWS has taken the responsibility.

6 Capacity and Competency Building

Four post-graduate students have been involved with this project in the Civil Engineering programme of UKZN over the last two and a half years:

- ***Scott Sinclair*** has worked with the project leader since the beginning of 1999 when he started his Masters studies on catchment modelling research project K5/1005: A Linear Catchment Model for Real Time Flood Forecasting (Pegram and Sinclair, 2002). He went on to work (as an engineer employed by Umgeni Water) on the WRC project K5/1217: Umgeni Nowcasting Using Radar – An Integrated Pilot Study (Sinclair and Pegram, 2004b); he is now completing his PhD. He has deputized for the project leader at several RUMSA/MTAP meetings and workshops and has filled in as the representative of the research group during the project leader's absence overseas. He has developed into a highly competent and knowledgeable scientist/engineer/manager who understands the intricacies of advanced computer coding, the workings of satellites and their data products, besides having mastered the applied mathematics and geostatistics necessary to develop the algorithms presented herein.
- ***Stephen Wesson*** has completed his MScEng degree, which he started in 2003. He was responsible for developing the ground clutter removal algorithm and the Cascade Kriging technique designed to extrapolate information from radar measurements aloft in order to estimate rainfall at ground level in WRC project K5/1425. He has developed keen research skills using geostatistics and advanced computer programming and mastered some difficult image processing algorithms. He has become scientifically mature, has shown encouraging sparks of originality and has made a sound contribution to this study.
- ***Mohamed Parak*** is completing his MScEng degree, which he started in 2004. Until the beginning of 2005, he was working in parallel on a flood study for the department of Transport under the supervision of the project leader. Since then he has made a contribution to this study through his work on geospatial statistics and GIS modelling. His major contribution to the WRC projects is his adaptation of the TOPKAPI model for distributed catchment modelling which has application in this project. He has shown a particular facility with the complexities of the mathematics of catchment modelling, its description and its local application.
- ***Ntokozo Nxumalo*** started his Masters studies at the beginning of 2005. He is working on a parallel WRC study K8/598: Soil Moisture Mapping from Satellites and the new WRC project: K5/1683: Soil Moisture from Satellites: Daily Maps over RSA. His contribution to the floods study has been peripheral, however together with all the graduate students in the group he meets with the project leader/supervisor every Friday morning when the week's work is discussed. He is growing rapidly as a researcher with flair and is showing a marked facility with image analysis.

7 Knowledge Dissemination

A large proportion of the material appearing in this report has (i) already been published, (ii) been submitted for publication (iii) been presented at national or international conferences, symposia or workshops. A list of these publications and other contacts made by those involved in the projects follow.

Degrees completed

Wesson, S,M. (2006). Radar Reflectivity Infilling Techniques, *MScEng thesis,* ***with distinction****, Civil Engineering Programme, University of KwaZulu-Natal, Durban*, 242 pages.

Papers Published in Journals

Pegram GGS (2003). Rainfall, Rational Formula and Regional Maximum Flood, Some Scaling Links, *Australian Journal of Water Resources*, Vol 7, No 1, pp 29-39

Pegram GGS (2004). Reply to comment by R French in, *Australian Journal of Water Resources,* Vol 8, No 1, pp 97-98

Pegram GGS and Parak M (2004). A review of the Regional Maximum Flood and Rational Formula using geomorphological information and observed floods, *Water SA*, **30(**3), 377-392

Wesson SM and Pegram GGS (2004). Radar rainfall image repair techniques, *Hydrol. Earth Syst. Sci.*, **8(2)**, 220 – 234.

Sinclair S and Pegram GGS (2005a). Combining radar and rain gauge estimates using conditional merging, *Atmos. Sci. Let.*, **6**, 19-22.

Sinclair S and Pegram GGS, (2005b), Empirical Mode Decomposition in 2-D space and time: a tool for space-time rainfall analysis and Nowcasting, *Hydrol. Earth Syst. Sci.*, **9**, 127-137.

Bardossy A, GGS Pegram and L Samaniego, (2005). Modeling data relationships with a local variance reducing technique: Applications in hydrology, *Water Resour. Res.*, 41, W08404, doi:10.1029/2004WR003851.

Sinclair, S and GGS Pegram (2005), Empirical Mode Decomposition in 2-D space and time: a tool for space-time rainfall analysis and nowcasting, *Hydrology and Earth System Sciences*, 9, 127–137, www.copernicus.org/EGU/hess/hess/9/127/SRef-ID: 1607-7938/hess/2005-9-127

Wesson, SM and GGS Pegram, (2006) Improved radar rainfall estimation at ground level, *Nat. Hazards Earth Syst. Sci.*, 6, 1–20, 2006.

Parak M and GGS Pegram, (2006). The Rational Formula from the Runhydrograph, *Water SA*, **32**(2), 163-180.

Papers Published on Websites

Pegram GGS., Deyzel ITH, Sinclair S, Visser P, Terblanche D and Green GC, (2004), Daily mapping of 24 hr rainfall at pixel scale over South Africa using satellite, radar and raingauge data, *2nd IPWG Workshop*, Naval Research Laboratory, Monterey, CA, USA, 25-28 October. http://www.isac.cnr.it/~ipwg/meetings/monterey/pdf/Pegram.pdf

Presentations at international symposia/conferences

Sinclair S, Ehret U, Bardossy A and Pegram GGS, (2003), Comparison of Conditional and Bayesian Methods of Merging Radar & Rain gauge Estimates of Rainfields, *Presentation at EGS - AGU - EUG Joint Assembly*, Nice, France, April.

Pegram GGS and Sinclair S, (2004), National Flood Nowcasting System towards an integrated mitigation strategy in South Africa, *Proceedings of the 6th International Symposium on Hydrological Applications of Weather Radar*, Melbourne, Australia, 2-4 February.

Sinclair S and Pegram GGS, (2004), Combining Radar and Rain Gauge Rainfall Estimates for Flood Forecasting in South Africa, *Proceedings of the 6th International Symposium on Hydrological Applications of Weather Radar*, Melbourne, Australia, 2-4 February.

Sinclair S and Pegram GGS, (2005), Space-time rainfall analysis and nowcasting using Empirical Mode Decompostion in 2D, *EGU General Assembly*, Vienna, Austria, April.

Wesson SMand Pegram GGS, (2005), Repairing Radar Volume Scans, *EGU General Assembly*, Vienna, Austria, April.

Pegram GGS, Sinclair S, Wesson SM & Visser P (2005). South African Offering for Ground Validation. *2nd International GPM Ground Validation Workshop*, 27 - 29 September 2005; Taipei, Taiwan

Chiew FHS, Peel MC, Amirthanathan GE & Pegram GGS, (2005) Identification of oscillations in historical global streamflow data using Empirical Mode Decomposition. In Regional Hydrological Impacts of Climatic Change - Hydroclimatic Variability, Proceedings of Symposium S6 held during the Seventh IAHS Scientific Assembly at Foz do Iguaçu, Brazil. IAHS Publ. 296, pp: 53-62.

Pegram GGS (2005a) How the SIMAR 24h rainfield over Southern Africa is constructed & how it could be used for Flash Flood Forecasting. Presentation at the *WMO WWRP Nowcasting Workshop*, SAWS, Pretoria, 28 November – 9 December 2005.

Pegram GGS (2005b) Soil Moisture from Space - Southern Africa. Presentation at *European Space Agency TIGER workshop*, ESRIN, Frascati, Rome, Italy, 3-4 October.

Pegram GGS and Nxumalo NS, (2006). Remote sensing of soil moisture in Southern Africa, *EGU General Assembly*, Vienna, Austria, April.

Pegram GGS and Sinclair S, (2006). Ground validation of GPM products in Southern Africa, *EGU General Assembly*, Vienna, Austria, April.

Presentation at national symposia/conferences

Sinclair S and Pegram GGS, (2003), Combining Traditional and remote sensing techniques as a tool for Hydrology, Agriculture and Water Resources Management, *Proceedings of the 11th South African National Hydrology Symposium*, Port Elizabeth, South Africa.

Wesson S and Pegram GGS, (2003), Efficient cleansing of Radar Rainfall images, *Proceedings of the 11th South African National Hydrology Symposium*, Port Elizabeth, South Africa.

Pegram GGS, Sinclair S, Wesson SM & Visser P (2005). South African Offering for Ground Validation. *2nd International GPM Ground Validation Workshop*, 27 - 29 September 2005; Taipei, Taiwan

Chiew FHS, Peel MC, Amirthanathan GE & Pegram GGS, (2005) Identification of oscillations in historical global streamflow data using Empirical Mode Decomposition. In Regional Hydrological Impacts of Climatic Change - Hydroclimatic Variability, Proceedings of Symposium S6 held during the Seventh IAHS Scientific Assembly at Foz do Iguaçu, Brazil. IAHS Publ. 296, pp: 53-62.

Pegram GGS (2005a) How the SIMAR 24h rainfield over Southern Africa is constructed & how it could be used for Flash Flood Forecasting. Presentation at the *WMO WWRP Nowcasting Workshop*, SAWS, Pretoria, 28 November – 9 December 2005.

Pegram GGS (2005b) Soil Moisture from Space - Southern Africa. Presentation at *European Space Agency TIGER workshop*, ESRIN, Frascati, Rome, Italy, 3-4 October.

Sinclair S & GGS Pegram (2005). Empirical mode decomposition in 2-D space and time: A tool for space-time rainfall analysis and nowcasting 12th SANCIAHS SYMPOSIUM, Johannesburg, 5 – 7 September

Parak M & GGS Pegram (2005). The Rational Formula from the Runhydrograph. 12th SANCIAHS SYMPOSIUM, Johannesburg, 5 – 7 September

Nxumalo NT & GGS Pegram (2005). Soil Moisture from Satellites, 12th SANCIAHS SYMPOSIUM, Johannesburg, 5 – 7 September

Wesson SM & GGS Pegram (2005). Radar-Rainfall infilling techniques, 12th SANCIAHS SYMPOSIUM, Johannesburg, 5 – 7 September 2005

International visits and contacts

Scott Sinclair presented two of the three papers at EGU in Nice in 2003 and had the benefit of arguing his case about Conditional Merging with Professor Ezio Todini, face to face.

Professor Geoff Pegram attended EGS in Nice in 2003 and then EGU in Vienna in 2005 and 2006 where he made presentations and attended the editorial board meetings of the EGU journal Hydrological and Earth System Sciences (HESS) as Associate Editor.

He was Visiting Research Fellow in the Civil and Environmental Engineering Department, University of Melbourne, during 2003, 2004, 2005 and 2006 for 8 weeks, where he continued his research collaboration association in areas of precipitation modelling and water resources. The last two visits were spent exploring the benefits of Empirical Mode Decomposition and non-stationary Adaptive Time Series modelling, a point of departure for ***Scott Sinclair's*** work. In 2006 he was involved with the research of Prof Jeff Walker, who is an international leader in remote sensing of soil moisture.

In 2003, he was Invited to participate as rapporteur (and future full member of the Steering committee) at the European Union project: MUSIC / CARPE DIEM Joint Workshop with End Users, at Düsseldorf-Neuss, Germany: "CURRENT FLOOD FORECASTING PRACTICE IN EUROPE". This invitation was repeated for the final meeting in Helsinki in June 2004. These visits continued to maintain the good research collaboration relationship with Professor Todini, one of the foremost stochastic hydrologists in Europe.

In March 2004 and again in April 2006, he was Visiting Professor and Guest Lecturer: ENWAT: International Doctoral Program 'Environment Water' University of Stuttgart, hosted by Professor Andras Bardossy, where work on non-linear modelling was undertaken and published in Water Resources Research in 2005. This visit will be repeated in 2007.

In July 2004 he was Visiting Professor at GRAHI (Group for Research Applications in Hydrology Institute), Barcelona Spain, hosted by Professor Daniel Sempere-Torres and working together with their Doctoral students on radar-hydrology, which gave great impetus to the work of ***Stephen Wesson*** in the UKZN group. This fruitful visit will be repeated in September 2006, when he will present WRC funded research products at the ERAD 2006 symposium in Barcelona, where there will be 270 presentations by scientists and engineers concerned with hydrological applications of weather radar.

In October 2004, as a direct result of meeting Prof Vincenzo Levizzani at the MUSIC workshop in Dusseldorf, he was an invited participant at 2nd International Precipitation Working Group meeting (a closed workshop, sponsored by Coordination Group for Meteorological Satellites, WMO, NASA & EUMETSAT) in Monterey, CA. Here he presented a summary of the WRC research project K5/1153: SIMAR. These contacts led to an invitation to the Global Precipitation Monitoring – Ground Validation workshop in September 2005 in Taipei, another closed workshop at which the current WRC research project was showcased. As a result of these contacts with leading American and Australian meteorologists, Dr Deon Terblanche of SAWS has volunteered to provide SAWS-based precipitation data for ground validation of rainfall data, remotely sensed using geostationary and polar orbiting satellites. This work is now established and on-going.

In 2005, while at the EGU Congress in Vienna, he met with Prof Wolfgang Wagner of the Vienna University of Technology. This is the European partner institution with which the Satellite Applications and Hydrometeorology Group in Civil Engineering at UKZN has a joint EU contract (TIGER: SHARE) to measure soil moisture from space over southern Africa. The research is based on the output of polar orbiting satellites and complements the WRC project K5/1683: Soil Moisture from Satellites: Daily Maps over RSA, which commenced in April 2006. This meeting led to further international connections with the expert practitioners in remote sensing of Soil Moisture, which had two positive spin-offs for this country. First, after a request from Prof Wolfgang Wagner, Dr Tom Jackson of US Department of Agriculture (USDA) and Dr Michael Berger of the European Space Agency (ESA) wrote very supportive letters to SAWS which led to their agreement (by Nico Kroese in particular) to invest in a network of soil moisture ground stations. Second, as a result of this contact, Prof Pegram was invited to the International Soil Moisture Working Group's first meeting for the Development of a Global In-Situ Soil Moisture Network - Workshop / Experts Meeting in Wageningen, Holland, in March 2006; here he again met with Jeff Walker and persuaded him to attend the inaugural meeting of SHARE in Vienna a week later before attending EGU.

The purpose of listing these contacts is to show how important it is to maintain international ties with world leaders in these areas of research.

- The Soil Moisture work has a direct impact on the estimation of flood-levels when rain falls – the wetter the soil, the more rain that runs off.
- The Flood Forecasting Workshops in Europe and elsewhere locally sharpen the minds and share the ideas in a field of study which is novel in engineering practice in South Africa.
- The continued improvement of the estimation of the quantity of precipitation (QPE) is essential if we are to be precise with our flood estimates – not only must they be accurate, they must be reliably available in real time.

8 Acknowledgements

The authors would like to express their thanks to the WRC for providing funding and in particular, the project steering committee for their valuable support, comments and suggestions throughout the life of this project. Specific thanks are also extended to SAWS and DWAF, without their support in providing data and scientific comment many of the achievements presented here would not have been possible.

The members of the steering committee were:

Dr GC Green	:	Water Research Commission – Chairman
Mr N Kroese	:	South African Weather Service (SAWS)
Mr D Terblanche	:	South African Weather Service (SAWS)
Mr DB Du Plessis	:	Department of Water Affairs and Forestry
Mr CG Swiegers	:	Department of Water Affairs and Forestry
Prof J Smithers	:	University of KwaZulu-Natal, Pietermaritzburg
Prof R Bharuthram	:	University of KwaZulu-Natal, Durban
Mr LJ Buys	:	National Disaster Management Centre, Pretoria
Mr B Wood	:	City of Cape Town, Metro Catchment Manager
Mr G Laskey	:	City of Cape Town, Disaster Management Co-Ordinator

Table of contents

List of Figures

1 Introduction and Background

Floods cannot be prevented. Through appropriate planning and management strategies, the devastating effects of floods can be reduced. Loss of life and damage to infrastructure can be minimized but never completely eliminated. The white paper on disaster management (WPDM, 1998) presents the data shown in table 1.1, showing the estimated losses resulting from several disasters in South Africa. Of particular relevance is the prominence of flood events amongst these disasters.

With large increases in population and increasing urbanization (largely driven by poverty) there are more people living in informal settlements (near cities). These settlements often encroach on floodplains, as this is the only undeveloped land, which remains available. The people living in these settlements are those who are most at risk, not only due to their geographical location in the floodplain but also because (without access to insurance policies) they do not have the financial resources to recover from damage caused by flooding. In addition many formal developments already exist in areas that are susceptible to flooding. When the nature of the development is such that significant damage would result from flooding, early warning systems can provide a means of reducing the risk to acceptable levels.

Place	Disaster	Cost
Ladysmith	Floods, 1994	• 400 families evacuated • R50 million damages
Merriespruit	Slimes dam, 1994	• 17 lives lost • R45 million damages
Pietermaritzburg	Floods, 1995	• 173 lives lost • Emergency shelter needed for 5 500
Ladysmith	Floods, 1996	Damages to infrastructure: R25 million
South Africa	Drought, 1991-92	• 49 000 agricultural jobs lost • 20 000 non-agricultural jobs lost • Associated with 27% decline in agricultural gross domestic product
Northern Province	Floods, 1996	R105 million damages
Mpumalanga	Floods, 1996	R500 million damages

Table 1.1: Counting the cost of disasters in South Africa.

The recently promulgated Disaster Management Act (Act 57 of 2002) advocates a paradigm shift from the current “bucket and blanket brigade” response-based mindset to one where disaster prevention or mitigation are preferred. It is in the context of mitigating the effects of flood events that the development and implementation reliable flood forecasting systems has major significance. In the case of flash floods even a small amount of lead-time (a few hours), can allow disaster managers to take steps, which may significantly reduce loss of life and damage to property.

The main requirement of an effective flood forecasting system is the provision of reliable, intelligible forecasts of flood flows with a reasonable lead-time and explicit error bounds. The forecasts must be made available at frequent intervals to hydrological operators, decision makers and disaster managers, in a clearly understandable form. The unfortunate reality is that South Africa is a long way off from realizing such a situation in practice.

Important key phrases for on-line operation are: long lead time, frequent updates, estimates including an indication of uncertainty, confirmatory information from the catchment, redundancy and feedback to update and improve estimates as new information becomes available.

For off-line work the key phrases are: evaluation of the system and instrumentation of catchments, improvement of models, commitment to recalibration, ability to simulate alternative scenarios, operator training and the development of a reliable intelligible alerting system.

In a typical flooding scenario, the alerting system should trigger the forecasting system to move from standby mode to yellow alert, upon which, the information stream goes on-line and the models are calibrated at operational, rather than at standby frequency. Once there is a perceived threat of flood damage as a result of no intervention, the system goes to orange alert and the flood mitigation strategy is employed. It is at this stage that the information stream arriving in the operations room is put to best use by disaster managers.

It is well known that in times of flood, things to do not work well: telemetering equipment gets damaged by water or lightning, phone lines go dead, radio links become erratic, computer links go down and people do unpredictable things. The important key to counteract these phenomena is redundancy in the information stream and well-trained disaster management personnel. The system needs to have available parallel measuring devices and alternative communication links.

The tools available can be loosely divided into hardware, software and algorithms. The appropriate hardware available for use in South Africa includes the following: meteorological satellites, weather radar, telemetering rain gauges, telemetering stream gauges, fast computers with large storage, telephones, cell phone networks, Internet, solar panels/batteries, UPS systems.

The software useful for flood forecasting, which is currently available and does not require a large amount of modification for incorporation into a system, includes: meteorological prediction of rainfall - location and probability, satellite estimation of rainfall, radar estimation of rainfall, Hydrologic catchment models, Hydraulic river channel models.

The Disaster Management Act charges local Municipalities with the legal responsibility for ensuring that appropriate mitigation strategies (including warning systems) are in place. It is with this in mind that this project was conceived and the project plan and deliverables developed. The aims of the project, as originally conceived, were as follows:

1. Put an effective, efficient, available national flood-forecasting system in place.
2. Use this system to forecast flood inundation levels routinely.
3. Use these forecast inundation levels to alert vulnerable people, industry, Disaster Managers (DMs) in order to mitigate the effects of floods.
4. Have recent information (satellite, radar and gauge estimation of rainfall) distributed from the NDMC/DWAF:PSU (National Disaster Management Centre/Department of Water Affairs & Forestry: Public Safety Unit) to the regions.

5. Provide flood nowcasts/forecasts (with horizons of 1/2, 1, 2, 4, 8 hour etc) to sensitive regions in as much detail as required.
6. Interact and work with local DMs and Local Authorities to convert flows to inundation levels.
7. Provide training initiatives (annual courses, presentations and software) for local DMs using simulated weather systems to augment training on historical events.

It turned out that critical issues related to capacity and the difficulty of prioritising a large number of demands on resources (both financial and human), have made the task of implementing systems a difficult one at the local municipal level. The approach to the project had to be adapted in accordance with these realities.

Besides the technical advances achieved, the most significant contribution of this study toward resolving the above-mentioned critical issues, has been its acting as a catalyst in bringing together the major role players and sensitising them to the issues, as well as creating an awareness (and expectation) among the Municipalities.

2 Implementing simplified access to data and identifying high hazard zones

As a step towards the development of an integrated national flood nowcasting and response strategy, High Hazard Flood Risk Areas in South Africa need to be identified. After consultation with DWAF experts in addition to the collation of a detailed library of historical events and data analysis, the following has been produced under the umbrella of DWAF Disaster Management, whose home page and URL are shown in Figure 2.1:

- Rainfall Atlas
- Flood Atlas containing:
  - Regional Maximum Floods
  - Streamflow Information
  - Reservoir Information

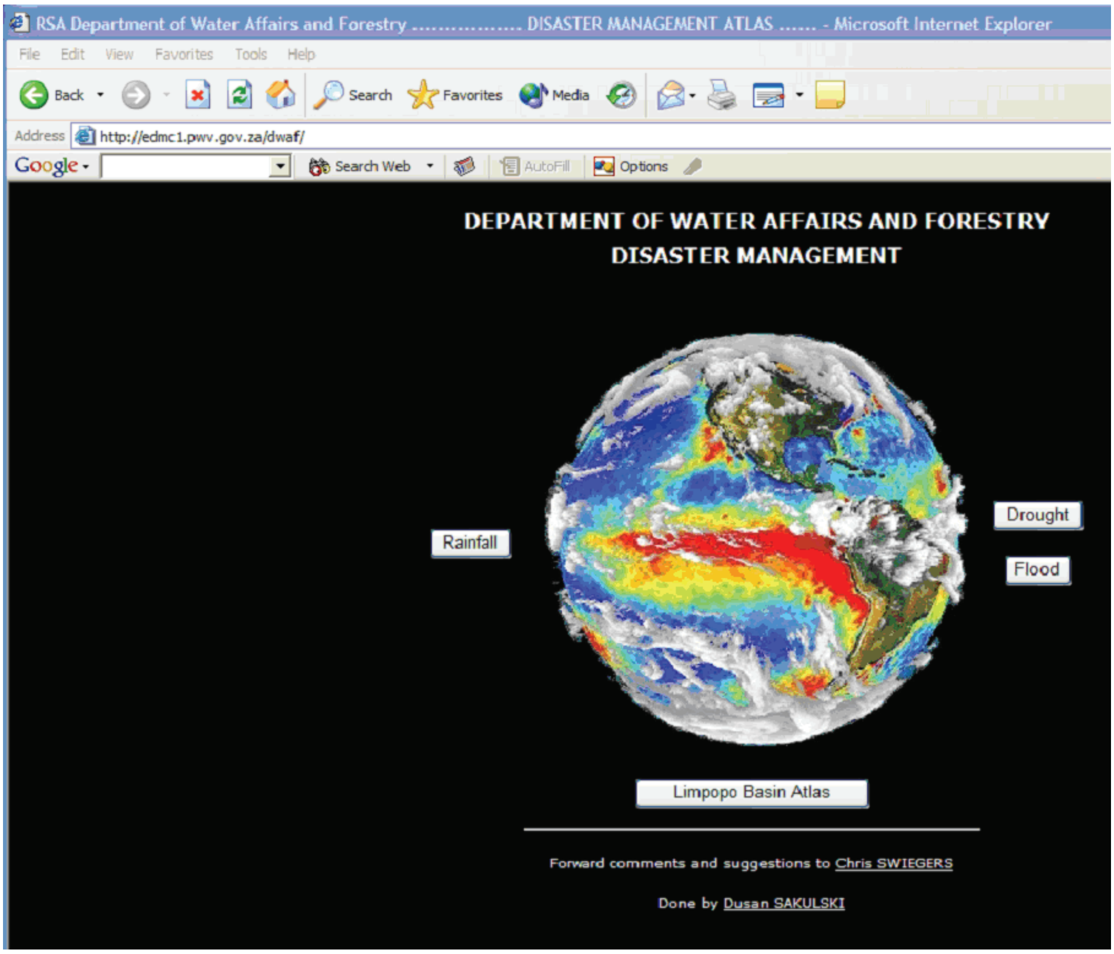


Figure 2.1 DWAF Disaster Management Home web page (http://edmc1.pwv.gov.za/dwaf)

A description of the contents and links provided within this site are below.

2.1 DWAF Rainfall Atlas

This Atlas provides convenient internet links (from a single web page) to a variety of sites already in existence. In accordance with the new Disaster Management Act, as well as the Disaster Management Framework, the new paradigm shift is to be in the direction of maximizing prevention. Special attention is to be taken in the area of early warning, as well as development of spatial and temporal Risk Profiles, at all levels of government: national, provincial and local. One of the most important segments of the overall risk profile is the water risk profile. It should consist of two major parts: flood and drought.

For both components, it is of strategic importance to continuously monitor rainfall. The SIMAR project (Kroese, 2004; Deyzel et al., 2004; Pegram, 2004) is fully in accordance with this requirement. The rainfall section of the Atlas enables users to quickly obtain a variety of information related to the rainfall, such as:

- Where is it raining now? (Figure 2.2) or in the previous 24 hours? (Figure 2.3)
- Where will it possibly rain in 1, 2, 3, or 4 days time? (Figure 2.4)
- What is the historical rainfall data and information per quaternary catchment or rainfall station for South Africa? (Figures 2.5-2.10)

The Rainfall Atlas links to many national, regional as well as international institutions, such as the South African Weather Service (RSA), the Department of Water Affairs and Forestry (RSA), National Disaster Management Centre (RSA), NOAA (USA), NASA (USA), European Space Agency, etc.

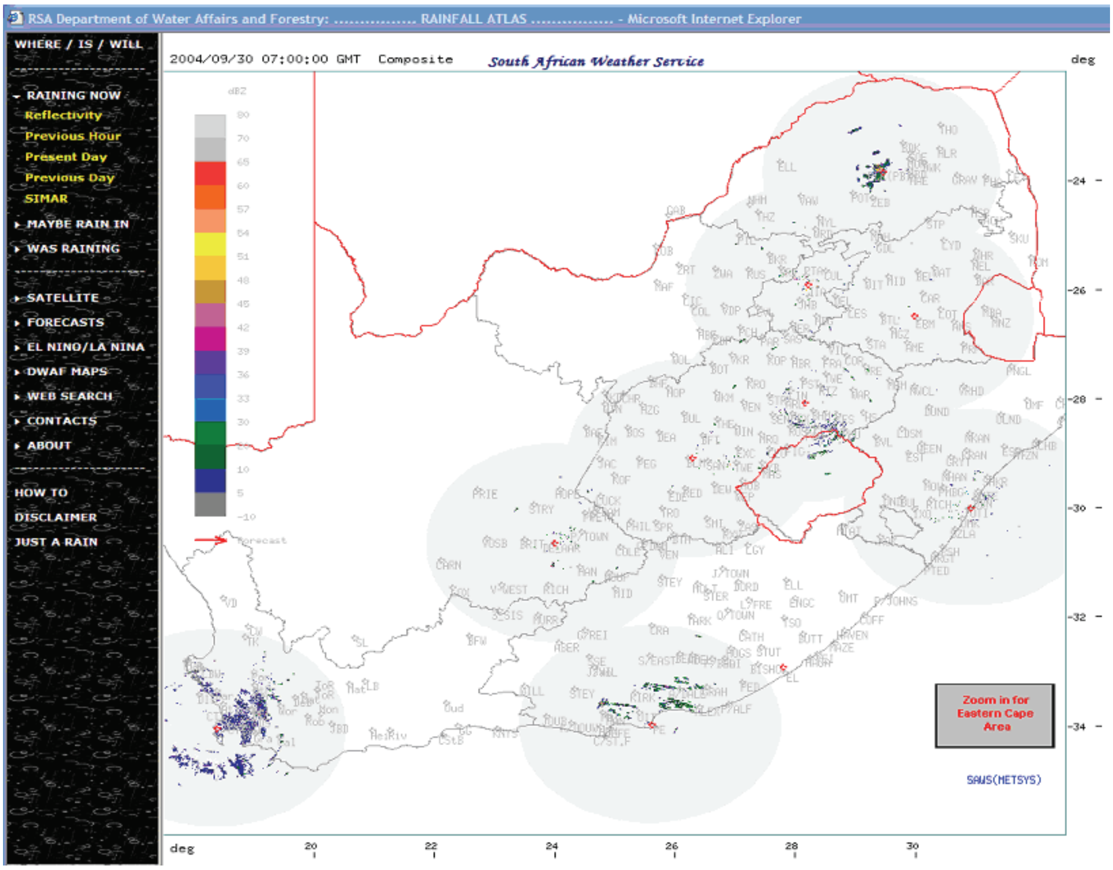


Figure 2.2 Rainfall Atlas: Radar reflectivity – current instantaneous rainfall estimates are derived from the reflectivity values.

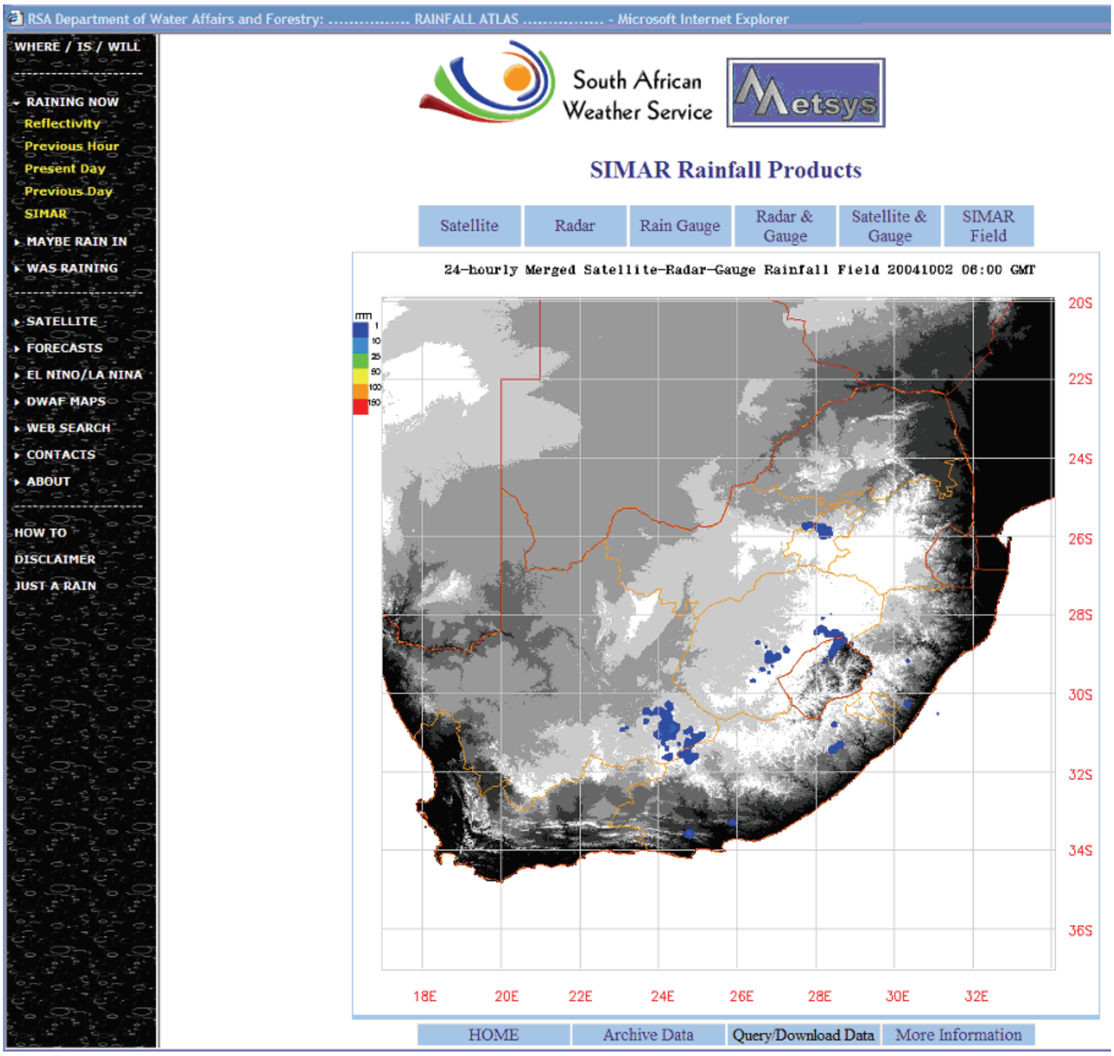


Figure 2.3 Rainfall Atlas: SIMAR rainfall estimation – combined radar, gauge and satellite.

Figure 2.4 shows forecast 24 hour precipitation accumulations for 30, 54, 75 and 102 hour lead-times. The forecasts are made using the NOAA GFS model and appear on the CPC website, along with a wealth of other forecast information.

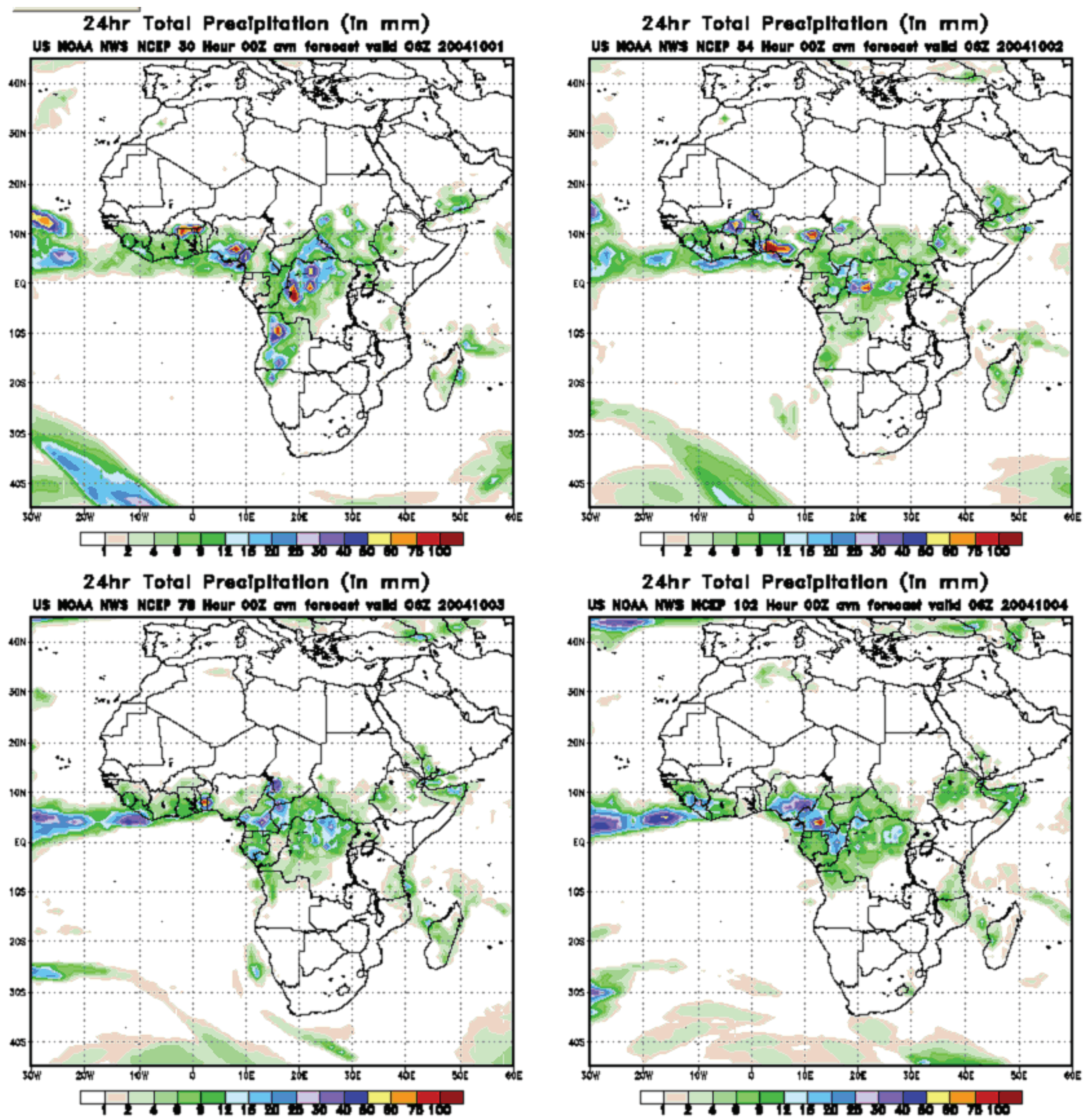


Figure 2.4 Modelled rainfall forecasts from the NOAA GFS model.

The historical rainfall data are built on two data sources: from the WR 90 data base (Midgley et al., 1994), as well as accumulated monthly rainfall data obtained by national Climatic Data Centre (NCDC), USA. Data have been stored in a relational database, and are fully searchable.

The historical rainfall's menu offers the user variety of statistical data analyses and visualizations:

- Time series graph for chosen period
- Time series graph for selected month for a chosen period
- Average annual distribution
- Total annual distribution
- Average monthly distribution
- Monthly rainfall exceedance
- Cumulative distribution
- Moving average
- Linear trend
- Percentiles

some of which are shown in Figures 2.5-2.10.

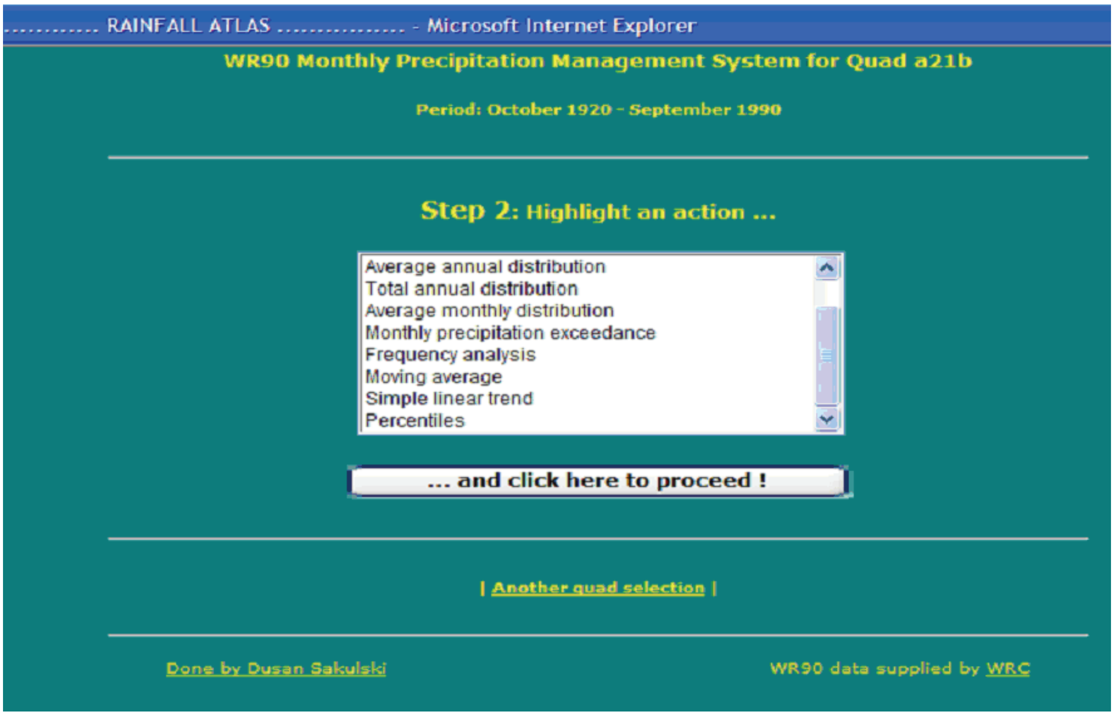


Figure 2.5 Menu for historical rainfall data analysis

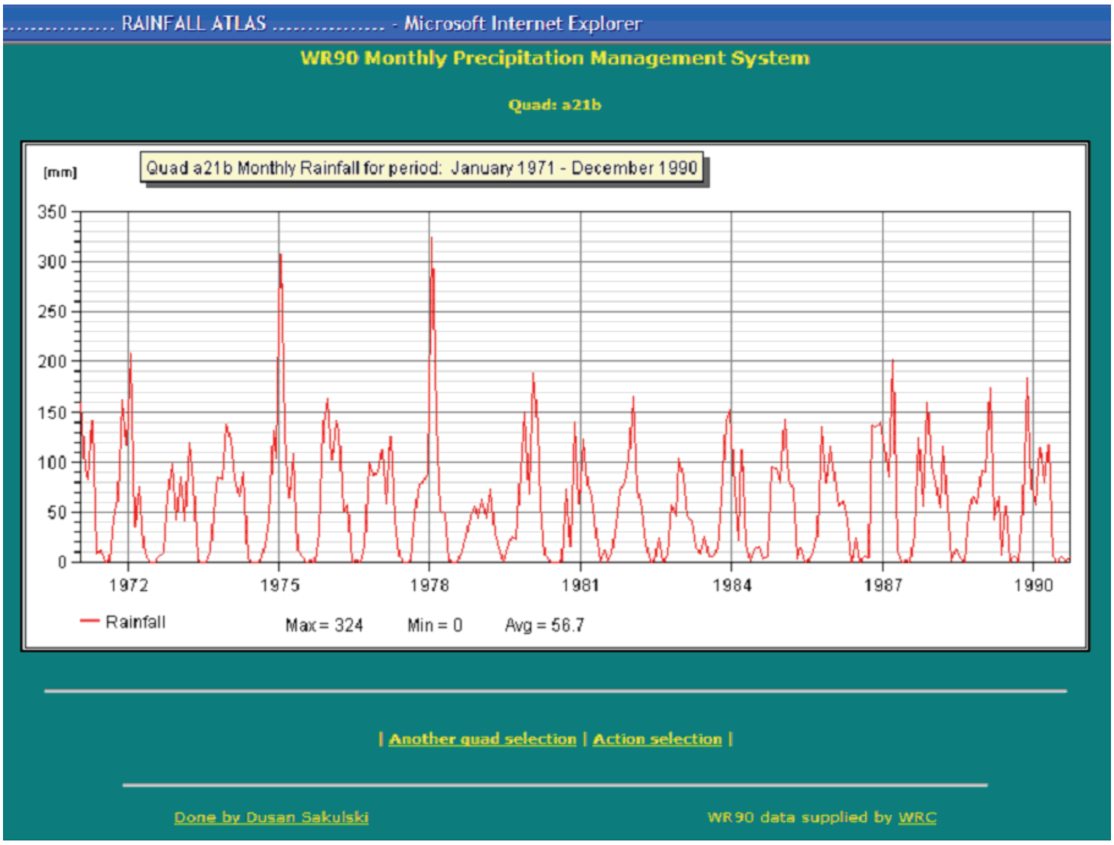


Figure 2.6 Monthly rainfall graph for chosen period

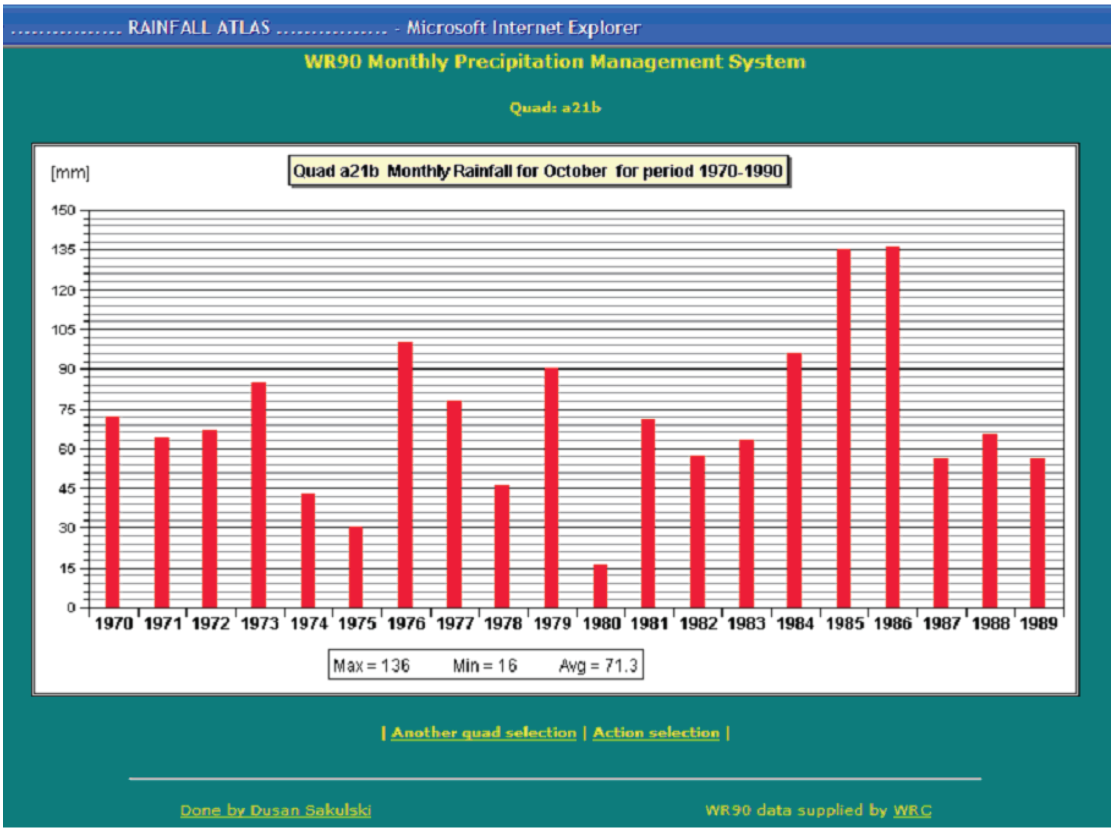


Figure 2.7 Rainfall for selected month (October) for chosen period

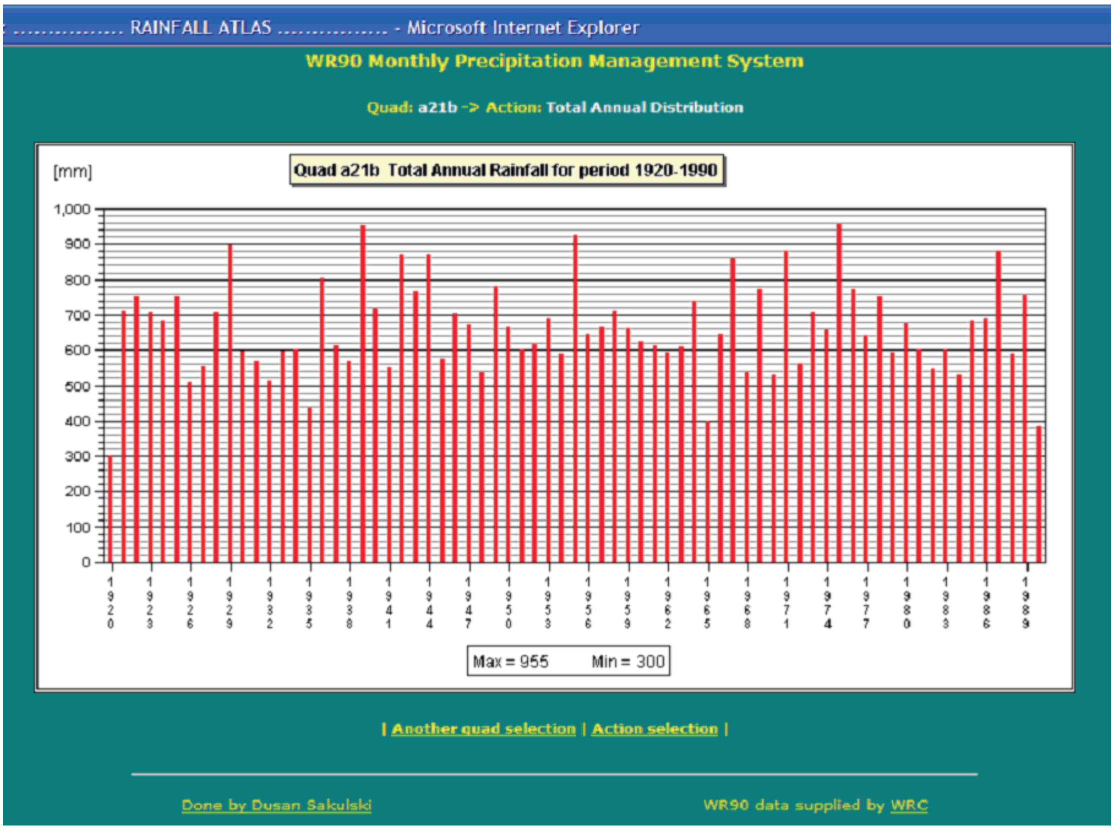


Figure 2.8 Total annual rainfall for chosen period

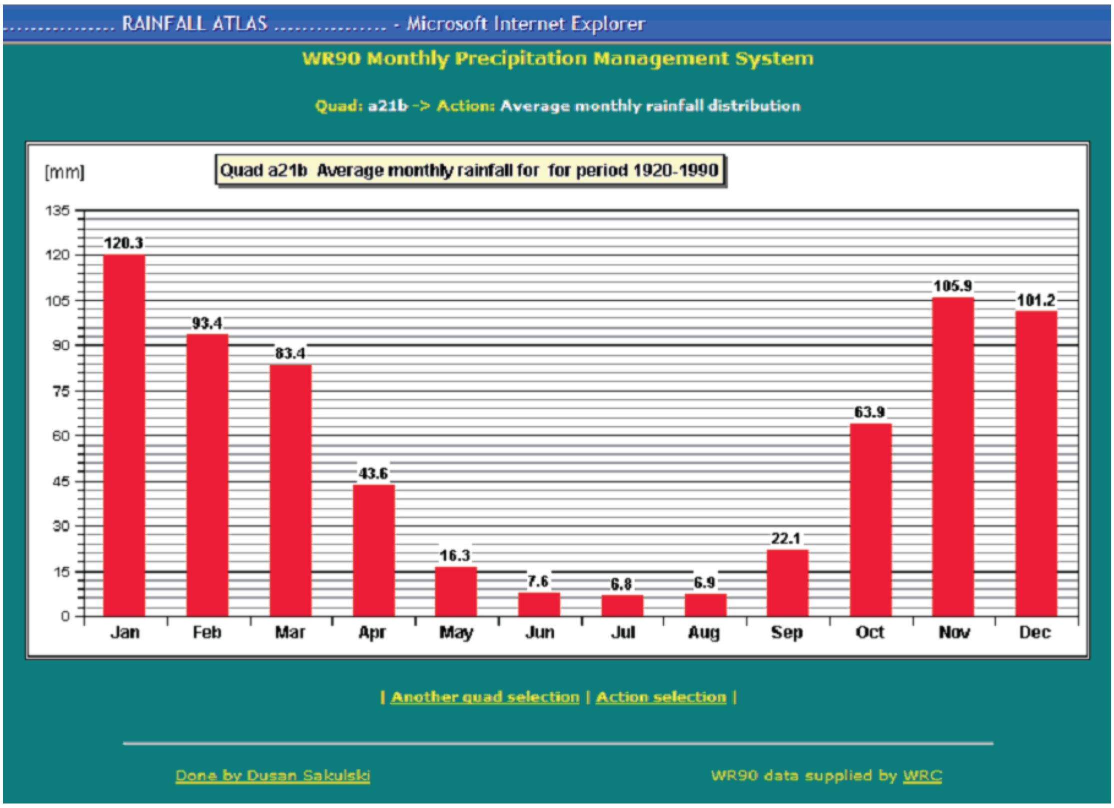


Figure 2.9 Average monthly rainfall for quaternary A21B

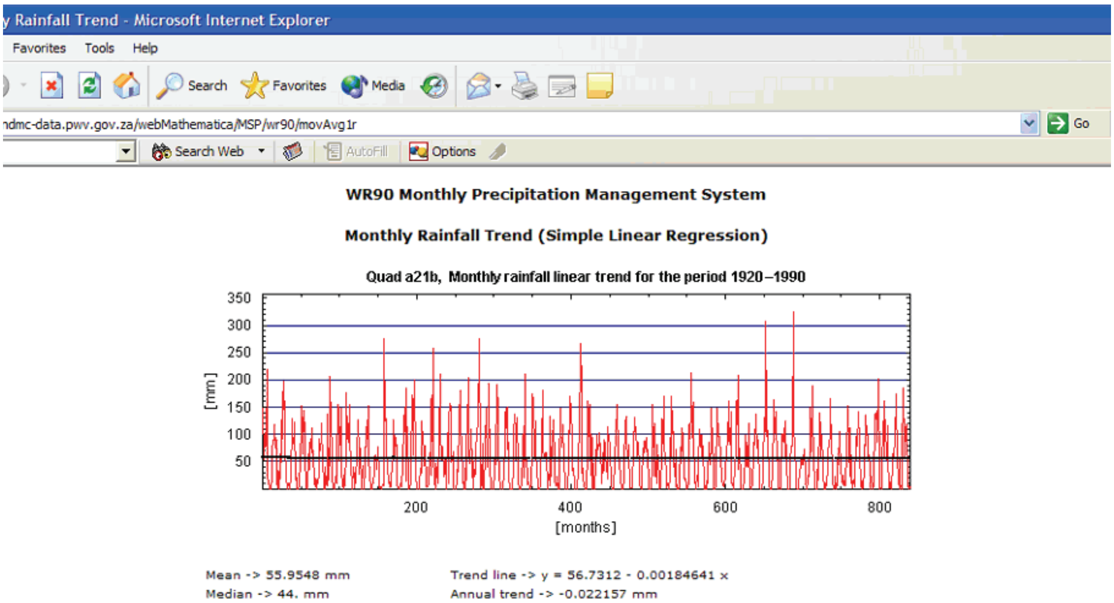


Figure 2.10 Rainfall trend for quaternary A21B

2.2 DWAF Flood Atlas

Clicking on the FLOOD button, on the main DWAF Disaster Management page, will open the Flood Atlas. The main menu of the Flood Atlas consists of the following options (Figure 2.11):

- About Flood
- Flood Estimation
- Historical Flood Info
- Link to Rainfall Atlas
- Link to DWAF streamflow information
- Link to DWAF reservoirs info and analysis
- Link to various web-based GIS mapping tools

some of which will be described below, following the buttons on the left of Figure 2.11.

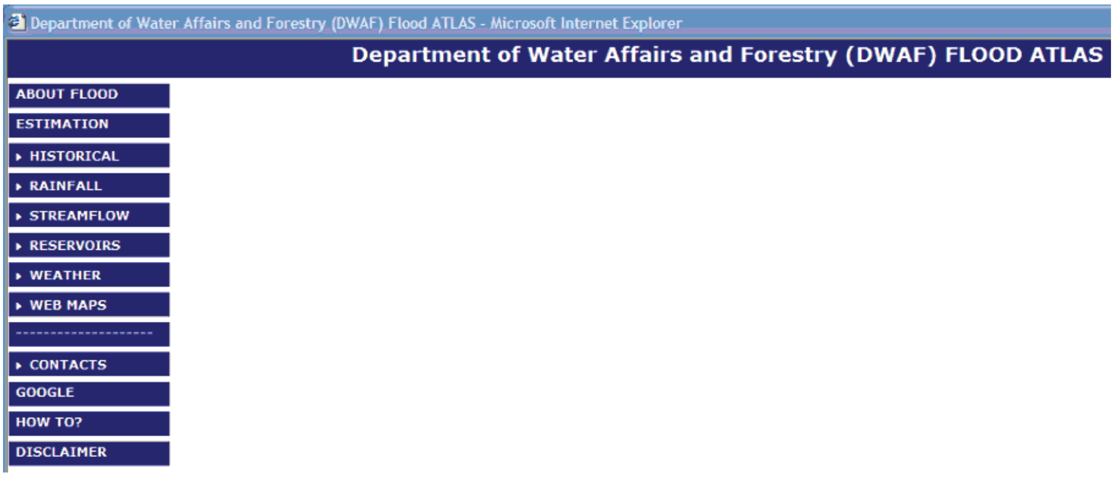


Figure 2.11 DWAF Flood Atlas's Menu

2.3 Historical Flood Information

2.3.1 FLOOD PEAKS - Visualisation of the historical five highest flood peaks for major South African rivers based on secondary catchment data

Source data for this part of the Atlas were extracted from the document "Historical Flood Documentation in South Africa 1652-1996", by D. van Bladeren. Data have been reloaded, from the source document, plain text table, into a database table, on the DWAF disaster management server (EDMC1).

The User can select a river by name, on the basis of secondary catchment data (Figure 2.12, top frame). The system will read flood peak data from the database and produce a bar chart (Figure 2.12, bottom frame). The chart contains the five highest flood peaks with their dates.

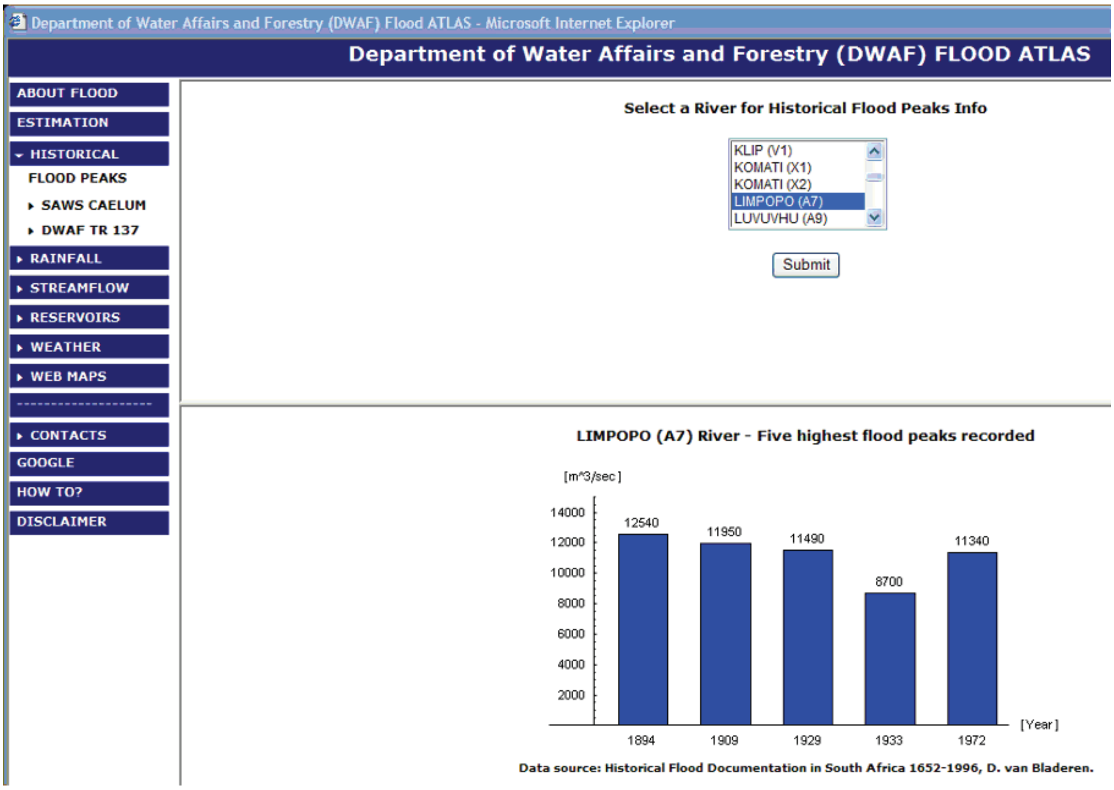


Figure 2.12 5 highest flood peaks for Limpopo (secondary catchment A7)

Newspaper reports and articles on weather-related events have been collected by the South African Weather Service Library for a number of years and provide the main source of information in compiling this summary. These reports, however, are not available for the whole period and are unfortunately also not representative of the whole country since use has been made almost exclusively of those newspapers published in only the major centres. The newspapers archived in the State Library were consulted where more details were required on previous occurrences of severe weather mentioned in some of these reports. Valuable information was also obtained from the meteorological report forms of SAWS weather and rainfall observers as well as SAWS publications such as the Monthly Reports, Annual Reports and Newsletters.

If the user clicks on SAWS CAELUM, in the top frame (Figure 2.13) this enables the user to select a particular flood from the list. After submission, information about the selected flood will appear in the bottom frame.

2.3.2 SAWS CAELUM - A database-driven web-enabled version of the CAELUM (a history of notable weather events in South Africa: 1800 - 1995)

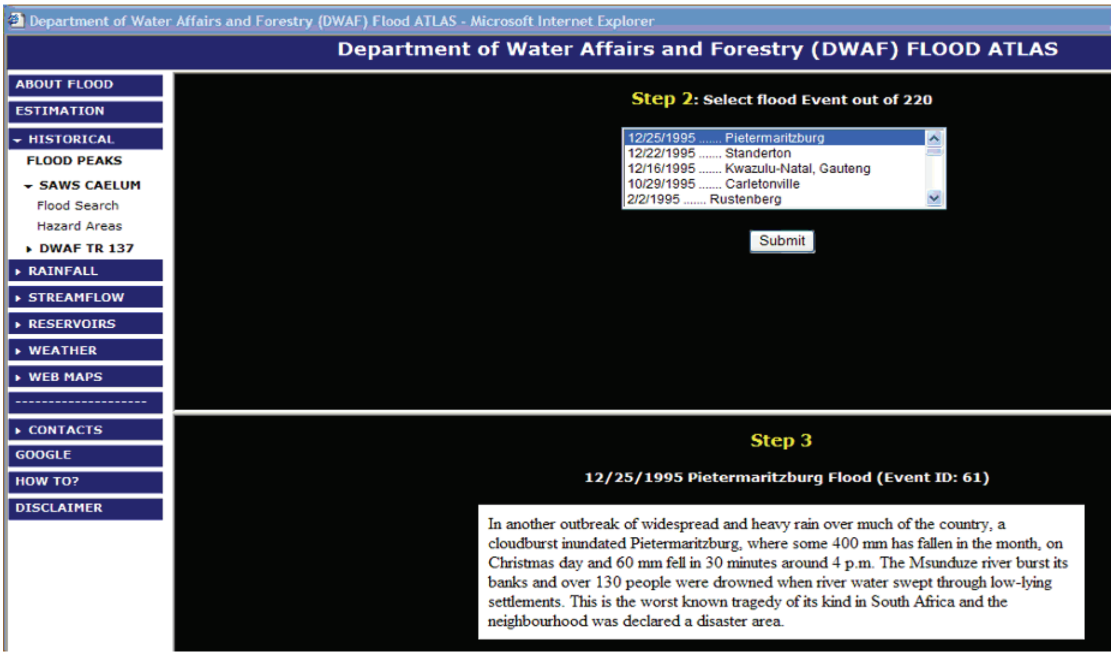


Figure 2.13 An example of the flood information contained in the CAELUM

The main database's table contains the following columns: year, place, description, number of people killed, and injured.

year	killed	place
1987	388	Natal
1995	130	Pietermaritzburg
1981	104	Laingsburg
1871	100	Victoria West
1971	83	Eastern Cape
1904	60	Bloemfontein
1959	60	Natal South Coast
1971	60	Natal North Coast
1976	50	Northern Natal
1988	34	Central interior
1973	30	Zululand
1974	26	Summer-rainfall region
1978	26	Wild Coast
1976	25	Natal Coast
1979	17	Eastern Cape
1981	17	Port Elizabeth
1970	15	Natal South Coast
1988	15	Natal
1989	15	Lebowa
1972	13	Transvaal
1993	12	Zululand
1968	11	Port Elizabeth
1978	11	Pretoria

Table 2.1: Result of SORT of field KILLED by descending order

Sorting, in descending order, the database column KILLED, will show the names of the flooded places and casualties (Table 2.1). The year 1987 and the Natal flood appear at the top of the table. Here follows the text content corresponding to that record:

> "*The floods on this Sunday and Monday were described as the most appalling disaster ever to have struck Natal. Heavy rain and floods prevailed over the entire province. The heaviest falls were in the region of Lake St Lucia. At Kwa-Mbonambi 525 mm was recorded on the 28th with a total of 881 mm over the 4-day period from the 26th to 29th. Some homes were washed entirely away, others collapsed or were buried in mud; at least 14 bridges were washed away, including the John Ross bridge over the Tugela River; thousands of kilometres of tarred and untarred roads were damaged and at one stage all the main entrance routes to Durban had to be closed. The water pipeline to Durban was severely damaged. Other places that were especially hard hit were Umzimkulu, Pietermaritzburg, Pinetown, Verulam, and Greytown. At Ladysmith alone, 3 000 homes were inundated when the Klip River burst its banks on the Sunday. The farming community suffered huge losses. The entire Natal was declared a disaster area and the total damage could have been as much as R1 500 million. Estimates put the number of deaths at 388 while 65 000 were left homeless.*"

Querying all flood description fields, based on the number of times specific place names (e.g. Durban) are mentioned, the following result appears:

- Durban 20 records
- Port Elizabeth 10 records
- Pretoria 8 records
- Cape Town 7 records

If the previous query is modified to show the number of people that died, in descending order, for all places containing a name like 'Durban', the result is shown in Table 2.2.

year	killed	place
1987	388	Natal
1959	60	Natal South Coast
1971	60	Natal North Coast
1976	25	Natal Coast
1970	15	Natal South Coast
1988	6	Durban

(6 row(s) affected)

Table 2.2: All places containing a name like 'Durban'

One can ask this question: "How many times has a flood occurred in a certain area?". Based on the same data-base (CAELUM), Figure 2.14 shows flood occurrences per DWAF Water Management Area, for the period between Years 1800 – 1995. It was not easy, based on the flood description, to determine the exact area / place the flood occurred, but the best effort was made.

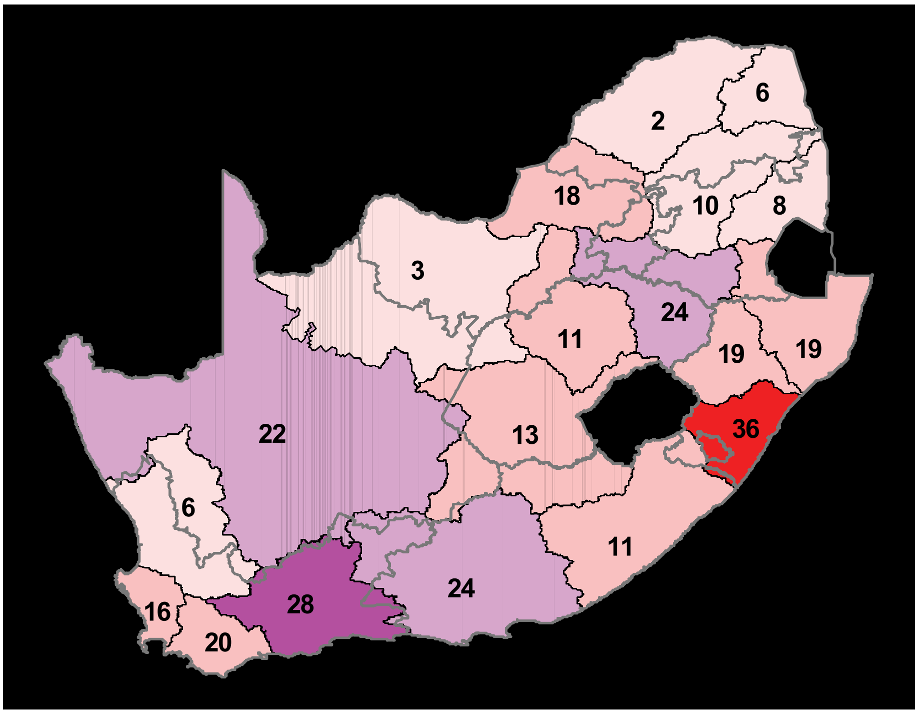


Figure 2.14 Number of floods per DWAF water management areas.

Figures 2.15-2.19 show the five most regularly flooded water management areas (based on the records in the SAWS CAELUM):

a) Mvoti to Umzimkulu – Durban, Pietermaritzburg (36 times)
b) Gouritz – George (28 times)
c) Fish to Tsitsikamma – Port Elizabeth (24 times)
d) Upper Vaal – Johannesburg South, Germiston, Sasolburg (24 times)
e) Breede (20 times)

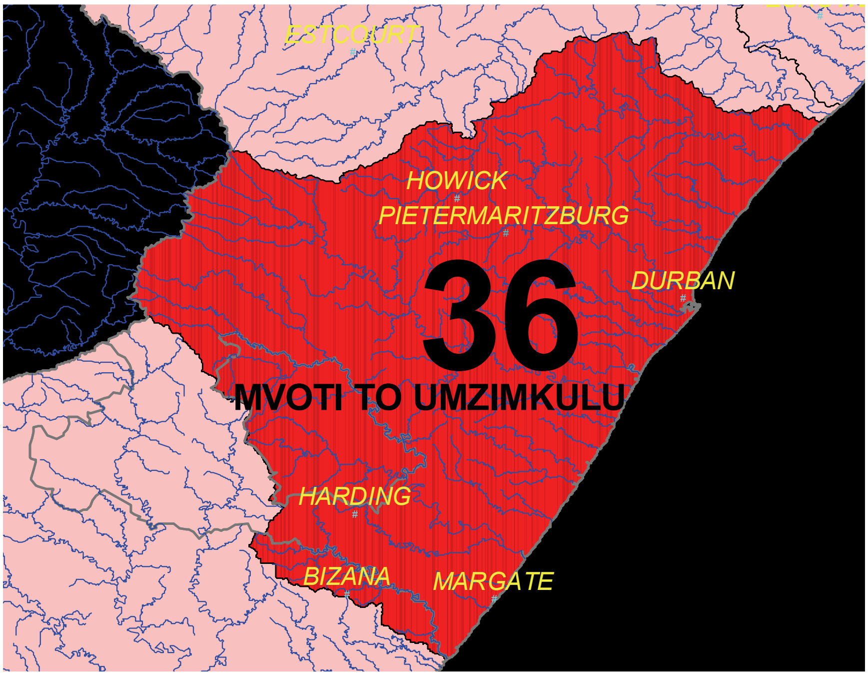


Figure 2.15 Mvoti to Umzimkulu area

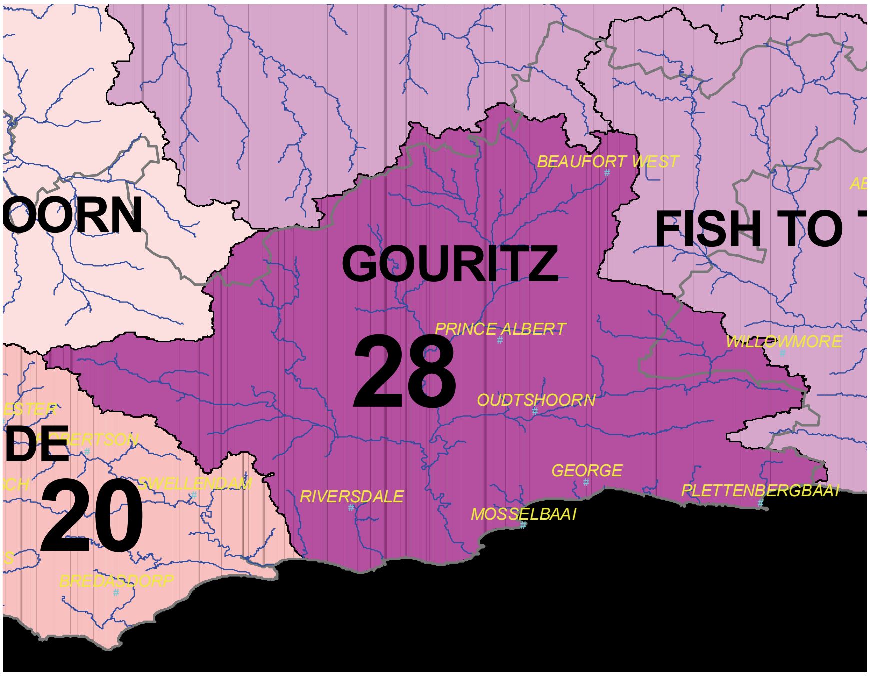


Figure 2.16 Gouritz area

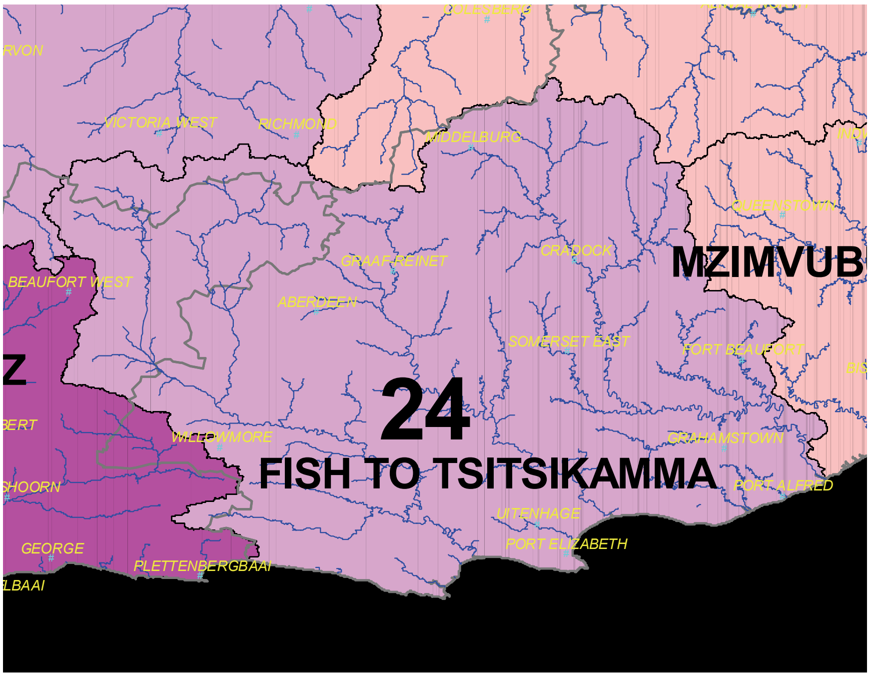


Figure 2.17 Fish to Tsitsikamma area

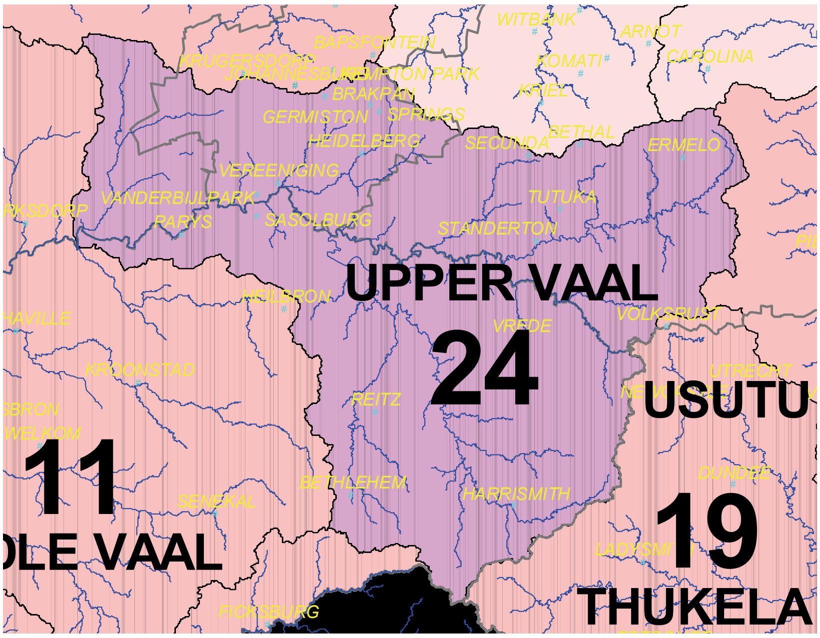


Figure 2.18 Upper Vaal area

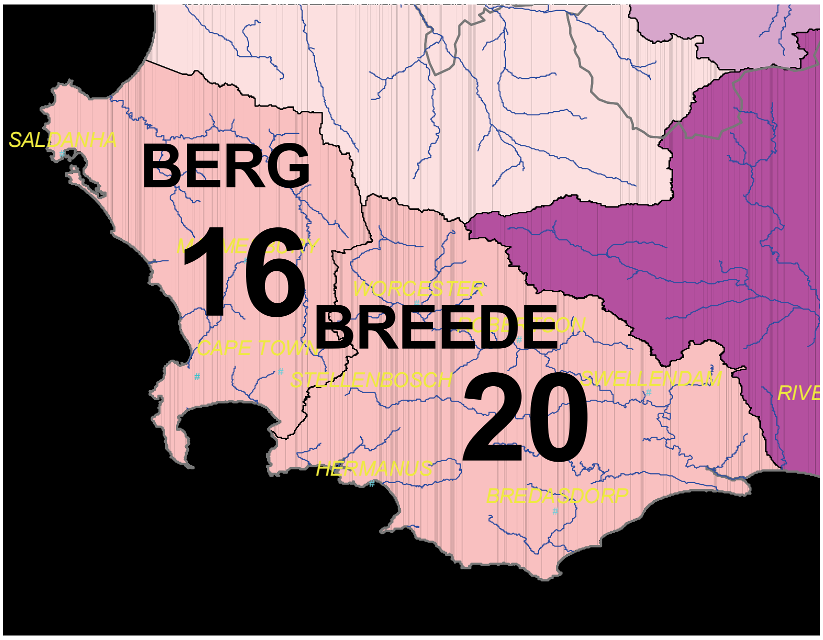


Figure 2.19 Breede area

After overlaying (using GIS tools) communities and population data on the DWAF water management areas (from Fig. 2.14), it was possible to calculate the numbers of communities and people living in the areas of highest number of flood occurrences (Table 2.3). Column 1 of the table represents the DWAF Water Management Area, column 2 represents number of communities and column 3 represents total population in that area.

Wateman_n	Count	Sum_Population
BERG	144	3584547.0000
BREEDE	109	441303.0000
CROCODILE(WEST) AND MARICO	901	7905662.0000
FISH TO TSITSIKAMMA	447	993737.0000
GOURITZ	435	515806.0000
INKOMATI	281	2076915.0000
LIMPOPO	747	1668572.0000
LOWER ORANGE	181	725179.0000
LOWER VAAL	1028	2109364.0000
LUVUVHU AND LETABA	792	2062479.0000
MIDDLE VAAL	150	2116027.0000
MVOTI TO UMZIMKULU	4555	4311946.0000
MZIMVUBU TO KIESKAMMA	7594	4924827.0000
OLIFANTS	1004	4576552.0000
OLIFANTS/DOORN	99	105127.0000
THUKELA	2879	1599394.0000
UPPER ORANGE	251	1791830.0000
UPPER VAAL	579	11223397.0000
USUTU TO MHLATHUZE	4167	2201231.0000

Table 2.3: Communities and population in the most frequently flooded areas

The Mvoti to Umzimkulu water management area, having the highest number of floods occurred (36), also contains the highest number of communities (4555), as well as second highest number of people – more than 4.3 million.

The Upper Vaal water management area has the highest total number of people. It contains the southern part of Johannesburg, Germiston, Sasolburg, and other densely populated communities and records 24 significant flood events.

2.3.3 REGIONAL MAXIMUM FLOODS - DWAF TR 137 - Visualization of the DWAF Technical Report

The Department of Water Affairs Technical Report Number 137 (Kovacs, 1988), is a comprehensive report related to historical flood peaks in South Africa.

It shows estimates the Regional Maximum Flood (RMF), as an empirically established upper limit of flood peaks that can be reasonably expected at a given site. This method is based on maximum flood peaks recorded at more than 500 sites, some records going back to 1856.

By this method, relative flood peak magnitude is expressed as a function of catchment area raised to a power depending on the Francou-Rodier regional coefficient, which ranges between 0 and 6.5. The main regional flood peaks envelope curves have been digitised and are presented here in GIS format. This enables various overlays to be combined, such as with other hydrological and population related data (Figure 2.20).

Figure 2.20 contains provincial boundaries (yellow lines) overlaid on the K coefficient boundaries (black lines), including K values for particular polygons. White lines represent DWAF water management areas.

The most frequently flooded areas have the following K coefficients:

- Mvoti to Umzimkulu (Durban, Pietermaritzburg): 5.4
- Gouritz (George): 5
- Fish to Tsitsikamma (Port Elizabeth): 5.2 – 5.4
- Upper Vaal (Johannesburg South, Germinston, Sasolburg): 4.6

This suggests that these water management areas are flood hazardous areas in terms of both frequency and magnitude.

The result of this spatial query, in regards to the number of people living in the area represented by K coefficient, is shown in Table 2.4.

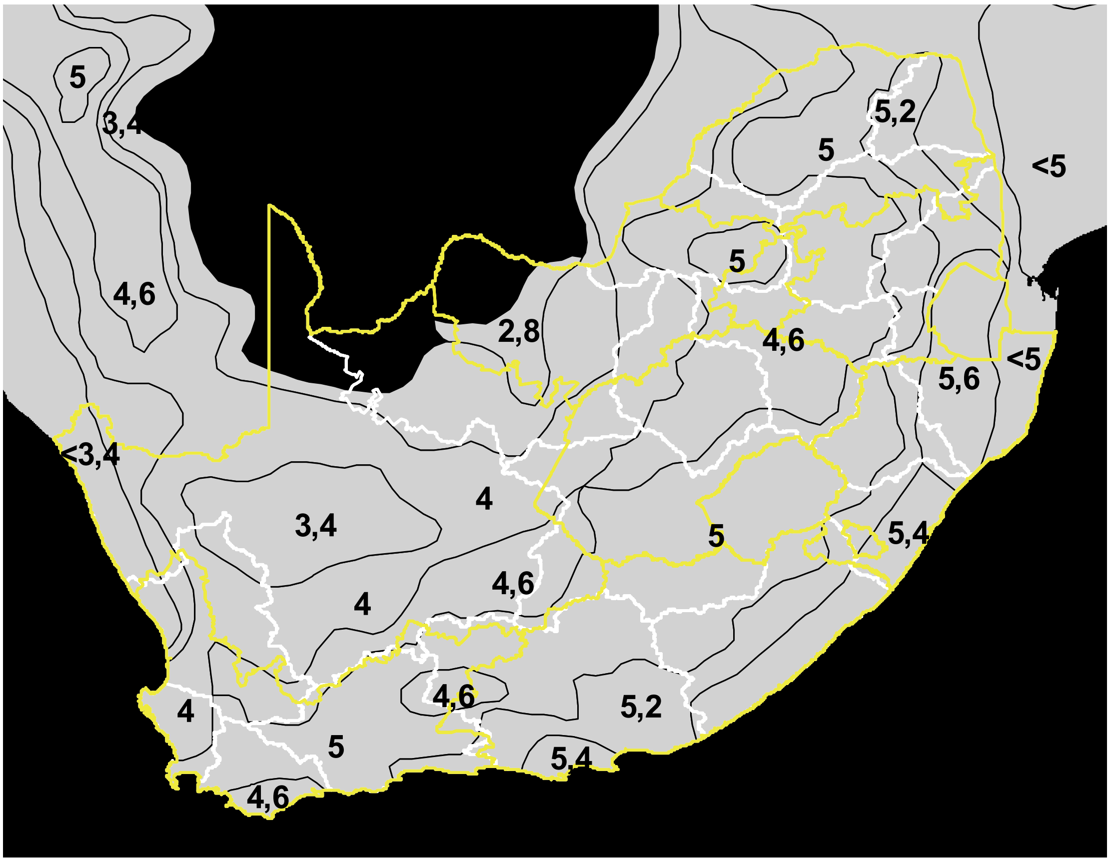


Figure 2.20 DWAF water areas overlaid over the RMF K-coefficient boundaries

sumpopke.dbf

Ke	Count	Sum_Population
2.8	302	224158.0000
3.2	45	78646.0000
3.4	587	1604771.0000
4.0	459	4724019.0000
4.6	1647	16304509.0000
5.0	6492	15509541.0000
5.2	5958	6627432.0000
5.4	6975	6633427.0000
5.6	3588	1865846.0000

Table 2.4: Sum of population per K areas

In Table 2.4 column Ke represents the K coefficient, Count represents the number of communities and Sum-Population represents total population in a particular area. Half the South African population lives in areas where the K-coefficient is equal to or greater than 5.0 and are thus in regions, which historically experience high flood magnitudes.

2.4 Streamflow Related Information

The Streamflow item of the Flood Atlas will link users to the set of web pages related to near real-time DWAF streamflow data, produced by the Hydrology Services Directorate (Figure 2.21).

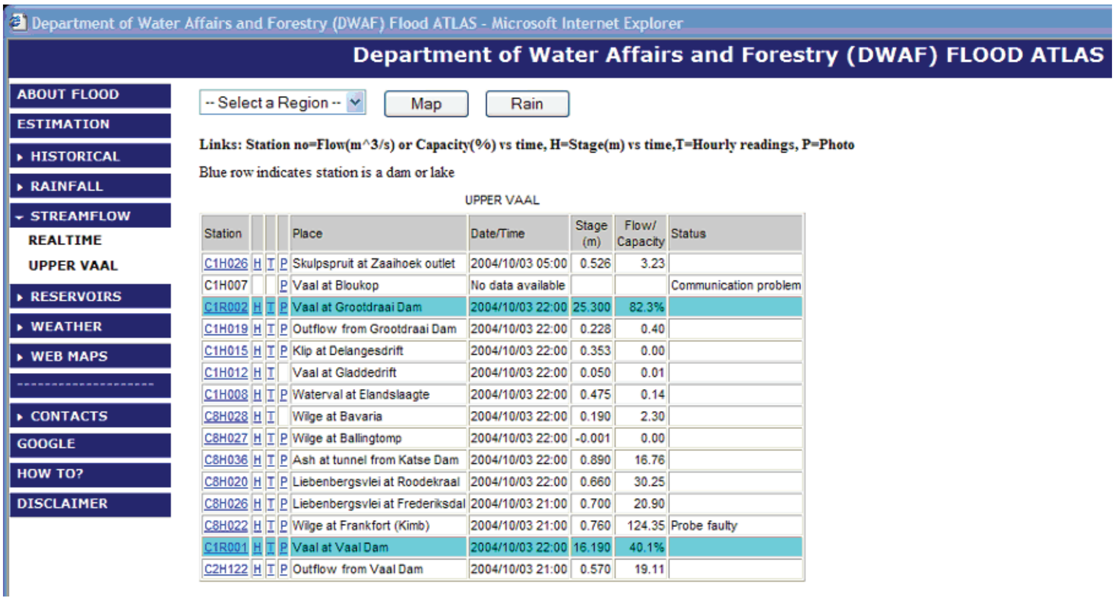


Figure 2.21 List of the Streamflow stations for Upper Vaal region.

The Pulldown menu, “Select a Region”, enables user to select different regions, including:

- Upper Vaal
- Middle Vaal
- Lower Vaal
- Upper Orange
- Lower Orange
- Limpopo
- Mpumalanga
- KwaZulu-Natal
- Eastern cape
- Western Cape

The Blue shaded rows in the table (Figure 2.21) highlight gauging stations at dams/lakes. Clicking on the station ID (first column named Station) flow or stage data, for the period of approximately two weeks, are shown (Figures 2.22-2.23).

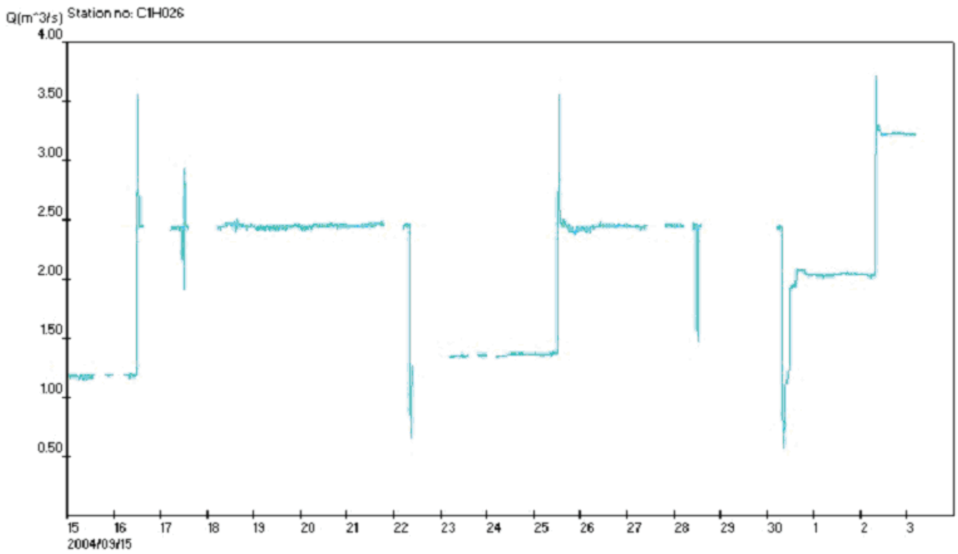


Figure 2.22 Flow Q [m^3/s] for the station C1H026, continuous, by date

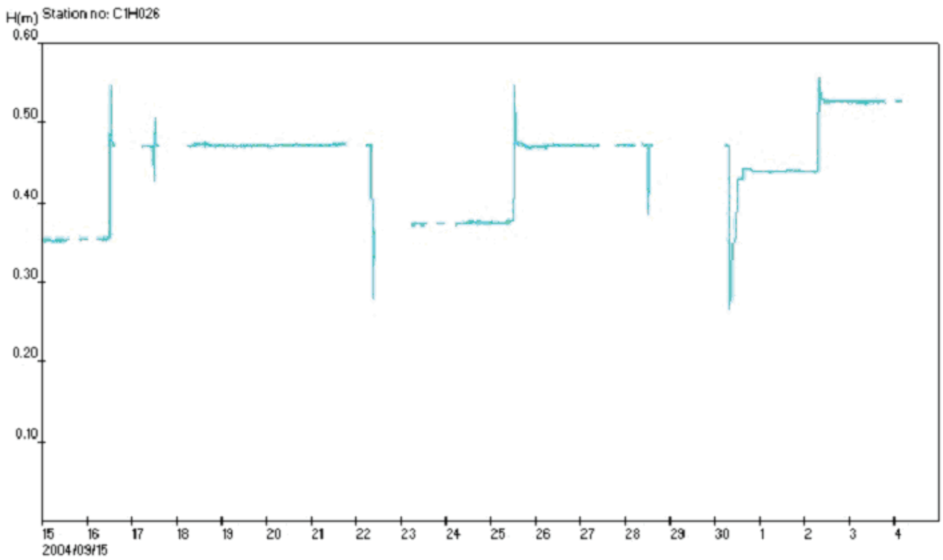


Figure 2.23 Stage [m] for the station C1H026

The button 'Map' links the user to a locality map of the selected region showing features like main rivers, dams/lakes, streamflow stations as well as main towns (Figure 2.24).

Figure 2.24 Upper Vaal region

For many stations, a photo of the gauging station is available, and can be seen by clicking on letter P (Figure 2.21, column 4). An example is given in Figure 2.25, for the station C1H026. This link (and H & T) is explained in the upper part of the page shown in Figure 2.21.

Figure 2.25 Station C1H026

2.5 Reservoir related information

To mitigate the impact of a potential flood, it is useful to continuously monitor the state of dams/reservoirs.

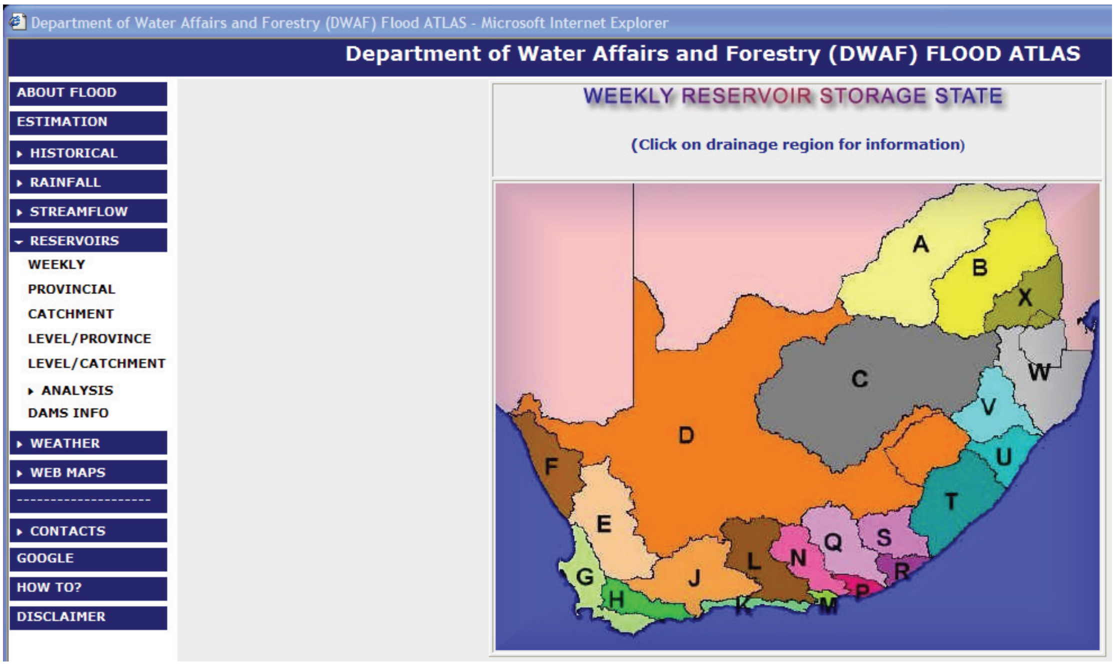
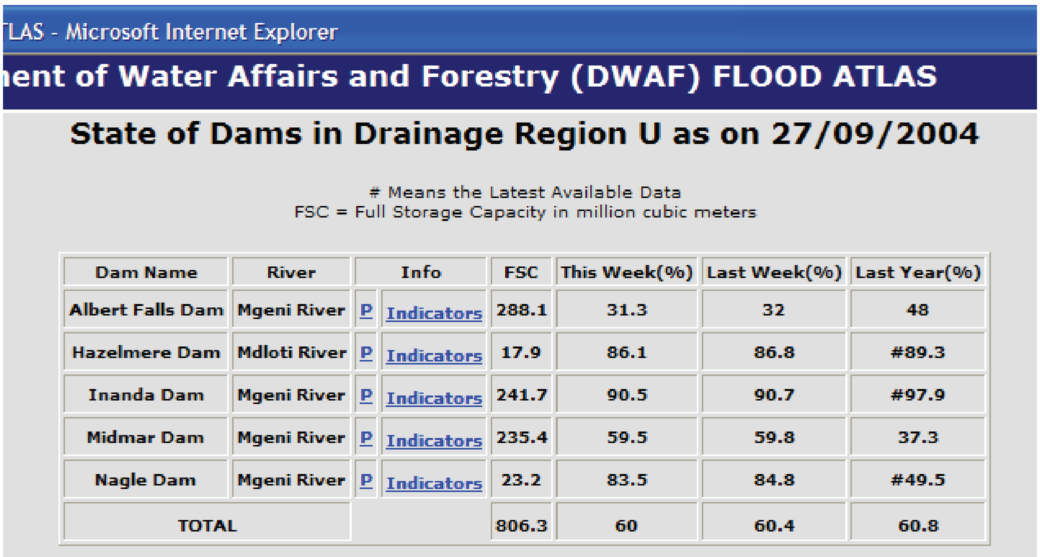


Figure 2.26 RESERVOIRS menu of the FLOOD Atlas

The RESERVOIRS menu (Figure 2.26) contains the following options:

- WEEKLY – Weekly major dams capacity. An example for region U appears in Figure 2.27
- PROVINCIAL – dam capacity, grouped by province
- CATCHMENT – dam capacity, grouped by catchment
- LEVEL/PROVINCE – dam levels per province
- LEVEL/CATCHMENT – dam levels per catchment
- ANALYSIS – dam's capacity visualization for a selected time interval



State of Dams in Drainage Region U as on 27/09/2004

# Means the Latest Available Data
FSC = Full Storage Capacity in million cubic meters

Dam Name	River	Info		FSC	This Week(%)	Last Week(%)	Last Year(%)
Albert Falls Dam	Mgeni River	P	Indicators	288.1	31.3	32	48
Hazelmere Dam	Mdloti River	P	Indicators	17.9	86.1	86.8	#89.3
Inanda Dam	Mgeni River	P	Indicators	241.7	90.5	90.7	#97.9
Midmar Dam	Mgeni River	P	Indicators	235.4	59.5	59.8	37.3
Nagle Dam	Mgeni River	P	Indicators	23.2	83.5	84.8	#49.5
TOTAL				806.3	60	60.4	60.8

Figure 2.27 Drainage region U - dam capacity info, as on 27/09/2004.

The ANALYSIS option offers flexible ways for the user to visualize capacity of any dam selected by: Primary Catchment, Province or River, for any selected time interval: see Figure 2.28 and an example of the storage trajectory of Bronkhorstspruit dam in Figure 2.29.

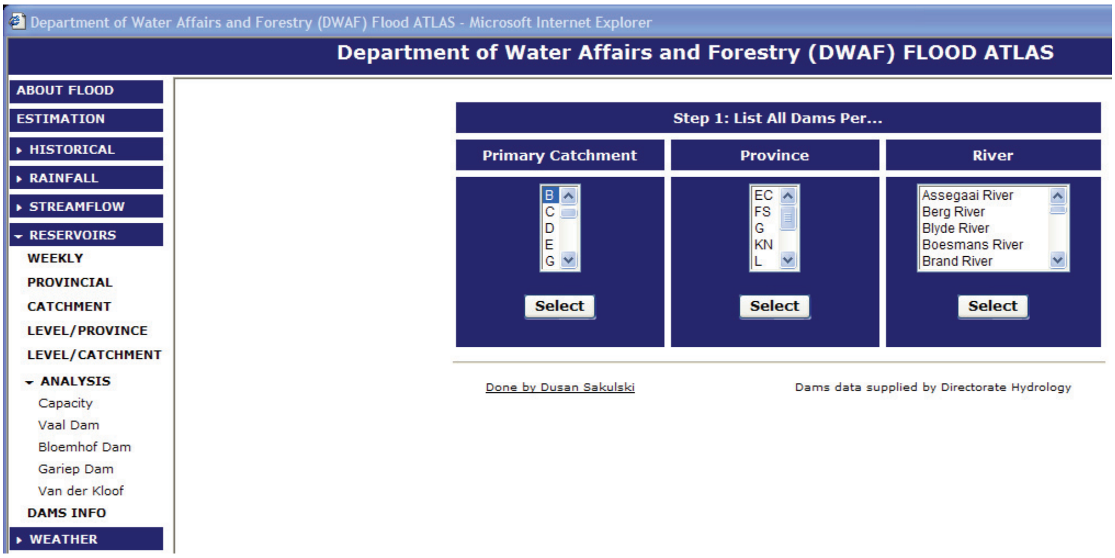


Figure 2.28 ANALYSIS - Capacity menu

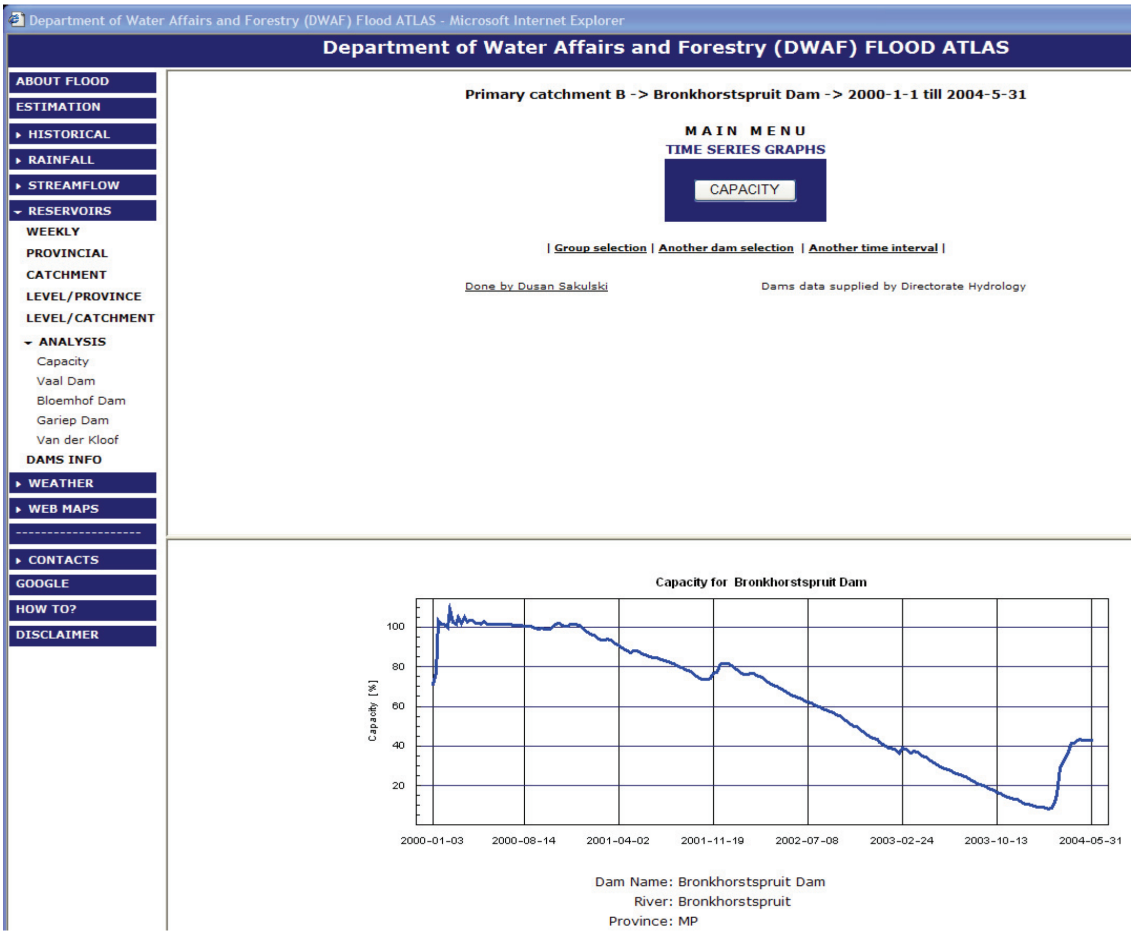


Figure 2.29 Bronkhorstspruit dam capacity graph, period Year 2000 - 2004

Further down the FLOOD Atlas selection button panel is “WEATHER”, which enables users to obtain various weather forecast related information, from a number of national and international sources. As an example of the links available, Figure 2.30 shows a weather forecast from NETFOR South Africa.

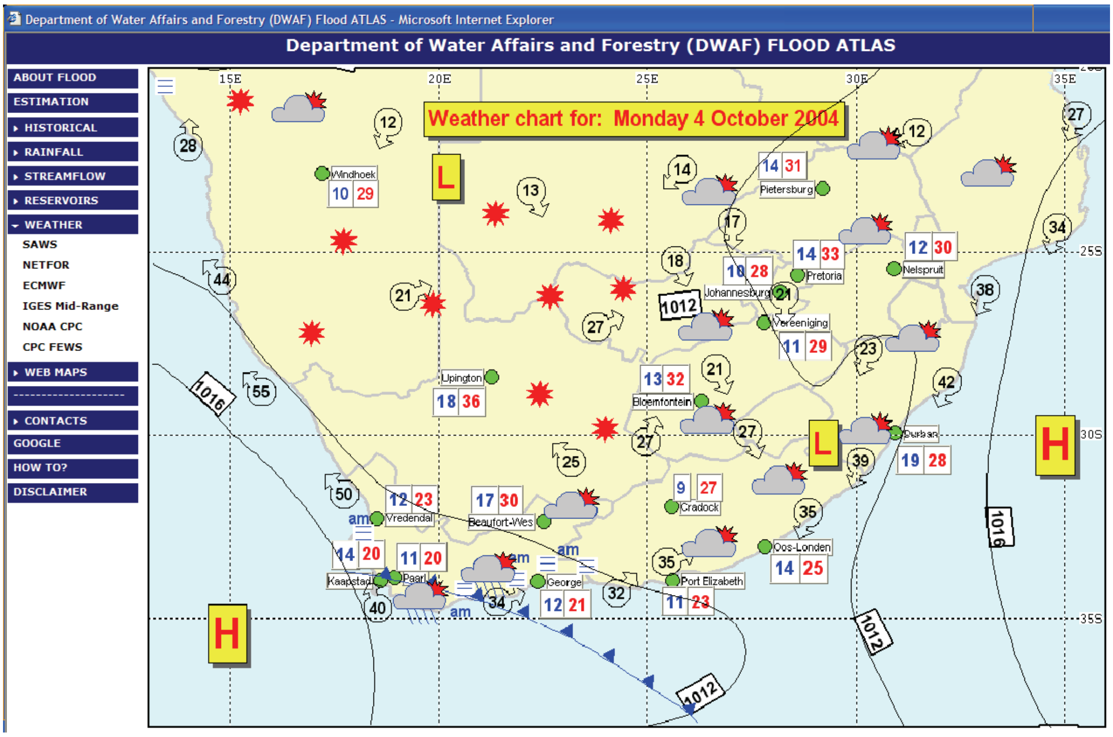


Figure 2.30 NETFOR weather forecast for South Africa, for Monday 04 October

Finally, the button “WEB MAPS” links to a set of maps available from the WRC and DWAF which allow one to zoom in for detail on soils, land cover etc.

In conclusion, this DWAF & NDMC web page enables one to identify countrywide or local threats and potential hazards. It appears that the most vulnerable areas that need immediate attention, with regards to flood forecasting and warning, are the Metros along the southern and eastern coastline (Durban, East London, Port Elizabeth and Cape Town) and in Gauteng. These have previously been earmarked for attention and personal visits during the course of this study confirm their inhabitants’ vulnerability.

3 Distributed catchment modelling

3.1 Introduction

The TOPKAPI model, a fully distributed physically-based hydrologic catchment model, was chosen for application in the Liebenbergsvlei catchment, which is instrumented with nine flow gauges, forty-five telemetering rain gauges and a weather radar (for remotely sensed precipitation data). This section is intended to introduce the model and its operations in sufficient detail for its application. Section 3.2 describes the model while the Section 3.3 explains the data required by the model and the methods of data acquisition. The explanations that follow are adapted from the descriptions in: Liu and Todini (2002), Bartholmes and Todini (2003), Martina (2004) and MUSIC Final Report (2004).

3.2 Description of the model

3.2.1 Introduction

TOPKAPI is an acronym, which stands for **TOP**ographic **K**inematic **AP**proximation **I**ntegration and is a physically based distributed rainfall-runoff model. It consists of five main modules comprising a soil module, an overland module, a channel module, an evapotranspiration module and a snow module. A key assumption in the model is that the horizontal flow in the soil, over the surface and in the channel of a drainage system can be approximated by the *kinematic* wave model at a point. These point-scale equations are then *integrated* in space to the finite dimension of a grid cell, which is taken as the pixel of the digital elevation model (DEM) that describes the *topography* of the catchment. The input parameters are directly obtainable from DEM's, soils maps and land use maps of the catchment in terms of slope, soil permeability, roughness and topology (Liu and Todini, 2002). The main advantage of the TOPKAPI model over other physically based distributed models is that the physical nature of the governing equations and state variable are preserved in the integration process (albeit as averages) up to a grid scale of 1km square (shown in Martina, 2004: 76).

The kinematic wave assumption is based on the simplification of the Saint-Venant Equation describing one-dimensional unsteady open channel flow. It assumes that the effects of local acceleration, convective acceleration and pressure acting on a control volume are negligible when compared to the affects of gravity and friction. The Saint-Venant Equation of *momentum conservation* is:

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + g\frac{\partial y}{\partial x} - g(S_o - S_f) = 0 \qquad (3.1)$$

where V represents the velocity, t the time, x the distance along the channel, g the gravitational acceleration and S_o and S_f the bed slope and friction slope of the channel respectively. The kinematic wave approximation of the momentum equation ignores the effects of local acceleration ($\partial V/\partial t$), convective acceleration ($V.\ \partial V/\partial x$) and pressure ($g.\ \partial y/\partial x$). Hence Equation 3.1 reduces to:

$$S_o = S_f \qquad (3.2)$$

where the forces of friction and gravity balance out. By combining this approximation with the continuity equation for a channel cross section (Equation 3.3), the description of the rainfall-runoff process is reduced to a cascade of three non-linear reservoir differential equations that describe the flow and storage in the soil, overland and channel modules for each processing cell. The *continuity equation* for a channel cross section, in conservation form is:

$$\frac{\partial A}{\partial t} = q - \frac{\partial Q}{\partial x} \tag{3.3}$$

where ($\partial A/\partial t$) is the rate of change of volume per unit width in a channel element, q is the inflow per unit length along the side of the channel and ($\partial Q/\partial x$) is the rate of change of channel flow with distance (Chow et al., 1988: 275). The two further modules, evapotranspiration and snow, are computed as functions of temperature, the former using the radiation method of Doorenbos and Pruitt (1977), while the latter is ignored in this research.

An important hydrologic module which is not accounted for in this model is groundwater recharge (percolation) from the soil store above, which governs groundwater flow. The reason for this, as explained in Liu and Todini (2002), is that the response time for the percolation of water through the thick layer of soil separating the saturated and unsaturated zones is so large that the flow in the saturated zone can be assumed to be almost constant and shows no significant response from one storm event to another. However, the inclusion of this module is necessary to faithfully simulate all the hydrologic processes of a catchment and its addition is planned, by the developers of the model, for future development of this model (Liu and Todini, 2002).

The focus of this research is in the real-time application of a rainfall-runoff model for flood forecasting. The TOPKAPI model was chosen for this purpose based on the following:

- it is fully distributed; the spatial range of the grid cell discretization within which the model is valid is up to 1km (Martina, 2004: 76)
- it is physically-based where the input parameters can be directly obtained from catchment data
- there are relatively few (seven) input parameters for a distributed model and hence a small number of parameters for calibration.

The major advantage in the application of such a distributed model is its ability to represent the spatial trend of the phenomena modelled in fine detail. In many applications, such as modelling the terrestrial - atmospheric flux (with Global Circulation Models – GCM's), models are required to represent phenomena at larger scales where the discretization schemes are based on grid sizes of hundreds of kilometres. The TOPKAPI model, although being a comprehensive distributed rainfall-runoff model, can also be applied in a lumped form to represent hydrologic processes at a basin level. This is achieved by using the distributed model to identify the mechanisms governing the dominant processes in the conversion of rainfall into runoff in order to obtain a "law underpinning the development of the lumped model" (Liu and Todini, 2002). It is shown in Martina (2004: 96) that the physical nature of the model is still maintained at the lumped scale, although the governing equations no longer have local meaning, but summarise local properties in a global manner where the input parameters represent basin averages.

The application of the TOPKAPI model, in lumped form, is an option, which is not explored in this research as it is beyond the scope of real-time flood- and flash flood-forecasting applications. The following sections are intended to explain the structure and methodology of the distributed TOPKAPI model by giving relevant background theory where necessary.

3.2.2 Model assumptions

The TOPKAPI model is based on five fundamental assumptions. The reasoning behind each of the assumptions will become clearer as the explanation of the model is expanded in the sections that follow. The assumptions are:

a) *The input precipitation is assumed to be constant over the grid cell (pixel).* Precipitation estimates from remote sensing measurements are raster-based and presented in pixel format, where the properties of each pixel are uniform. If rain gauge data are used, suitable averaging techniques of these point estimates have to be performed to acquire the data at the required finite pixel resolution.
b) *A Dunne mechanism (Dunne, 1978), or saturation excess mechanism, is used as the sole mechanism for the formation of overland flow.* This mechanism assumes that all the precipitation input into a cell is infiltrated into the soil, unless the soil store in that cell is already saturated, in which case the input precipitation will become overland flow.
c) *The slope of the groundwater table coincides with the slope of the ground, unless the slope of the ground is very small (i.e. < 0.01%).* This constitutes the fundamental assumption of the kinematic wave model, and justifies the use of the kinematic model for unsaturated horizontal subsurface flow.
d) *Horizontal subsurface flow in a cell depends on the total water content in the soil.* This requires the integration of the soil water content profile in the vertical.
e) *Saturated hydraulic conductivity is constant with depth in a soil layer and much larger then the conductivity in deeper layers.*

3.2.3 Soil water flow model

The soil water store is regarded as the most "characterising aspect of the model" (Liu and Todini, 2002) because of the regulating function that it plays in terms of the soil water balance. The overland flow component of a cell is activated upon the saturation of the soil store and together with subsurface flow, both contribute directly to the flow in the channel (Liu and Todini, 2002). Overland flow refers to surface runoff which flows down flat slopes in shallow sheets while subsurface flow, in terms of the TOPKAPI model, is regarded as the "flow in a horizontal direction that occurs in a soil layer of limited thickness and high hydraulic conductivity (due to macro-porosity)" (Liu and Todini, 2002). The TOPKAPI model assumes that flow in the vertical direction of a given soil store, i.e. infiltration, is lumped and that the horizontal subsurface flow is a function of the total moisture stored within a soil store. The following sub-sections deal with the kinematic wave formulation for the soil water flow model, by first giving relevant background theory, and then an explanation of the vertical lumping performed in this component.

a) Background

The hydraulic behaviour of soil is characterised by two important properties of the soil, namely the *suction pressure head* ψ, which is the electrostatic force between the water molecules' polar bonds and the soil particle surface (Chow et al., 1988: 102), and the *hydraulic conductivity K*, which is the rate at which water moves through a porous medium per unit cross-sectional area. For unsaturated conditions, both these soil properties vary as a function of the *moisture content* θ of the soil. The soil moisture content θ is defined as the ratio of the volume of water to the total volume of the pore spaces within the control volume. Figure 3.1, from Chow et al. (1988: 103), shows the relationships of the suction pressure head and the hydraulic conductivity with moisture content for an unsaturated clay soil.

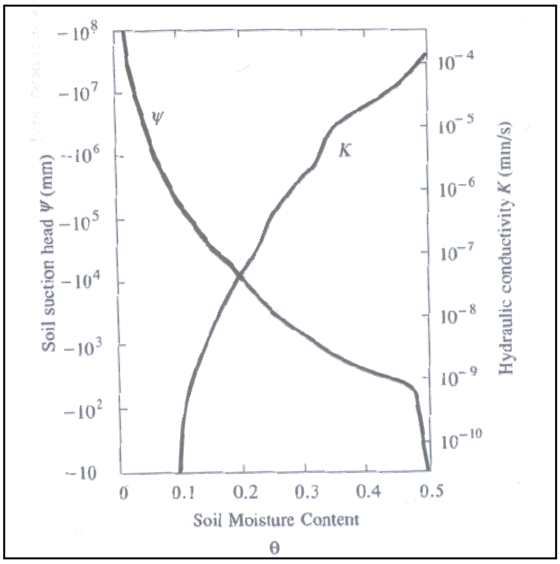


Figure 3.1 Variation of suction pressure head ψ and hydraulic conductivity *K* with moisture content θ for an unsaturated clay soil (Chow et al., 1988:103).

Flow in an unsaturated porous medium, such as subsurface flow, is described by Darcy's Law, which gives the momentum equation for the volumetric flow per unit area of medium:

$$q = KS_f \qquad \left[\text{ms}^{-1}\right] \tag{3.4}$$

where *q* is the volumetric flux (flow per unit area) of a cross section of a porous medium, *K* is the hydraulic conductivity of the cross section and S_f is the friction slope or head loss per unit length of flow in the *x*-direction. The friction slope is defined as $S_f = -\frac{dh}{dx}$, where the negative sign indicates that the head is decreasing in the direction of flow due to friction. For flow in an unsaturated medium, the forces involved are gravity, friction and suction pressure and hence the total head driving the flow are the sum of gravity and suction pressure, i.e. $h = z + \psi$. For saturated flow, the pressure head is no longer applicable. Substituting for S_f in Equation 3.4 for unsaturated flow yields:

$$q = -K\left(\frac{\partial\psi + \partial z}{\partial x}\right) \qquad \left[\text{ms}^{-1}\right] \tag{3.5}$$

where ($d\psi/dx$) is the pressure head loss and (dz/dx) is the gravity head loss in the x direction respectively.

By combining the Darcy Equation, for flow in the vertical direction (z), with the continuity equation, Richard's Equation (1931) is derived, which is the governing equation for unsteady unsaturated flow in a porous medium. Richard's Equation is the basic theoretical equation for infiltration into a porous medium, and is given as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(D \frac{\partial \theta}{\partial z} + K \right) \tag{3.6}$$

where θ is the soil moisture content, t represents time, z represents the vertical direction of flow, K is the hydraulic conductivity of the medium and D is a term which represents soil water diffusivity and equals $K(d\psi/d\theta)$. No analytical solution to Richard's Equation exists due to its non-linearity. Infiltration models of Horton (1940) and Philip (1957) are approximate solutions to the one-dimensional form of Richard's Equation. Green and Ampt (1911) proposed an alternative method whereby approximations were made with regard to the physical theory governing infiltration but with an exact solution (Chow et al., 110).

b) Vertical lumping

In the TOPKAPI model, the dominant mechanism driving subsurface flow is assumed to be gravity and is described as follows, paraphrasing Martina (2004). Water, after having infiltrated into the soil, will perch on a lower impermeable or semi-impermeable boundary of the soil layer. This boundary forms the separation between the subsurface soil layer and the deeper groundwater layer. At this boundary, a horizontal propagation of unsaturated subsurface flow is driven under gravity due to the highly conductive (due to macro-porosity) nature of the soil layer. Since the depth of the soil layer (of thickness one to two meters) is negligible with regard to the horizontal dimension of the overall grid cell, according to Todini (1995) "it is possible to avoid within the range of reasonable errors the integration of the unsaturated soil vertical infiltration equation, namely Richard's Equation" (Equation 3.6). Thus the TOPKAPI model assumes subsurface horizontal flow to be similar to flow in an unconfined aquifer, where "flows in unconfined aquifers are analogous to free-surface flows in streams" (Dingman, 2002: 327).

In order to lump the subsurface flow vertically, the dependency of the hydraulic conductivity with the soil moisture profile is neglected and the soil moisture content is averaged over the soil depth. In practice, as explained in Martina (2004), the subsurface flow evaluated from assuming a constant saturated hydraulic conductivity with depth does not differ strongly from the flow evaluated from the consideration of the actual soil water profile in the vertical.

The formulation of the relevant equations is as follows. Firstly, the TOPKAPI model applies the kinematic wave approximation to the subsurface flow and thus the effects of suction pressure in terms of Darcy's Law are ignored. Secondly, the model assumes that the slope of the groundwater table (and thus the slope of flow perched on the lower impermeable or semi-impermeable boundary) is equivalent to the slope of the topographic surface β. Thus dz/dx in Equation 3.5 equals $\tan\beta$, where β is the local angle of slope of the topographic surface of a cell. Equation 3.5 thus reduces to:

$$q = K \cdot \tan\beta \quad \left[\mathrm{ms^{-1}}\right] \tag{3.7}$$

where K is the hydraulic conductivity of the soil and $tan\beta$ is the trigonometric tangent of the ground slope angle β. When dealing with saturated horizontal flow paths, such as in an unconfined aquifer, the term *transmissivity* is used instead of hydraulic conductivity. Transmissivity is defined as $T = H \cdot K$, where H is the saturated flow depth and K is the hydraulic conductivity. Thus K in Equation 3.7 is replaced with T and q now represents flow per width (i.e. m^2s^{-1}). Based on assumption (4), from Section 6.2.2, local transmissivity depends on the integration of the particular soil moisture profile present in the soil over the cross sectional depth L. This is calculated as follows:

$$T = \int_0^L K\left(\bar{\theta}(z)\right)dz = \int_0^L K_s\left(\bar{\theta}(z)\right)^{\alpha} dz \tag{3.8}$$

where K (K_s) is the (saturated) hydraulic conductivity as a function of the *effective soil saturation* $\bar{\theta}$ at depth z and α is a pore-size distribution parameter. The effective soil saturation is the ratio of the available moisture (θ-θ_r) to the maximum possible moisture content (θ_s-θ_r), i.e. $\bar{\theta}(z) = \frac{\theta - \theta_r}{\theta_s - \theta_r}$ (Chow et al., 1988: 114). θ_r is the residual soil moisture content after the soil has been thoroughly drained and θ_s is the saturated soil moisture content. The replacement of the integrand on the left of Equation 3.8 with an approximation shown on the right is based on the work of Brooks and Corey (1964) who established the relationship $K\left(\bar{\theta}\right) = K_s\left(\bar{\theta}\right)^{\alpha}$, where the variables are defined as before; they established this formula after studying the relationships between suction pressure head ψ and hydraulic conductivity K with the moisture content θ of many soils.

By assuming a constant saturated hydraulic conductivity with soil depth and by using the average soil moisture content over the depth, the expression for the transmissivity given by Equation 3.8 is replaced by:

$$T(\bar{\Phi}) = K_s L \bar{\Phi}^{\alpha} \tag{3.9}$$

where $\bar{\Phi}$ is the *average* effective soil saturation content over the depth L, i.e. $\bar{\Phi} = \frac{1}{L}\int_0^L \bar{\theta}(z)dz$, K_s is the saturated hydraulic conductivity and α is a pore-size distribution parameter which is dependent on the characteristics of the soil type. Thus from Equation 3.7, the horizontal subsurface flow (in m^2s^{-1}) is given as:

$$q = \tan(\beta) \cdot K_s L \bar{\Phi}^{\alpha} \quad \left[m^2s^{-1}\right] \tag{3.10}$$

where β is the local slope angle of the ground surface, k_s is the saturated hydraulic conductivity (in ms^{-1}), L is the depth of the surface soil layer (in m), $\bar{\Phi}$ is the average effective soil moisture content and α is a pore-size distribution parameter which depends on the characteristics of the soil.

c) Kinematic wave formulation for subsurface flow

The momentum equation (Equation 3.10) and the continuity equation (Equation 3.3) are used to obtain the following pair of equations that describe the flow and storage of soil moisture at a point in the soil store:

$$q = \tan(\beta) \cdot k_s L \overline{\Phi}^{\alpha} \qquad \left[\mathrm{m^2 s^{-1}}\right] \tag{3.11a}$$

$$(\theta_s - \theta_r) L \frac{d\overline{\Phi}}{dt} = p - \frac{dq}{dx} \qquad \left[\mathrm{ms^{-1}}\right] \tag{3.11b}$$

where x is the direction of flow in a cell, t is time, q is the subsurface flow term (in $\mathrm{m^2s^{-1}}$), p is the input precipitation intensity (in $\mathrm{ms^{-1}}$) and the rest of the variables are defined as before. The term on the left-hand side of Equation 3.11b represents the rate of change of moisture storage (depth) in the soil store while the expressions on the right-hand side are the inflow and outflow balance. The model is written in terms of total differential operators instead of partial differential operators, since the flow in the TOPKAPI model is assumed to be characterised by a preferential direction which is defined as the direction of maximum slope.

From the combination of the Equation 3.11a and Equation 3.11b, the resulting equation that follows states that the rate of change of storage ($d\eta/dt$) is equal to the difference between the inflow (p) and outflow ($d(C\eta^{\alpha})/dx$):

$$\frac{d\eta}{dt} = p - \frac{d}{dx}\left(C\eta^{\alpha}\right) \qquad \left[\mathrm{ms^{-1}}\right] \tag{3.12}$$

where η is the total depth (in m) of the actual moisture in the soil (defined by Equation 3.13), C represents a local conductivity coefficient (defined by grouping the constant physical terms in Equation 3.14) and the rest of the variables are as before. The expression for the soil moisture depth (Equation 3.13) is based on the average effective soil moisture $\overline{\Phi}$ of the soil layer of depth L.

$$\eta = (\theta_s - \theta_r) L \overline{\Phi} \qquad [\mathrm{m}] \tag{3.13}$$

$$C = \frac{L \cdot k_s \cdot \tan\beta}{(\theta_s - \theta_r)^{\alpha} \cdot L^{\alpha}} \qquad \left[\mathrm{m^{2-\alpha} s^{-1}}\right] \tag{3.14}$$

Equation 3.12 expresses continuity at a point-scale over the horizontal plane of the grid cell, but is lumped in the vertical dimension. In order to represent the processes over an entire pixel or grid-cell, Equation 3.12 needs to be integrated, firstly over the longitudinal dimension X and then over the width X of the grid-cell. Figure 3.2 depicts the dimensions of a typical grid-cell defined by the pixels of a digital elevation model (DEM).

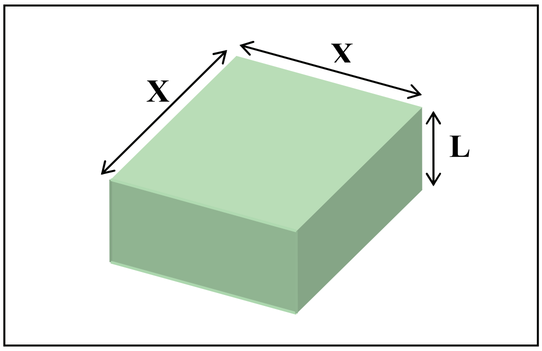


Figure 3.2 The dimensions of a pixel (in m) as defined by a DEM and as required by TOPKAPI. L is the soil depth and X is the dimension in the horizontal plane.

For the i^{th} pixel, assuming the pixel to be a source-cell with no upstream cells contributing flow (i.e. precipitation is the only input into the cell), the integration of Equation 3.12 in the longitudinal direction yields the following:

$$\int_0^X \frac{d\eta}{dt} = \int_0^X \left(p - \frac{d}{dx}\left(C\eta^{\alpha}\right)\right) \\ \Rightarrow \frac{dv_i}{dt} = pX - C_i\eta_i^{\alpha} \qquad \left[\mathrm{m^2 s^{-1}}\right] \tag{3.15}$$

where v_i is the volume per unit width (m^3m^{-1}) stored in the i^{th} cell, i.e. $v_i = \eta_i \cdot X$ in m^2 assuming the variation of the vertical water content η_I is constant. After integration, the conductivity coefficient C no longer comprises measurable quantities at a point, but now represents average values over the cell. The total volume (in m^3) stored in the i^{th} cell is V_i, where $V_i = v_i \cdot X = \eta_i \cdot X \cdot X$. Thus, by making the substitution for η in Equation 3.15 and integrating over the width of the i^{th} source cell, the non-linear reservoir equation for the soil store of a source cell is:

$$\int_0^X \frac{dv_i}{dt} = \int_0^X \left(pX - C_i\eta_i^{\alpha}\right) \\ \Rightarrow \frac{dV_i}{dt} = p_i X^2 - \frac{C_i X}{X^{2\alpha}} V_i^{\alpha} \qquad \left[\mathrm{m^3 s^{-1}}\right] \tag{3.16}$$

where V_i is the volume stored in the i^{th} cell in m^3. In a similar manner, a non-linear reservoir equation can be formulated for a generic "non-source" cell which, in addition to precipitation input, receives contributions from the soil and overland stores of the upstream cell. The connectivity between cells in the TOPKAPI model is such that an active cell may only receive upstream contributions from the three cells adjacent to the edges of the active cell and may only have one "preferential" outflow direction. A further explanation of this is given in Section 3.2.6. Referring to Figure 3.3, the non-linear reservoir equation for a generic cell is:

$$\frac{dV_{s_i}}{dt} = p_i X^2 + Q_o^u + Q_s^u - \frac{C_{s_i} X}{X^{2\alpha_s}} V_{s_i}^{\alpha_s} \qquad \left[\mathrm{m^3 s^{-1}}\right] \tag{3.17}$$

where Vs_i is the volume stored in the i^{th} cell and $Q_o{}^u$ and $Q_s{}^u$ are the contributions from the upstream overland and soil stores respectively, which were effectively added to the right-hand side of Equation 3.16 for a non-source cell. The subscripts o and s have been introduced to distinguish between the overland and soil stores respectively and *u* denotes an upstream contribution.

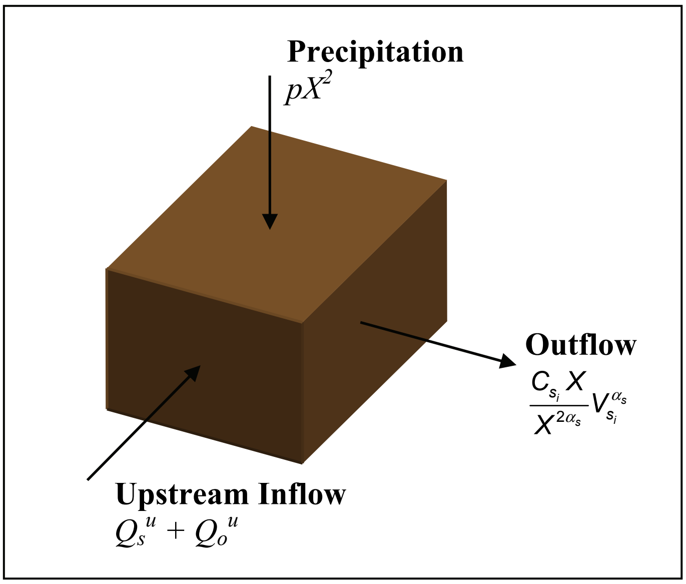


Figure 3.3 The water balance for the soil store of a generic non "source" cell derived in Equation 3.17 for the TOPKAPI model (from MUSIC Final Report, 2004: 53).

3.2.4 Overland and channel water models

The overland and channel components are controlled by the soil store. Overland storage is activated when the soil store is saturated, based on the saturation excess mechanism of Dunne (1978), and proportions of the outflow from the soil and overland stores feed the channel store. This section deals with the kinematic wave formulation for the overland and channel flow models by first giving the necessary background theory.

a) Background

Based on the kinematic approach for the conservation of momentum, flow in the overland store (surface flow) and flow in the channel store (channel flow) are described by Manning's Equation. The Manning Equation is valid for one-dimensional steady open channel flows and is given as (in SI units):

$$Q = \frac{1}{n} \cdot A \cdot R^{2/3} \cdot S_f^{1/2} \tag{3.18}$$

where Q is the volumetric flow rate (in m^3s^{-1}), n is Manning's roughness coefficient (in $m^{-1/3}s$), A is the cross sectional area of flow (in m^2), S_f is the friction slope (which is equivalent to the ground slope $tan\beta$ based on the kinematic approximation) and R is the hydraulic radius (in m), which is defined as the ratio of the cross-sectional area of flow (A) to the length of the cross-sectional wetted perimeter of flow (P), i.e. $R = \frac{A}{P}$.

Referring to Figure 3.4, the cross sectional area for a rectangular channel is yB and the wetted perimeter is $2y+B$. A common assumption made when using Manning's Equation is that the cross section of flow is rectangular with the width of flow B being much larger than the height of flow y, i.e. the channel is wide and rectangular. This assumption is valid when one considers overland flow as this flow is akin to sheet flow. However, when the flow is in a channel, the cross section of flow needs to be shallow and wide enough for the assumption to be valid. Nevertheless, Dingman (2002: 427) says that in most natural channels, the hydraulic radius *R* is "virtually identical to the average depth *y*", which arises from the *wide rectangular channel* assumption. This assumption reduces Equation 3.18 to the following approximation:

$$q = \frac{Q}{B} = \frac{1}{n} \cdot (\tan\beta)^{1/2} \cdot y^{5/3} \tag{3.19}$$

where q is the flow per width in the channel (in m^2s^{-1}).

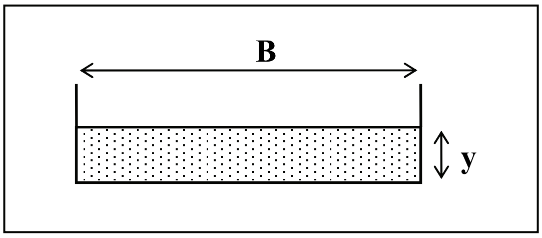


Figure 3.4 The rectangular cross section of an open channel flow of flow height *y* and flow width *B*.

b) Kinematic wave formulation for overland flow

The momentum equation (Equation 3.19) and the continuity equation (Equation 3.3) for the overland store are used to obtain the following pair of equations that describe the flow and storage of overland water at a point in the overland store:

$$q_o = C_o \cdot h_o^{\alpha_o} \quad \left[m^2s^{-1}\right] \tag{3.20a}$$

$$\frac{dh_o}{dt} = r_o - \frac{dq_o}{dx} \quad \left[ms^{-1}\right] \tag{3.20b}$$

where h_o is the depth of flow over the ground surface (in m), $C_o = \frac{1}{n_o}\sqrt{\tan\beta}$ and $\alpha_o = 5/3$, both of which derive from Equation 3.19. In Equation 3.20b, r_o is defined as saturation excess flow (in ms^{-1}) which results from the saturation of the soil store. The subscript *o* denotes the overland flow model.

In a similar treatment to that of the soil store, Equation 3.20a and Equation 3.20b can be combined and integrated over the horizontal dimensions of the grid cell by assuming that the depth of flow h_o is constant over the surface of the cell. Referring to Figure 3.5, the non-linear reservoir equation for the overland store of a generic cell is given as:

$$\frac{dV_{o_i}}{dt} = r_{o_i} X^2 - \frac{C_{o_i} X}{X^{2\alpha_o}} V_{o_i}^{\alpha_o} \quad \left[m^3s^{-1}\right] \tag{3.21}$$

where V_{oi} is the overland volume stored in the i^{th} cell, $\frac{dV_{o_i}}{dt}$ is the rate of change of surface water storage in the overland store, $r_{o_i} X^2$ is the input term and $\frac{C_{o_i} X}{X^{2\alpha_o}} V_{o_i}^{\alpha_o}$ is the outflow term.

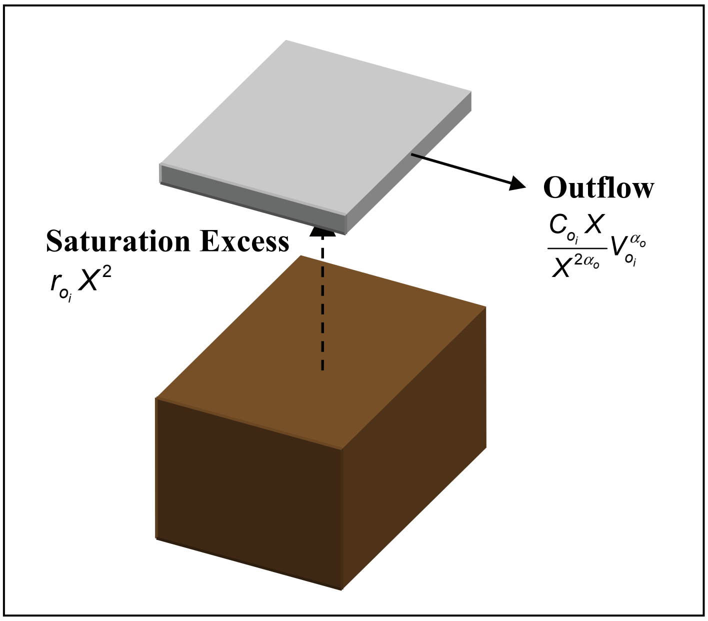


Figure 3.5 The water balance for the overland store of a generic cell derived in Equation 3.21 for the TOPKAPI model (from MUSIC Final Report, 2004: 55).

c) Kinematic wave formulation for channel flow

The channel flow model is only applicable in those cells that consist of a channel reach. This is determined from a geomorphologic analysis of the catchment through the use of a digital elevation model (DEM). The distinction, between cells characterised by overland runoff only (hillslope cells) and cells characterised by commensurate overland and channel runoff (channel cells), is important for the type of water balance to be created for each cell. This is dealt with in Section 3.2.6.

In a similar manner to what was done for the soil and overland stores, the momentum equation (Equation 3.19) and the continuity equation (Equation 3.3) for the channel store are used to obtain the following system of equations that describe the flow and storage of water at a point in a channel reach:

$$q_c = C_c \cdot y_c^{\alpha_c} \quad \left[\mathrm{m^2 s^{-1}}\right] \tag{3.22a}$$

$$\frac{dy_c}{dt} = r_c - \frac{dq_c}{dx} \quad \left[\mathrm{ms^{-1}}\right] \tag{3.22b}$$

where y_c is the depth of flow in the channel reach (in m), $C_c = \frac{1}{n_c}\sqrt{\tan\beta}$ and $\alpha_c = 5/3$, both of which derives from Equation 3.19 (assuming that the cross section of flow in the channel reach to be wide and rectangular). In Equation 3.22b, r_c is defined as the lateral drainage input (in $\mathrm{ms^{-1}}$) which results from the contribution of the outflows of the soil and overland stores of the cell. The subscript *c* denotes the channel flow model.

Equations 3.22a and 3.22b can be combined and integrated over the horizontal dimensions of the channel reach in the grid cell by assuming that the depth of flow y_c is constant in the channel reach. The horizontal dimensions of a channel reach, as depicted in Figure 3.6, do not occupy the entire width of the grid cell. The width W_i of a channel reach is assumed to remain constant over the entire length of the cell, but is larger in downstream cells (increasing towards the channel outlet as a function of the area drained (see Equation 3.24)). Referring to Figure 3.6, the non-linear reservoir equation for a channel reach in a generic cell is:

$$\frac{dV_{c_i}}{dt} = r_{c_i} X W_i + Q_c^u - \frac{C_{c_i} W_i}{(XW_i)^{\alpha_c}} V_{c_i}^{\alpha_c} \qquad \left[\mathrm{m^3 s^{-1}}\right] \tag{3.23}$$

where Vc_i is the channel volume stored in the channel reach of the i^{th} cell and $Q_c{}^u$ is the channel inflow from an upstream cell. From Equation 3.23, it is evident that the proportion of soil and overland flow from the i^{th} cell that feeds the channel of the i^{th} cell is proportionate to the ratio of the width W_i of the channel to the overall width X of the cell. If Qs_i and Qo_i are the soil and overland flows available to feed the channel reach of the i^{th} cell in each time interval respectively, then $Q_{s_i} + Q_{o_i} = r_{c_i} \cdot X \cdot X$ and $r_{c_i} \cdot X \cdot W_i = \left(r_{c_i} \cdot X \cdot X\right) \cdot \frac{W_i}{X} = \left(Q_{s_i} + Q_{o_i}\right) \cdot \frac{W_i}{X}$ in $\mathrm{m^3 s^{-1}}$. Thus the amount of soil and overland flow available to feed the cell downstream (cell $i+1$) is proportional to $\left(1 - \frac{W_i}{X}\right)$. This proportioning can be seen in Figure 3.6. The width W_i of the channel reach of the i^{th} cell is calculated as follows:

$$W_i = W_{\max} + \left[\frac{W_{\max} - W_{\min}}{\sqrt{A_{total}} - \sqrt{A_{threshold}}}\right]\left(\sqrt{A_{drained_i}} - \sqrt{A_{total}}\right) \quad [\mathrm{m}] \tag{3.24}$$

where A_{total} is the total area drained, $A_{threshold}$ is the threshold area, which is the minimum drainage area required to initiate a channel, $A_{drained_i}$ is the area drained by the i^{th} cell, w_{max} is the maximum width of the channel (in meters) at the basin outlet and w_{min} is the minimum width corresponding to the threshold area. These are determined from a geomorphological analysis based on a DEM of the catchment.

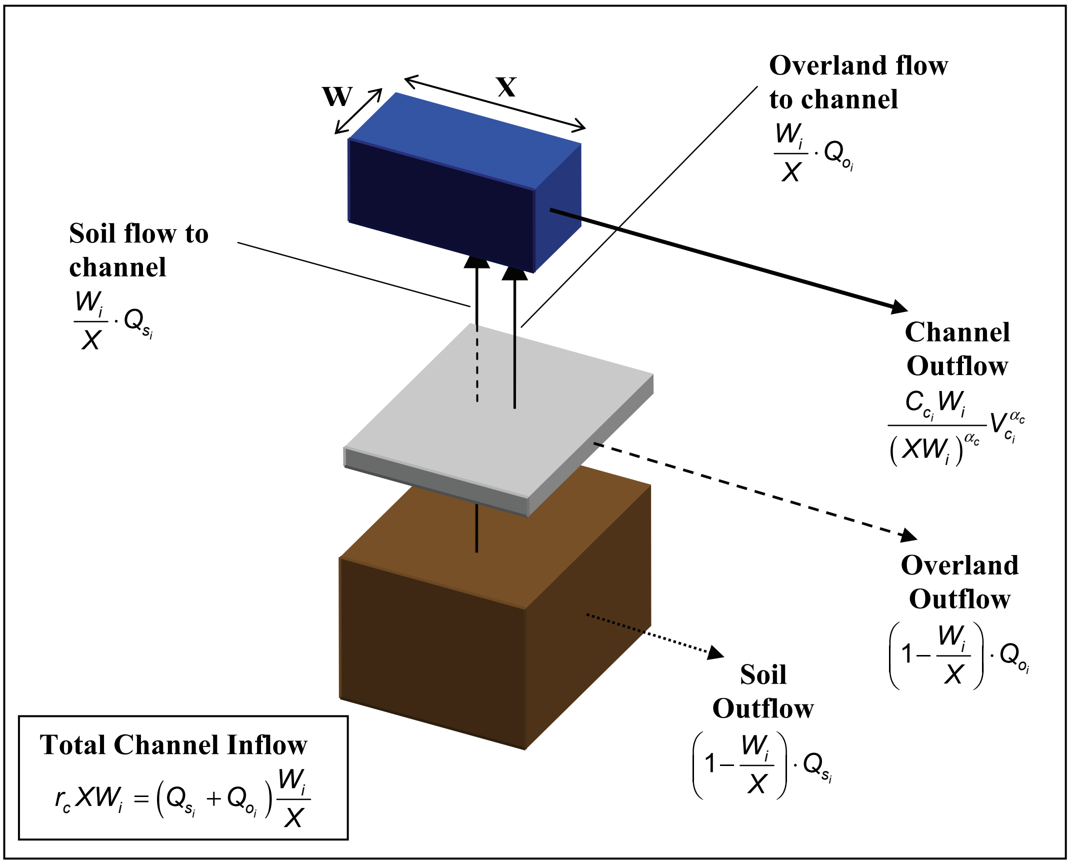


Figure 3.6 The water balance for the channel store of a "source" cell derived in Equation 3.23 for the TOPKAPI model.

3.2.5 Evapotranspiration model

The evapotranspiration module in the TOPKAPI model is basically a moisture loss and subtracted from the soil store as an accumulated amount in each time step. The computation of evapotranspiration losses was not done dynamically in the integration of Equation 3.17, the non-linear reservoir equation for a soil store, as its instantaneous impact was not considered important in the rainfall-runoff process. It was felt by the developers of the model, that evapotranspiration losses would have a small dynamic effect during a time step and that it was only necessary to preserve the cumulative volumetric balance in order to maintain the correct soil moisture budget (MUSIC Final Report, 2004: 51).

a) Background

Evapotranspiration is the combination of evaporation from the soil surface and transpiration from vegetation (Chow et al., 1988: 91). The factors that govern evapotranspiration are energy supply, vapour transport and the supply of moisture at the evaporative surface. The actual rate of evapotranspiration, for a given crop and climate, is based on the rate of evapotranspiration of a reference crop. The *reference crop evapotranspiration* (E_{tr}) is defined as "the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water" (Doorenbos and Pruitt, 1977: 1). The *potential evapotranspiration*, which is the evapotranspiration that "would occur from a large area completely and uniformly covered with growing vegetation which has access to an unlimited supply of soil water" (Dingman, 2002: 232), of a crop growing under the same conditions as the reference crop is calculated by multiplying the reference crop evapotranspiration (E_{tr}) by a crop coefficient k_c. The value of k_c depends on the stage of growth of the crop and range from 0.2 to 1.3 (Doorenbos and Pruitt, 1977: 35). The *actual evapotranspiration* (E_t) is calculated by multiplying the potential evapotranspiration by a *soil coefficient* k_s which takes into account the condition of the evaporative soil surface. Values of k_s range from 0 to 1. Thus the actual evapotranspiration E_t is calculated by:

$$E_t = k_s k_c E_{tr} \tag{3.25}$$

where k_s is the soil coefficient, k_c is the crop coefficient and E_{tr} is the reference crop evapotranspiration.

In practice, the method used to calculate the reference crop evapotranspiration depends on the data available at the site. Following Jensen et al. (1990: 80), the methods used to calculate E_{tr} can be classified according to the data required. These are categorized as the *temperature-based method*, which uses air temperature and day length, the *radiation-based method*, which uses net radiation and air temperature, the *combination method*, which uses net radiation, air temperature, wind speed and relative humidity, and the *pan method*, which is based on the evaporation from an open water pan with modifications depending on wind speed, temperature and humidity.

The combination method is based on the Penman-Monteith Equation (Monteith, 1965) and is a modification of the original equation developed by Penman (1948). It is considered as the most "complex and physically realistic" (Liu and Todini, 2002) method for the calculation of actual evapotranspiration. However the data required to support such a model are not extensively available and almost never exist in real-time. According to Liu and Todini (2002), the need for an extremely accurate expression for the calculation of evapotranspiration losses is not necessary in the rainfall-runoff process provided the integral effect is preserved. Thus in the TOPKAPI model, as applied by Liu and Todini (2002), evapotranspiration is calculated based on a simplified approach of the *radiation method* of Doorenbos and Pruitt (1977). It is the intention, with the application of the TOPKAPI model in this environment, to test this concept in a follow-up study.

b) Radiation method

The radiation method is suggested for areas where the measured climatic data include air temperature, and sunshine hours or cloud cover or radiation levels (Doorenbos and Pruitt, 1977: 8). A general knowledge of the levels of humidity and wind are also required. The relationship for the reference crop evapotranspiration E_{tr} (in mm.day^{-1}), based on the radiation method for each grid cell, is given as:

$$E_{tr} = C_v W_{ta} R_s \tag{3.26}$$

where C_v is an adjustment factor which is obtainable from tables (Doorenbos and Pruitt, 1977: 14) as a function of the mean relative humidity and the mean daytime (07:00-19:00) wind speed at 2m height above the soil surface; W_{ta} is a compensation factor which is dependent on temperature and altitude for which tabulated values also exist (Doorenbos and Pruitt, 1977: 13); and R_s (in mm.day^{-1}) is the measured short wave solar radiation that reaches the earth's surface. R_s can be measured directly, but this data is usually not easily available for the area of investigation. It (R_s) is dependent on the radiation received at the top of the atmosphere (R_a in mm.day^{-1}), and the transmission of this radiation through the atmosphere, which is dependent on cloud cover. Thus $R_s = \left(0.25 + 0.5 \, n/N\right) R_a$, where n/N is the ratio of actual hours of sunshine to the maximum possible hours of sunshine in a day. R_a is dependent on latitude and the time of the year, for which tabulated values exist (Doorenbos and Pruitt, 1977: 12), and tabulated mean monthly values of N are also available (Doorenbos and Pruitt, 1977: 13) as a function of latitude.

In the above expression for R_s, values of actual hours of sunshine n are not usually readily available over the individual cells of a catchment. Thus Todini (1996) sought an empirical relationship that relates the reference crop evapotranspiration E_{tr} to W_{ta}, the compensation factor, the mean recorded temperature of the month T_m and the maximum number of sunshine hours N. The result is:

$$E_{tr} = \alpha + \beta \cdot N \cdot W_{ta} \cdot T_m \tag{3.27}$$

where α and β are regression coefficients which are to be estimated for each grid cell. Equation 3.27 is structurally similar to Equation 3.26, the radiation-method equation, except in this instance air temperature is taken as an index of radiation and a constant has been added. According to Todini (1996), the relationship developed in Equation 3.27 is linear in temperature and permits the disaggregation of the monthly results on a daily or sub-daily (hourly) basis. Thus the reference crop evapotranspiration E_{tr} is expressed in mm.Δt^{-1}, and T_m, the area's mean air temperature, is averaged over Δt.

The compensation factor W_{ta}, which is dependent on the long-term mean monthly air temperature and the altitude of each grid cell, is tabulated in Doorenbos and Pruitt (1977: 13). Alternatively, W_{ta} can be approximated by a fitted parabola as shown in Todini (1996).

For reasons of limited data availability, the next chapter proposes a different method for the spatial estimation of evapotranspiration when the TOPKAPI model is applied to the Liebenbergsvlei catchment. This method proposes the use of calculated estimates of potential evapotranspiration, which can be made at Automatic Weather Stations (AWS) throughout South Africa (using for example the Penman-Monteith Equation). Thereafter, through the use of a Numerical Weather Prediction (NWP) model, these values can be spatially interpolated for the areas of interest. This is discussed in more detail in the next chapter. The use of actual evaporation measurements from Evaporation Pans located throughout South Africa can also be used in this instance. However, as attractive as such data is in the application of the model, the data are notoriously inaccurate and biased and should not be used (Everson, 1999).

3.2.6 Moisture accounting in each cell

Moisture accounting in each cell is regulated by the soil store insofar as it experiences precipitation input and evapotranspiration losses directly. Furthermore, through horizontal subsurface flow, the soil store directly feeds the channel store of that cell and, upon its saturation, activates the overland store component, which in turn drains into the channel as overland flow.

In the TOPKAPI model, the grid cells are connected together in a tree shaped network. The flow of water through this network is characterised by a single preferential downstream direction in each cell, starting from "source cells" (cells without upstream contributors) downward toward the catchment outlet. The preferential direction is evaluated according to a neighbourhood relationship from a DEM of the catchment and is based on the principle of minimum energy cost (Band, 1986). This method takes into account the maximum elevation difference between the active cell and the four surrounding cells connected along the edges of the active cell. The flow path from an active cell to an edge cell is assigned in the direction of maximum slope, in either a north, south, east or west direction. Thus flow paths to the four cells diagonally adjacent to the corners of an active cell are ignored in this method. As depicted in Figure 3.7, an active cell may have up to three contributing cells but may only feed a single downstream cell in one of the four cardinal directions.

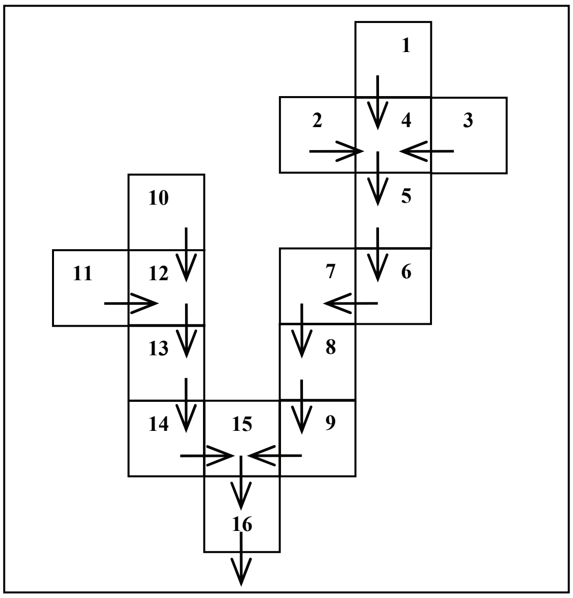


Figure 3.7 The tree-shaped network form by the cells of the TOKAPI model (from MUSIC Final Report, 2004: 53).

The intra-cell operations, together with the inter-cell flows, can best be explained by examining a generic catchment consisting of three typical cells. This scenario is depicted in Figure 3.8 where *Cell 1* (source cell) flows into *Cell 2* which in turn flows into *Cell 3*. Cell 1 is classified as a *hillslope cell*, where all surface flow is of the overland type, while the two latter cells consist of channel flow as well as overland flow. This distinction is important since not all cells have channelled flow. The classification is based on the minimum threshold area required to initiate a channel and is made from the digital elevation model (DEM) of the catchment.

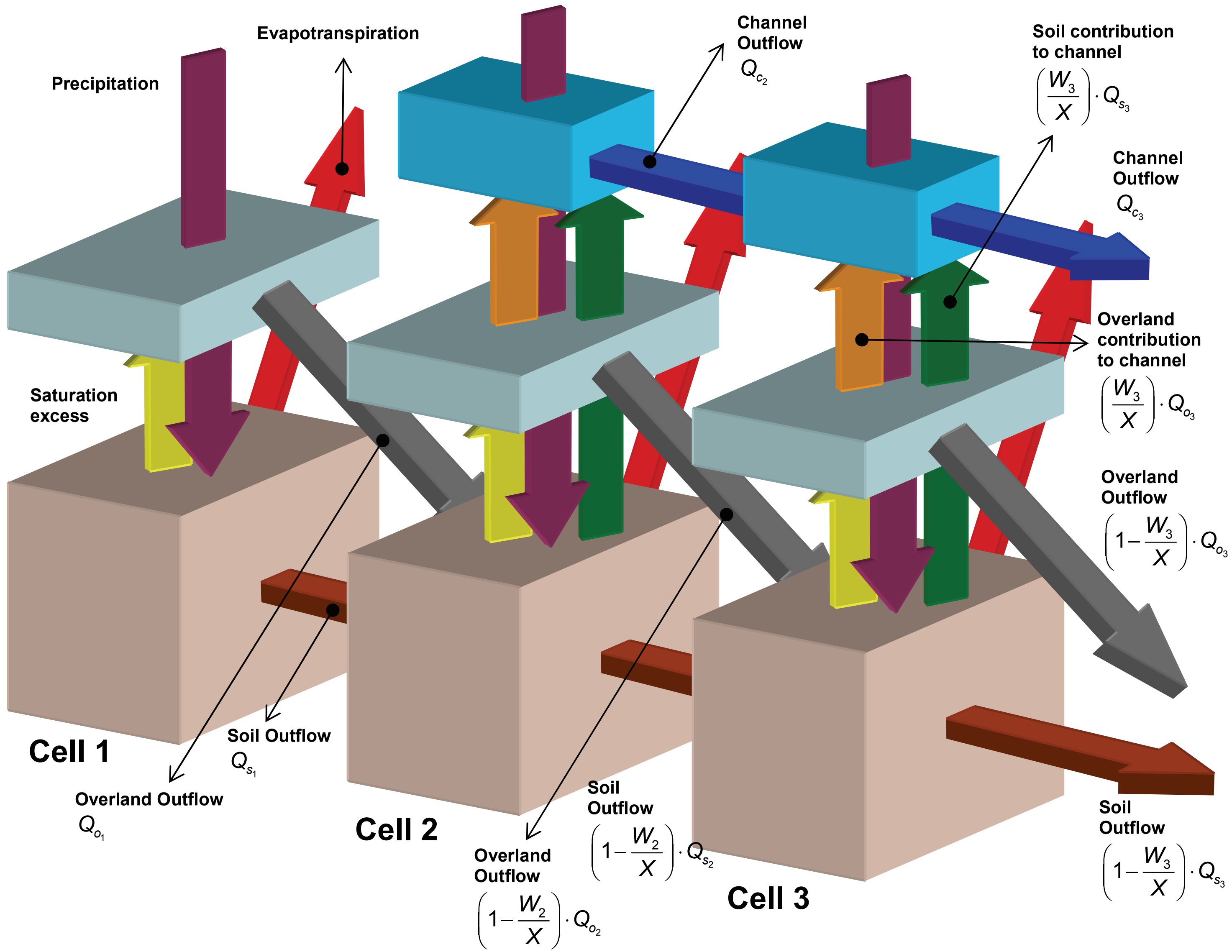


Figure 3.8 A generic catchment consisting of three cells showing the intra- and inter-cell operations of the TOPKAPI model.

Within each cell, the storages operate in the following manner (with reference to Figure 3.8). The soil store of Cell 1 receives input from incident precipitation as a single lumped input at the beginning of each time step t_o. Evapotranspiration losses occur from the soil store and are subtracted as a lumped amount from the intermediate soil moisture storage $V'_{s1}(t_o+\Delta t)$ at the end of each time step ($t_o+\Delta t$). The intermediate soil moisture volume $V'_{s1}(t_o+\Delta t)$ is the solution of the non-linear differential reservoir equation (Equation 3.17) at time $t_o+\Delta t$. Thus the actual soil moisture volume $V_{s1}(t_o+\Delta t)$ stored in Cell 1 at the end of the time interval ($t_o+\Delta t$) results from the subtraction of evapotranspiration losses (E_a), incurred over the interval, from the intermediate soil moisture volume. This computation is shown in Equation 3.28 for two cases, i.e. before soil saturation and after soil saturation, where in the latter case the intermediate soil moisture storage is the saturated soil moisture volume V_{sm1}.This is computed as:

$$V_{s_1}\left(t_o+\Delta t\right)=\begin{cases} Before\,saturation: V'_{s_1}\left(t_o+\Delta t\right)-E_aX^2 \\ After\,saturation: V_{sm_1}-E_aX^2 \end{cases} \tag{3.28}$$

where $V_{s1}(t_o+\Delta t)$ is the actual soil moisture volume (in m^3) stored in Cell 1 at time $t_o+\Delta t$, $V'_{s1}(t_o+\Delta t)$ is the intermediate soil store and results from the discrete solution of the non-linear differential reservoir equation (Equation 3.17) at time $t_o+\Delta t$, E_aX^2 is the volumetric evapotranspiration losses over the time interval Δt and cell area X^2 and V_{sm1} is the saturated soil moisture storage of Cell 1.

The regulating function of the soil is shown in Equation 3.29 and is explained as follows. Once the soil store becomes saturated, all precipitation received by it becomes precipitation excess (or saturation excess) e_o which becomes the input to and hence activates, overland storage. The algorithm for this computation, for the soil store of Cell 1 in Figure 3.8, is given by the following equation:

$$e_o=\begin{cases} Before\,saturation: V'_{s_1}\left(t_o+\Delta t\right)-V'_{s_1}\left(t_o+\Delta t\right)=0 \\ After\,saturation: V'_{s_1}\left(t_o+\Delta t\right)-V_{sm_1} \end{cases} \tag{3.29}$$

where e_o is the saturation excess (in m^3) at the end of the interval, i.e. at time $t_o+\Delta t$, $V'_{s1}(t_o+\Delta t)$ is the intermediate soil store and results from the discrete solution of the non-linear differential reservoir equation (Equation 3.17) at time $t_o+\Delta t$ and V_{sm1} is the saturated soil moisture storage of *Cell 1*.

The outflow from the soil store of Cell 1 (S1) will begin to flow into the soil store of Cell 2 (S2) once S1 has any moisture stored within it. This outflow, from S1 to S2, is computed as an average value over the time interval Δt at the end of each time step by the following equation:

$$Q_{s_1}=\left(p_1X^2+Q^u_{o_1}+Q^u_{s_1}\right)-\frac{V_{s_1}\left(t_o+\Delta t\right)-V_{s_1}\left(t_o\right)}{\Delta t} \tag{3.30}$$

where Q_{s1} is the average soil outflow (in m^3s^{-1}) of Cell 1 over the time interval Δt which is computed at the end of the time interval ($t_o+\Delta t$), $\left(p_iX^2+Q^u_{o_i}+Q^u_{s_i}\right)$ is the total inflow into the cell at the beginning of the time interval t_o, and $\frac{V_{s_1}\left(t_o+\Delta t\right)-V_{s_1}\left(t_o\right)}{\Delta t}$ is the average rate of change of soil moisture storage over the time interval. The outflow (Q_{s1}) will reach a maximum at the saturation of S1, and at this point in time, no more infiltration takes place and all incident precipitation becomes precipitation excess (or saturation excess e_o). The saturation excess computed from Equation 3.28 is calculated at the end of the time interval t_o, i.e. at time $t_o+\Delta t$, and becomes the input for the overland storage at the beginning of the next time interval, i.e. $t_1= t_o+\Delta t$. Outflow from the overland store of Cell 1 (O1) will flow into the soil store of the next cell S2 and will infiltrate into S2 directly, unless S2 is saturated from the previous time interval. The overland outflow from O1 to S2 is computed at the end of each time step in a similar manner to the soil outflow (Equation 3.30) as an average value over the time interval Δt by the following equation:

$$Q_{o_1} = \left(r_{o_1} X^2\right) - \frac{V_{o_1}(t_o + \Delta t) - V_{o_1}(t_o)}{\Delta t} \tag{3.31}$$

where Q_{o1} is the average overland outflow (in m^3s^{-1}) of Cell 1 at the end of the time interval ($t_o+\Delta t$), $\left(r_{o_1} X^2\right)$ is the total inflow into the cell at the beginning of the time interval t_o due to saturation excess, and $\frac{V_{o_1}(t_o + \Delta t) - V_{o_1}(t_o)}{\Delta t}$ is the average rate of change of overland storage over the time interval.

Continuing with the flow processes of Cell 2, the soil and overland components of this cell operate as for Cell 1, except that Cell 2 has a channel component. As such, the soil and overland components of Cell 2 (S2 and O2 respectively) will contribute some of its outflow to the channel of Cell 2 (C2) as well as to the downstream cell. The amount that S2 and O2 contribute to C2 is proportional to the ratio of the width of the channel of Cell 2 (W_2) to the overall width of the cell (X-dimension of the cell). This is understood from the fact that $r_{c2}{\cdot}X{\cdot}W$ from Equation 3.23, which is the input term of the non-linear differential reservoir equation describing channel storage, is derived from multiplying $r_{c2}{\cdot}X{\cdot}X$ (in m^3/s) by the ratio of W_2/X to obtain $r_{c2}{\cdot}X{\cdot}W_2$ for Cell 2. The term $r_{c2}{\cdot}X{\cdot}X$ comprises of the sum of the overland Q_{o2} and soil Q_{s2} outflows for Cell 2, i.e. $r_{c_2} \cdot X \cdot X = Q_{s_2} + Q_{o_2}$. Thus, a proportion equal to W_2/X of the soil and overland outflow of Cell 2 feed the channel of Cell 2, and therefore a proportion equal to ($1-W_2/X$) of the soil and overland flow of Cell 2 contribute to Cell 3 downstream. The outflow from the channel of Cell 2 (C2) flows into the downstream channel of Cell 3 (C3) and is computed in a similar manner to the outflow from the respective soil and overland stores of the cell, i.e. it is computed at the end of each time step as an average value over the interval Δt:

$$Q_{c_2} = \left(r_{c_2} XW + Q^u_{c_1}\right) - \frac{V_{c_2}(t_o + \Delta t) - V_{c_2}(t_o)}{\Delta t} \tag{3.32}$$

where Q_{c2} is the average channel outflow (in m^3s^{-1}) leaving Cell 2 at the end of the time interval ($t_o+\Delta t$), $\left(r_{c_2} XW + Q^u_{c_1}\right)$ is the total inflow into the cell at the beginning of the time interval t_o due to lateral drainage and upstream channel contributions (for the example of Cell 2, $Q^u{}_{c1} = 0$), and $\frac{V_{c_2}(t_o + \Delta t) - V_{c_2}(t_o)}{\Delta t}$ is the average rate of change of channel storage over the time interval.

In a similar manner, the moisture balance for the soil, overland and channel components for any generic cell in a catchment operate in the method explained. The subsequent outflows from the representative stores to the downstream cells also operate in the manner explained. All cells of a catchment operate in this manner and the outflows from each cell are drained downwards toward the catchment outlet to give the overall outflow from the catchment.

3.2.7 Solution of the non-linear differential reservoir equations

The solution of the non-linear differential reservoir equations, describing the rate of change of moisture storages in the soil store (Equation 3.17), overland store (Equation 3.21) and channel store (Equation 3.23), require complex computational procedures. This aspect of physically based distributed catchment modelling has in the past rendered the feasibility of such models for real-time flood forecasting impractical. However, with computer power, this difficulty is no longer a hindrance in this type of modelling.

There are two categories of methods that offer solutions to these equations, exact methods (analytical solutions) or approximate methods (numerical solutions). Ideally, an analytical solution for the governing equation would be preferred, as this would reduce the computational cost of such models (which is a boon for flood forecasting), however in practice most non-linear equations cannot be solved exactly. Equations 3.17, 3.21 and 3.23 can be written in a generalised non-linear differential form (after Liu and Todini, 2002):

$$\frac{dy}{dt} = a - by^c \tag{3.33}$$

where y represents the volume term, a the input term, b the multiplier and c the exponent of the actual equations. If the value of the exponent c is 1, then Equation 3.33 reduces to a linear form for which an analytical solution exists. However, in the TOPKAPI application of these equations, values of c range from $^5/_3$, which is the exponent derived from Manning's Formula for overland and channel flow, and between 2 and 4 (Liu and Todini, 2002) for the soil (subsurface) flow. A numerical solution for the non-linear differential equations can be achieved through a variable step fifth-order Runge-Kutta algorithm due to Cash and Carp (1990) (MUSIC Final Report, 2004: 56). However, Liu and Todini (2002) present a quasi-analytical solution for Equation 3.33 and suggest that this can reduce the computation time by one order of magnitude (MUSIC Final Report, 2004; 56).

The following subsection explains the quasi-analytical solution offered by Liu and Todini (2004). However, it was discovered in this research that exact solutions exist for Equation 3.33 for exponents $c=2$ and 4 (Gradshteyn and Ryzhik, 1980: 63). This is explored further in the next Chapter.

a) Quasi-analytical solution

The quasi-analytical solutions offered by Liu and Todini (2002) are presented for three cases as there are different solutions for each case. Following from the general form of the non-linear equation given in Equation 3.33, the three cases are:

1) for $1 \le c \le 2$; for the solution of the overland and channel reservoir differential equation, where $c={}^5/_3$,
2) for $c > 2$; for the solution of the soil reservoir differential equation, and
3) for $a=0$; when the input term in the time step is zero.

Case 1: In Equation 3.33, the term y^c can be approximated by a second order polynomial, i.e. $y^c = \beta y^2 + \alpha y = y(\alpha + \beta y)$, where the parameters α and β are fitted by a least squares method. Thus Equation 3.33 can be approximately written as:

$$\frac{dy}{dt} = a - by(\alpha + \beta y)$$
$$= a - b\alpha y - b\beta y^2 \qquad (3.34)$$
$$= (-b\beta)\left(-\frac{a}{b\beta} + \frac{\alpha}{\beta}y + y^2\right)$$

Assuming A=-$b\beta$, B=$^{\alpha}/_{\beta}$and C=$^{-a}/_{b\beta}$, and after rearranging, Equation 3.34 reduces to:

$$\frac{dy}{dt} = (A)\left(C + By + y^2\right)$$
$$\Rightarrow \frac{dy}{y^2 + By + C} = (A)dt \qquad (3.35)$$

If p_1 and p_2 are the two roots of the equation $y^2 + By + C = 0$, then $(y - p_1)\cdot(y - p_2) = 0$ and:

$$p_{1(2)} = \frac{-B \pm \sqrt{B^2 - 4C}}{2} \qquad (3.36)$$

where p_1 / 0 and $p_2 \leq 0$. The left hand side of Equation 3.35 can be written and solved for $y_{(t+\Delta t)}$ as:

$$\int_{y_t}^{y_{t+\Delta t}} \frac{dy}{y^2 + By + C} = \int_{y_t}^{y_{t+\Delta t}} \left(\frac{1}{p_1 - p_2}\right)\left(\frac{1}{y - p_1} - \frac{1}{y - p_2}\right)dy \qquad (3.37)$$

When $y_t < p_1$ (for the flow rising period) the analytical solution to Equation 3.37 is obtained by:

$$y_{t+\Delta t} = p_1 - \frac{p_1 - p_2}{1 - A(p_1 - p_2)(\Delta t)\dfrac{y_t - p_2}{p_1 - y_t}} \qquad (3.38)$$

where $y_{t+\Delta t}$ is the y at time $t+\Delta t$ and y_t is the initial value of y at each time step. Similarly, for y_t / p_1 (for the flow recession period) the analytical solution to Equation 3.37 is obtained by:

$$y_{t+\Delta t} = p_2 - \frac{p_1 - p_2}{1 - A(p_1 - p_2)(\Delta t)\dfrac{y_t - p_1}{y_t - p_2}} \qquad (3.39)$$

Case 2: For horizontal subsurface flow in the soil store, the value of the exponent c ranges from 2 to 4 (Liu and Todini, 2002). By making the substitution $u = y^{-(c-1)}$, then:

$$\frac{du}{dy} = \frac{-(c-1)}{y^c}$$
$$\Rightarrow \frac{dy}{y^c} = \frac{du}{-(c-1)} \qquad (3.40)$$

By substituting this result into Equation 3.33, the following is obtained:

$$\frac{dy}{dt}\frac{1}{y^c} = \frac{a}{y^c} - b$$
$$\Rightarrow \frac{du}{dt}\frac{1}{-(c-1)} = \frac{a}{y^c} - b \qquad (3.41)$$
$$\Rightarrow \frac{du}{dt} = b(c-1) - \frac{a(c-1)}{y^c}$$

It can be shown that $\frac{1}{y^c} = u^{\frac{c}{c-1}}$ from the initial substitution of $u = y^{-(c-1)}$, and thus Equation 3.41 reduces to:

$$\frac{du}{dt} = b(c-1) - a(c-1)u^{\frac{c}{c-1}} \qquad (3.42)$$

Since the term $\frac{c}{c-1}$ falls into the range of 1 to 2 for *c* in the range of 2 to 4, the term $u^{\frac{c}{c-1}}$ can be approximated by the second order polynomial in the method described for *Case 1*, i.e. $u^{\frac{c}{c-1}} = u(\alpha + \beta u)$. In this case:

$$\frac{du}{dt} = A\left(u^2 + Bu + C\right) \qquad (3.43)$$

where $A = -a(c-1)\beta$, $B = \frac{\alpha}{\beta}$ and $C = -\frac{b}{a\beta}$. The parameter *a* represents the input terms, *b* the multiplier, *c* the exponent, and α and β the fitted variables. The solution of Equation 3.43 can be accomplished in the same manner as for *Case 1*.

Case 3: In this case the term *a* is zero. This situation arises when there is no more inflow into a cell, either from precipitation input or from upstream cells. Therefore, Equation 3.33 reduces to the following:

$$\frac{dy}{dt} = by^c$$
$$\Rightarrow \frac{dy}{y^c} = (-b)\,dt \qquad (3.44)$$

This is easily integrated and the difference equation takes on the following non-linear form:

$$y_{t+\Delta t} = \left[y_t^{(1-c)} + b(c-1)(\Delta t)\right]^{\frac{1}{(1-c)}} \qquad (3.45)$$

where $y_{t+\Delta t}$ is the *y* at time $t+\Delta t$ and y_t is the initial value of *y* at each time step.

3.3 The application of the TOPKAPI model

3.3.1 Data requirements

The TOPKAPI model requires two kinds of input data, namely static and dynamic. The static data required are terrain data (from a digital elevation model (DEM) of the catchment), soil data and vegetation cover or landuse data. The dynamic data required are estimates of measured and/or calculated evapotranspiration and precipitation.

In terms of the static parameters, there are seven classes of input parameters that are required by the model in each grid cell, namely L (the thickness of the surface soil layer, in m), k_s (the saturated hydraulic conductivity of this layer in ms^{-1}), θ_r (the residual moisture content of the soil), θ_s (the saturated moisture content of the soil), α_s (the pore-size distribution exponent for the transmissivity of the soil, which is taken as constant for all the cells in a catchment) and n_o and n_c (which are the surface and channel roughness coefficients respectively (in $m^{-1/3}s^{-1}$) according to Manning's Equation). The first five classes of parameters relate to the soil and are responsible for the production of runoff. These parameters are obtainable from literature as a function of the soil type. The type of soil present in each cell is identified from a *soils map* of the catchment. The last two classes of parameters are responsible for the routing of runoff, over the hillslopes and in the channel respectively. These are also obtainable from literature as a function of the landuse or landcover properties of the cell, which is identified from a *landuse map* of the catchment.

The DEM application in the model consists of describing the topographic and geomorphologic elements of the catchment, in terms of calculating the surface slopes, areas drained, identifying the flow pathways and detecting the drainage networks. The primary source of this data and the methods of manipulation and analyses are through GIS techniques, which are described in detail in the subsections that follow. Since each pixel of a DEM forms the primary unit of the processing cells in the TOPKAPI model, it was decided to model the hydrologic processes of the Liebenbergsvlei catchment at the 1km spatial scale. It has been shown that the distributed operations of the TOPKAPI model are still physically valid up to a grid cell size of 1km square (Martina, 2004: 76). Thus, the decision was taken to undertake the modelling at this resolution as the various static input data are easily and freely available at this scale and, more importantly, distributed rainfall input (remotely sensed from radar) is only available at this accuracy in South Africa. However, it was found that a DEM resolution at this scale was too coarse in accurately identifying the flow pathways and detecting the drainage networks of the Liebenbergsvlei catchment and so it was necessary to resample a finer resolution DEM up to the desired scale (1km square). This, and other manipulation techniques that were necessary, are expanded on in more detail in the subsections that follow. However, these explanations are preceded by a description of the test catchment that was used in this study, i.e. the Liebenbergsvlei catchment.

3.3.2 The Liebenbergsvlei catchment

The Liebenbergsvlei catchment is a sub-catchment of the Vaal drainage basin and is situated near Bethlehem in the Free State Province. The area of the catchment is approximately $4625km^2$ and consists predominantly of dry cropland and grassland. The location of the catchment, in relation to South Africa, is shown below in Figure 3.9 together with its quaternary sub-catchment divisions and river network (from Midgley et al., 1994), which are shown at a spatial detail of 1:250 000. The locations of the 45 telemetering raingauges and the 9 flow gauges that are found in the catchment are also shown as well as the location of MRL5 S-Band weather radar that covers the catchment. These instruments provide temporally and spatially detailed hydrologic data necessary to implement a distributed catchment model such as the TOPKAPI.

Topographic data for the Liebenbergsvlei catchment, in terms of the DEM, was sourced from HYDRO1k (1996) and DLSI (1996) for pixel resolutions of 1km and 218m square respectively. The 1km square DEM is shown in Figure 3.10, where this resource is derived from the geographic database of the United States Geological Survey (USGS) '30 arc-second digital elevation model of the world. This DEM is freely available from the USGS website (http://edcdaac.usgs.gov/gtopo30/hydro) for all the continents of the world at the 1km spatial resolution and includes other topographically derived data sets, such as stream networks and drainage basins.

It was the aim of this research to model the Liebenbergsvlei catchment at the 1km spatial resolution and as such it was initially intended to use the HYDRO1k (1996) DEM for this purpose. However, the resolution of this DEM proved to be too coarse in terms of accurately tracing the catchment boundaries and the stream networks (Section 3.3.3). This was determined by comparing the stream network delineated from the 1km DEM with that digitised from topographic maps. The latter information (Midgley et al., 1994) was captured at a spatial detail of 1:250 000 and is shown in Figure 3.9. Thus a finer resolution DEM was sought (DLSI, 1996) and the topographic analysis of the Liebenbergsvlei catchment that proceeded was based on this DEM. In order to maintain the chosen modelling scale of 1km square, the pixel resolution of this latter resource was resampled to the desired scale (Section 3.3.3). The soils type and landuse information was obtained from SIRI (1987) and GLCC (1997) respectively. The processing of these data is covered in Section 3.3.4 and 3.3.5 respectively.

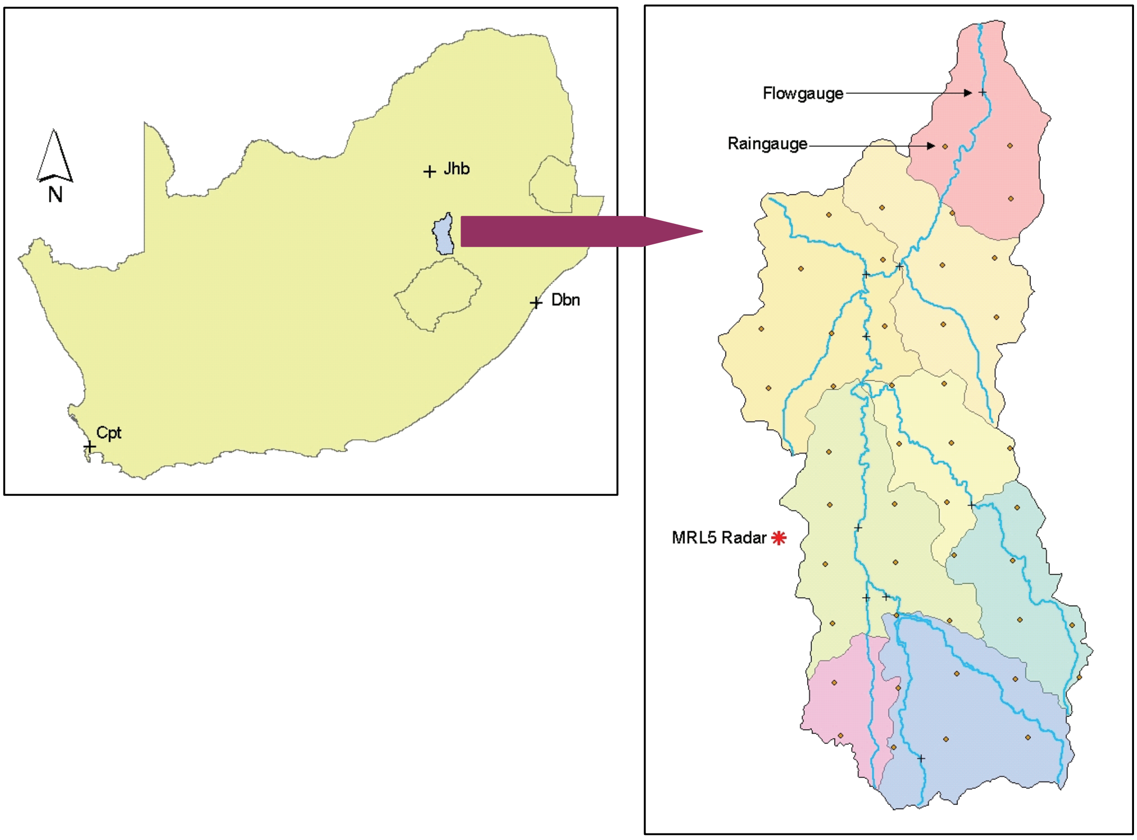


Figure 3.9 The Liebenbergsvlei catchment in South Africa showing the eight quaternary sub-catchments and the river network, which is shown at a spatial detail of 1:250 000 (Midgley et al.,1994). Also shown are the locations of the 45 telemetering raingauges, 9 flow gauges and the S-Band MRL5 weather radar.

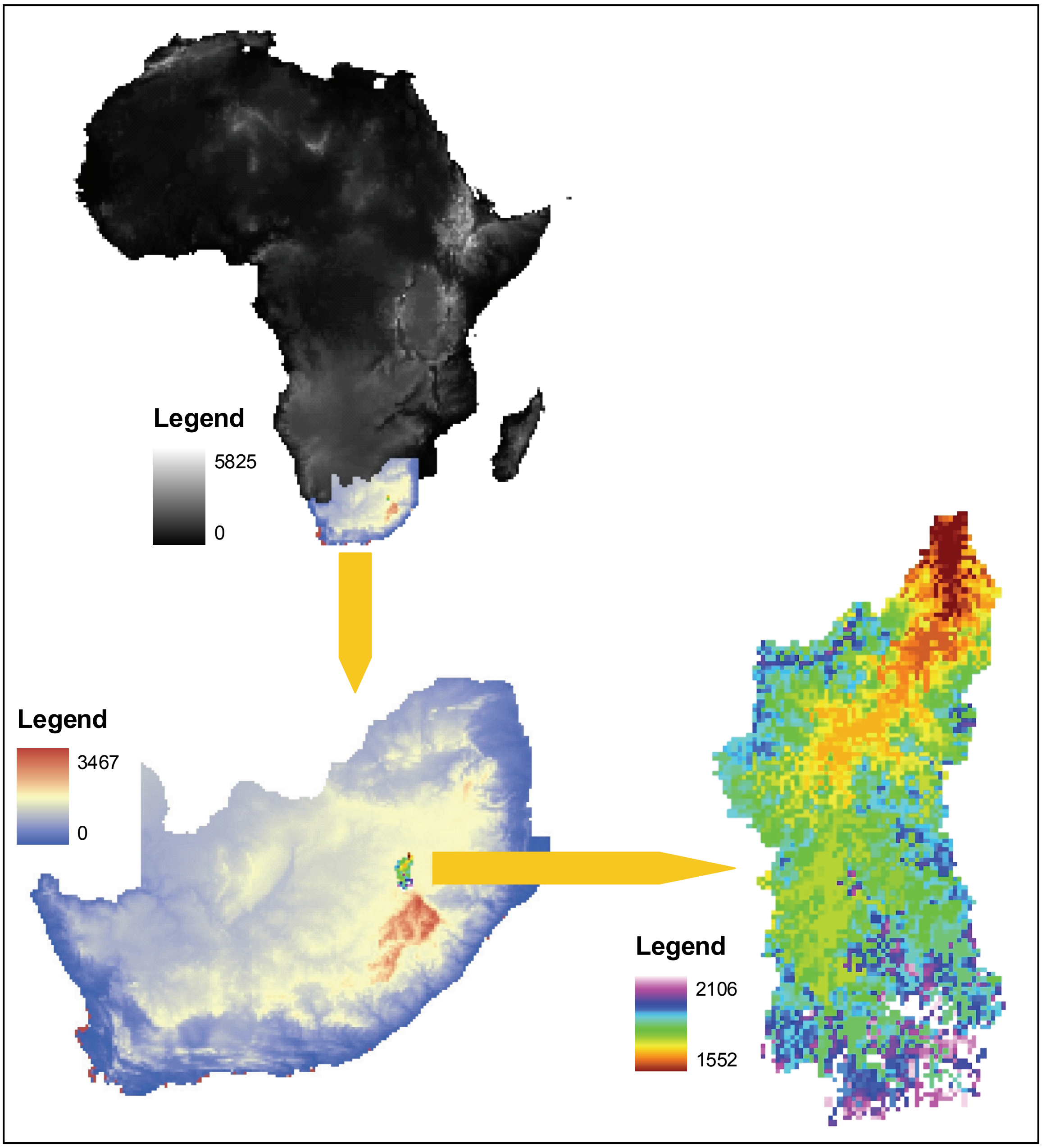


Figure 3.10 A DEM of Africa, South Africa and the Liebenbergsvlei catchment at a grid resolution of 1km square from the geographic database of the United States Geological Survey (HYDRO1k, 1996).

3.3.3 Digital Elevation Model (DEM)

a) Background

A DEM is a raster-based description of a continuous surface and represents a grid of elevation heights, in cells or pixel format, above some datum (such as sea level). The accuracy of the DEM is highly dependent on the resolution of the grid cells, where a coarser resolution DEM is more prone to contain errors and is not able to accurately represent surface features and permit the detection of flow pathways.

A common problem in DEM's is the occurrence of *sinks*. A sink, also referred to as a depression or pit, is a cell or area that is surrounded on all sides by higher elevation values. As such, a sink is an area of internal drainage and prevents the downslope routing of water and, unless it is an actual case such as a lake or swamp, it is an error.

By contrast, a peak is a cell or area surrounded by lower elevation values and drains water away from it. Peaks are sometimes erroneous, but are more likely to be natural features. However, it is vary rare that sinks are natural features and are more likely to be errors in the DEM (Mark, 1988). These errors often arise due to the sampling techniques used in processing a DEM or due to the rounding off of elevation values.

In order to create an accurate representation of the flow direction, it is best to use a DEM that is free of sinks, a *depressionless DEM*. To create such a DEM from an existing DEM, the sinks need to be filled. This is an iterative process, since the filling of a sink cell or area may create a new sink at the boundary of the filled cell, which in turn needs to be filled. A sink is filled to its outflow point, which is the minimum fill elevation required in order for water to flow out of the cell into a neighbouring cell. This can be achieved using commonly available tools in a GIS software package, e.g. ArcGIS.

Once a depressionless DEM is created the next step in the delineation of the stream network is the determination of the outflow direction of each cell, i.e. the direction of the steepest outflow path from an active cell to the neighbouring cells. A common algorithm used for this purpose is the *D8 flow model* of O'Callaghan and Mark (1984). This method assigns the outflow from an active cell into its neighbour along one of the eight possible paths to which it could flow, i.e. the four cardinal paths and the -four diagonal paths. This path is defined as the path of steepest slope. Figure 3.11 shows how this method works as applied in the ArcGIS environment. Given a DEM (on the top left of Figure 3.11), a drainage *direction code* is assigned to each cell (shown on the top right of Figure 3.11) based on the direction codes, which are shown in the bottom panel. This code depends on the direction of maximum slope, which is calculated as the maximum difference in elevation divided by the horizontal distance from the centre of the active cell to the centres of the eight surrounding cells. If the maximum slopes to several cells are the same, then the neighbourhood around the active cell is enlarged until the direction of steepest slope is found. Figure 3.12 shows the flow direction raster computed on ArcGIS for the Liebenbergsvlei catchment based on the 218m square resolution DEM (DLSI, 1996); from here on this DEM will be referred to as the 200m DEM.

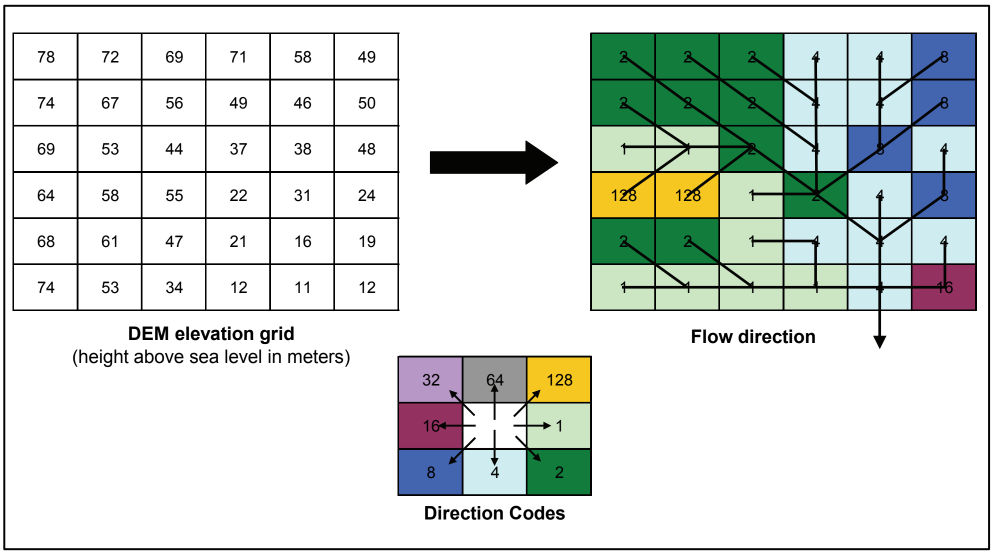


Figure 3.11 The *D8 flow model* of O'Callaghan and Mark (1984) as applied in ArcGIS.

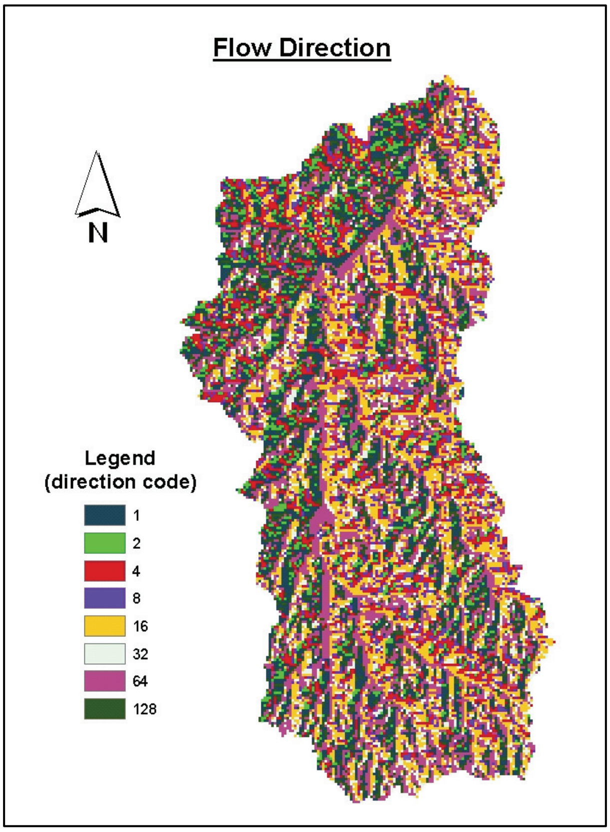


Figure 3.12 A flow direction raster showing the direction code of each cell determined using ArcGIS for a 200m square resolution DEM of the Liebenbergsvlei catchment.

The next step in the delineation of stream networks is to determine the number of upslope cells that contribute flow into each cell, i.e. the flow (in terms of contributing cells) accumulated in each cell. This is also done on ArcGIS using a standard tool. Figure 3.13 shows the flow accumulation raster for the Liebenbergsvlei catchment. The colour palette indicates, for each cell, the number of upslope cells that feed it. The main trunk of the stream network is easily visible from this image as the pixels having the highest value of flow accumulation.

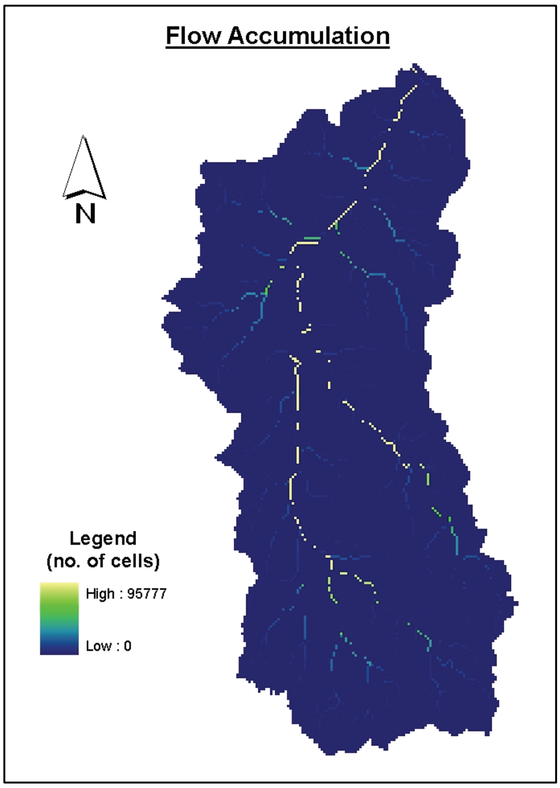


Figure 3.13 A flow accumulation raster showing the number of upslope cells flowing into each cell determined using ArcGIS for the Liebenbergsvlei catchment.

The final step in delineating the stream network from a DEM is to assign a threshold value to the *flow accumulation* raster, for the minimum number of upslope cells that are required to initiate a channel in an active cell. The determination of this threshold value depends on, according to Tarboton et al. (1991), climate, slope and soil characteristics. Tarboton et al. (1991) present procedures in order to "rationally select the scale at which to extract channel networks" which correspond to networks obtained through more traditional methods, such as from topographic maps or fieldwork. Figure 3.14 shows a comparison between the stream network delineated from the 200m DEM in the manner described above (shown on the left of Figure 3.14) and a stream network digitised from a topographic map of the catchment (shown on the right of Figure 3.14) at a spatial scale of 1:250 000 (from Midgley et al., 1990). The threshold value chosen was 500 pixels, which corresponds to an area of approximately 20km^2 for a pixel size of 200m square. The comparison shows good correspondence between the two sources of networks.

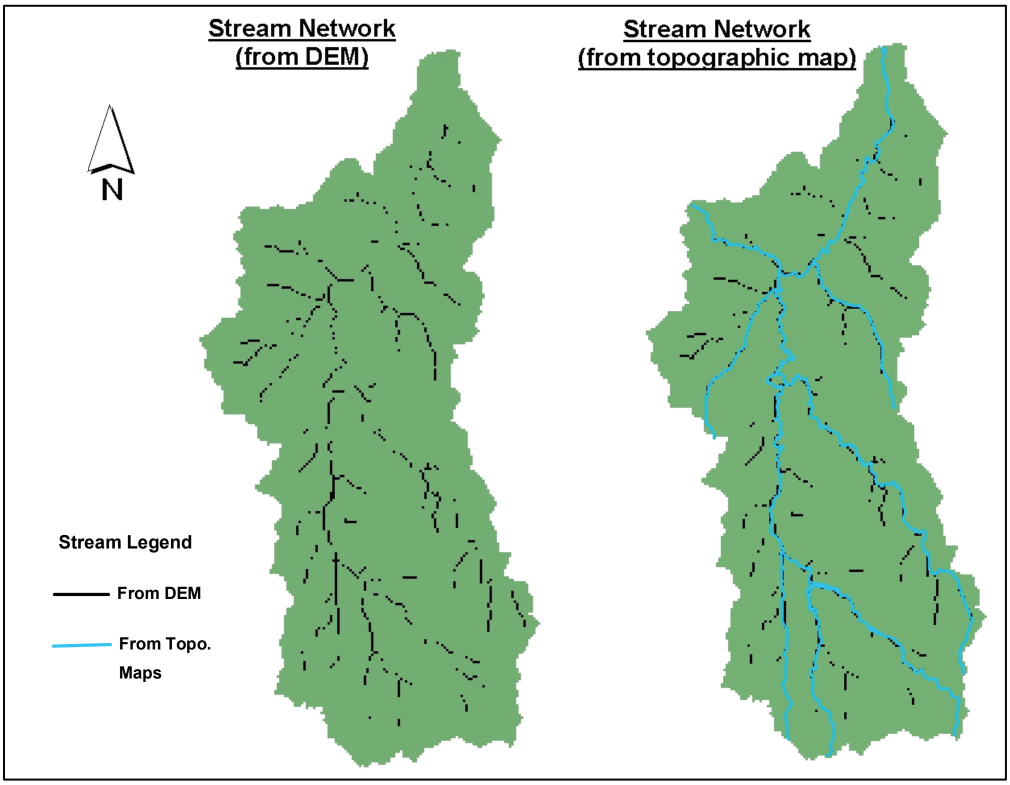


Figure 3.14 A comparison between a stream network delineated for the Liebenbergsvlei catchment from a DEM, using a threshold value of 500 cells and a stream network digitised from a topographic map (at a spatial scale of 1:250 000 from Midgley et al. (1990)). The DEM delineated network shown on the left, although appearing disjointed in the image, is continuous in reality.

A further topographically derived input of the TOPKAPI model is the order of the stream network, according to the method of Strahler (1964). This raster can easily be computed from the delineated stream network using ArcGIS. The TOPKAPI model also requires the calculation of the surface slope of each pixel from a DEM. The surface slope raster is also easily computed from a DEM using a tool on ArcGIS. The computational methods of these rasters will not be explained here since they are standard procedures using the GIS software.

b) DEM application in the TOPKAPI Model

As mentioned in Section 3.3.2, it was desirous to model the Liebenbergsvlei catchment using a 1km grid cell resolution. To accurately achieve this, the 218m square pixels of the 200m DEM were transformed to 1000m (1km) square pixels. This was achieved using an inbuilt function on ArcGIS called "resample". The result of this is shown in Figure 3.15 (on the right). The 1000m resampled DEM shown in Figure 3.15 (from here on referred to as the 1km DEM) has been processed for sinks. The "resample" function has the option of three interpolation techniques, i.e. nearest neighbour assignment, bilinear interpolation and cubic convolution. Nearest neighbour assignment uses the closest value from the cell on the input raster to assign to the new "resampled" cell on the output raster. It is appropriate for categorical data, such as landuse rasters. For continuous data, such as elevation rasters, the bilinear interpolation and cubic convolution techniques are preferred as they make use of a greater number of nearby cells (four and sixteen respectively) to compute the value of the new transformed cell. These techniques (bilinear and cubic) make use of a weighted average, based on distance from the centres of the input cells to the centre of the output cell, to compute the new "resampled" value. In this instance, the bilinear interpolation function was used to resample the 200m DEM into a 1km DEM as the cubic convolution method often gives values outside of the input range. The height range of the resampled 1km DEM can be seen to be less than the height range of the original 200m DEM. This is a result of the resampling function, but, as will be seen further on, it does not affect the delineation of the catchment boundaries and stream networks.

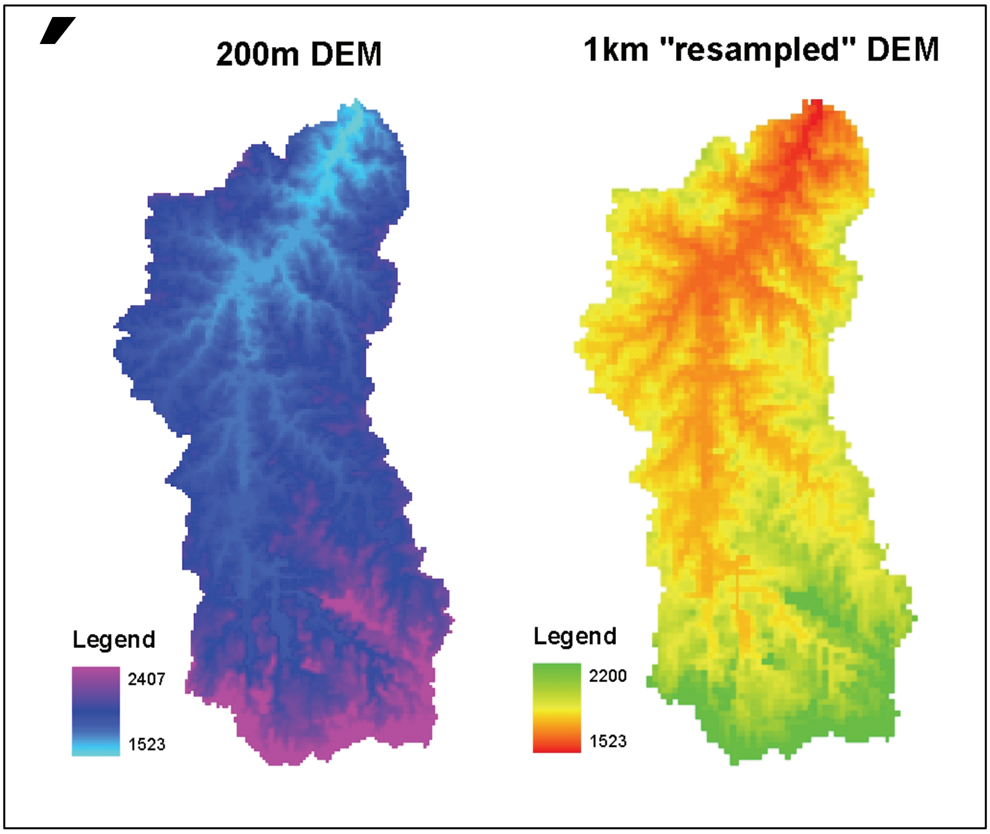


Figure 3.15 A 218m square pixel resolution DEM of the Liebenbergsvlei catchment is shown on the right (from DLSI, 1996). The pixels of this DEM were "resampled", using an inbuilt function on ArcGIS, to a resolution of 1000m square (shown on the left).

Once the 1km DEM was obtained, the topographical processes described in subsection (a) above were performed in order to obtain the desired input for the TOPKAPI model. These included the surface slope raster, the determination of the outflow direction of each cell and the computation of the stream networks and stream orders. However, the determination of the outflow direction of each cell required additional manipulation techniques outside the scope of the capabilities of ArcGIS. This was in regard to a specific requirement of the TOPKAPI model which was that the outflow path from each cell was to be limited to either a north, south, east or west direction. Thus the *D8 flow model* of ArcGIS was not suitable for the determination of the flow direction raster for input into the model. Therefore, further manipulation was required with regard to this aspect of the research and is detailed below.

i) Flow direction and flow accumulation

A flow direction raster computes the direction of flow from each cell in the catchment. This is an important aspect of catchment modelling as it determines the connectivity between cells and is the first step in tracing the stream network. On the ArcGIS platform, the flow directions of each cell are determined based on the D8 method, i.e. flow is assigned in one of eight directions from an active cell. The TOPKAPI model operates on the four cardinal directions only, in such a manner that an active cell may receive flow from three upstream cells and may only have one outflow direction to a downstream cell. Since the flow direction function on ArcGIS operates on the D8 method, it was necessary to create a "D4" flow direction function which would be compatible with the TOPKAPI's requirements.

It was decided that the simplest manner in which to produce a D4 flow direction raster was to resolve the four diagonal directions of a D8 flow direction raster into the four cardinal directions. This is shown in Figure 3.16, where the four diagonal direction codes (i.e. *128*, *2*, *8* and *32*) are resolved into direction codes *1*, *4*, *16* and *64*, while those cells that had direction codes reflecting the four cardinal directions from the original D8 raster were obviously left unchanged. The D8 flow direction raster for the Liebenbergsvlei catchment was produced using the GIS software ArcGIS. In order to resolve a diagonal direction into either a north/south or a east/west direction, three methods were tested. The first was to resolve the diagonal direction code toward that neighbouring vertical or horizontal direction that had the lowest elevation (based on a DEM), and hence toward that neighbouring direction of steepest slope. The second option was to arbitrarily resolve the diagonal directions in a clockwise manner. Referring to Figure 3.16 for example, direction code *128* would be resolved clockwise to direction code *1*; direction code *2* would be resolved to direction code *4*, and the rest of the codes would be resolved in this manner. The third option that was tested was to resolve the direction codes in an anti-clockwise manner. The resolving processes were accomplished through M-File Programming Functions that were written on MATLAB.

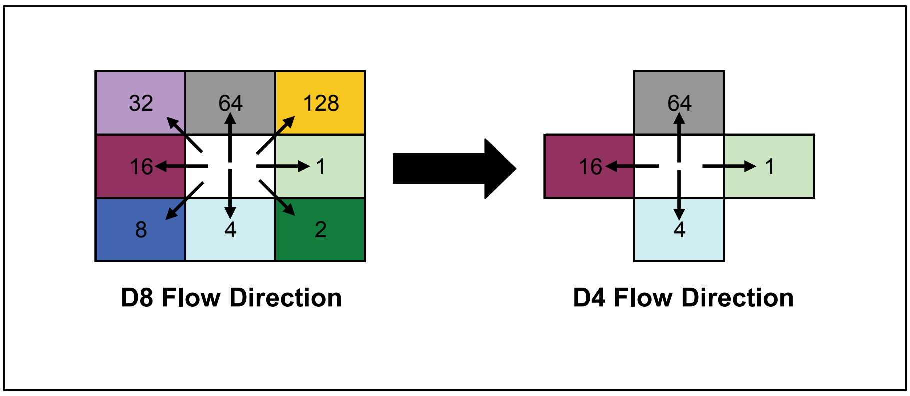


Figure 3.16 The D8 flow direction raster codes resolved into a D4 flow direction raster.

The results of all three tests had similar outcomes, in terms of the flow accumulation rasters that were produced. An example of the D4 flow direction raster of the Liebenbergsvlei catchment, output from the first test of this exercise (i.e. assigning the diagonal direction code toward that neighbouring vertical or horizontal direction that had the lowest elevation), is shown on the left of Figure 3.17. Intuitively, resolving of the direction codes based on lowest elevation makes more sense than resolving the codes arbitrarily in one direction, however, it is interesting to note that the different methods used had similar results. The resultant flow accumulation raster, from the new D4 flow direction raster, is shown on the right of Figure 3.17.

It is evident from Figure 3.17 that the flow accumulation raster is discontinuous and hence does not accurately reflect the flow paths and stream networks. Secondly, the total number of pixels, at a resolution of 1km square, that cover the Liebenbergsvlei catchment are 4625. This number should be reflected in the accumulation raster's legend at the catchment outlet since all cells of the catchment should contribute flow at this point. The number of cells shown is 1947 which indicates that all cells of the catchment are not contributing flow at the outlet. These points show that the process of resolving the D8 direction codes into the four cardinal direction codes had created areas of internal drainage within the catchment. These areas of internal drainage are sinks created artificially as a result of limiting the outflow drainage directions to four. This would not exist in the D8 flow direction model of this catchment since all sinks were previously filled based on the eight surrounding cells. This situation is visually explained in Figure 3.18, where the sinks were created as a result of anomalous positions of direction codes (based on the D4 method) that cause flow towards each other.

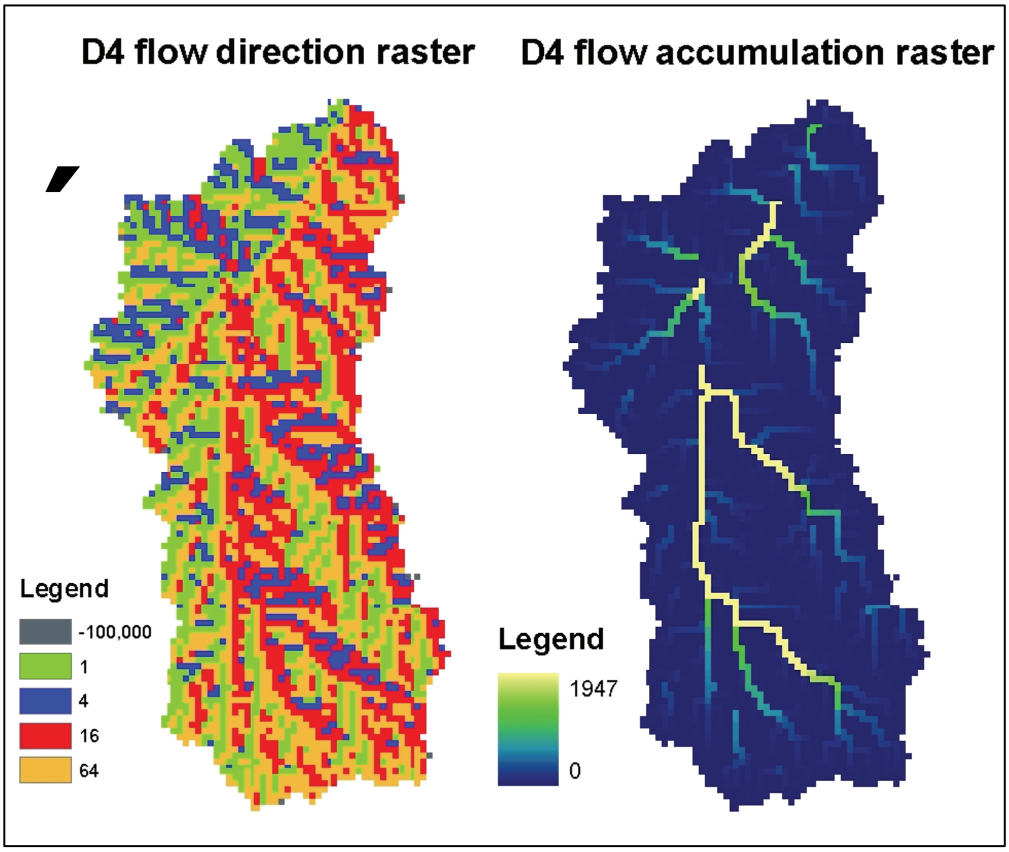


Figure 3.17 On the left is shown a D4 flow direction output as a result of resolving a D8 direction raster of the Liebenbergsvlei catchment into the four cardinal directions only. The legend of the direction raster show the four cardinal direction codes as well as an error code (*-100 000*) to mark those cells whose resolved directions flowed out of the catchment. On the right is shown the resulting flow accumulation raster based on the D4 method.

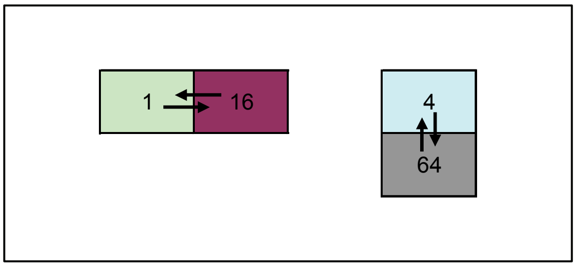


Figure 3.18 Anomalous positions for direction codes that resulted from the resolving of a D8 flow direction raster into a D4 raster. These pixels created areas of internal drainage within the catchment.

In order to solve this problem, further code was written in MATLAB to identify the “problem” pixels shown in Figure 3.18 as well as those pixels along the catchment boundary that flowed outwards. A “catchment mask”, which displayed the problem pixels, was then created on Microsoft Excel by importing the code’s output. The direction codes of the problem pixels were then easily rectified (by hand) based on this masking technique. The number of instances that required rectification was: 12 pixels that flowed outwards, 13 cases of pixels flowing toward each other in a north/south direction and 14 cases of pixels flowing toward each other in an east/west direction. The result of this can be seen in Figure 3.19, were the flow accumulation raster is shown on the left after manual checking of the direction codes was performed (in the manner explained above). The accumulation raster is overlain on the right of Figure 3.19 with the stream network traced from a topographic map (from Midgley et al., 1994) at spatial scale of 1:250 000.

The results shown in Figure 3.19 summarise, visually, that the processes explained above are able to trace the correct flow paths of the catchment based on a D4 method, which is a requirement of the TOPKAPI model. Secondly, the number of pixels that contribute flow to the catchment outlet is shown in the legend of Figure 3.19 as 4625. This number is in agreement with the number of pixels contained in the Liebenbergsvlei catchment at a resolution of 1km square.

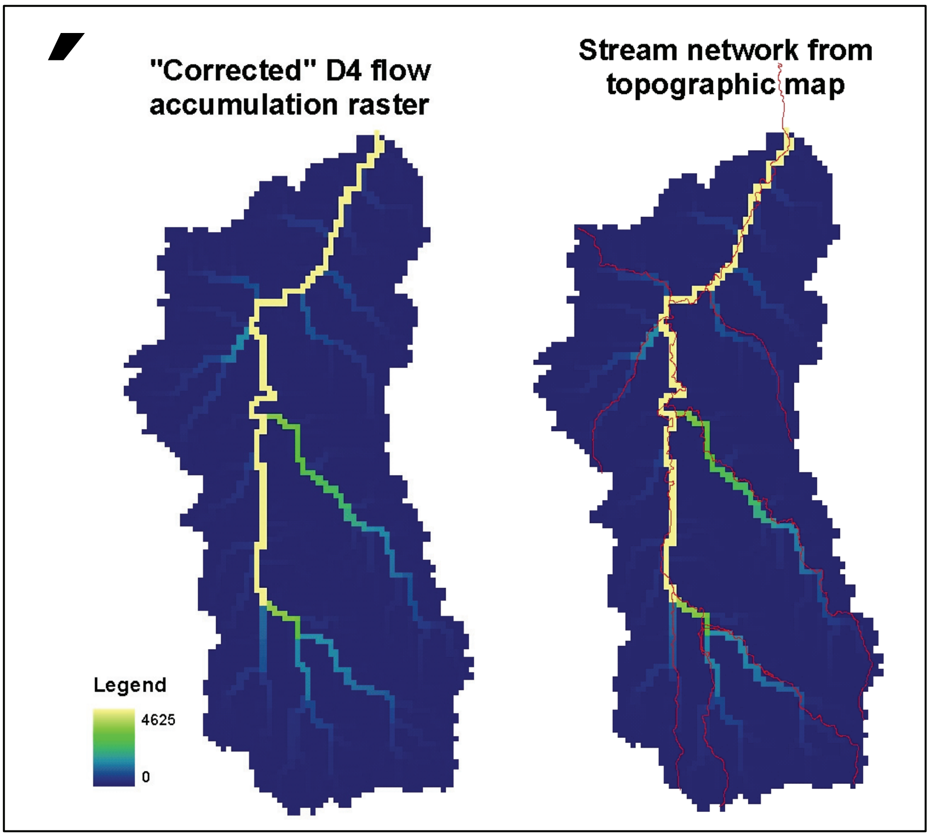


Figure 3.19 The "corrected" flow accumulation raster is shown on the left which is overlain on the right with a stream network (in red) traced from a topographic map (from Midgley et al., 1994) at a spatial scale of 1:250 000.

ii) Stream networks

The delineation of a catchment's stream network is important in catchment modelling as it determines which cells contain a channel and which do not. The pixels or grid cells of the catchment would then be modelled accordingly. In the TOPKAPI model, the surface flow of a cell that does not consist of a channel will be modelled with an overland store only. For a cell that does contain a channel, the surface flow will be modelled with both an overland store and a channel store and the flow within that cell would be partitioned between the two stores respectively.

The stream network delineation is made from the flow accumulation raster by assigning a threshold value to define the minimum number of upslope cells (or area) which are required to initiate a channel. Figure 3.20 shows the difference when stream networks were delineated using five different threshold values, i.e. 5, 10, 25, 50 and 65 pixels.

Since the pixel resolution of the flow accumulation raster used was 1km^2 (from Figure 3.19), these threshold values are equivalent to areas of 5, 10, 25, 50 and 65km^2 respectively. The drainage densities of the extracted networks are shown in Table 7-1; drainage density (in km^{-1}) is defined as the ratio of total stream length to total catchment area. Since the drainage direction of the flow accumulation raster is based on a D4 method, the total length of the stream network drained is equal to the number of channel pixels (based on the raster's resolution of 1km^2). This can be understood from the fact that the north/south or east/west distance across a cell is 1km given a raster resolution of 1km^2. This is shown in the third column in Table 7-1. The drainage density (column 4 in Table 7-1) is computed by dividing the total length of the stream network by the total catchment area, which is 4625 km^2 (from 4625 pixels in Figure 3.19).

	Threshold Area (km^2)	No. of channel Pixels (also *total stream length* in km)	Drainage Density (km^{-1})
Stream net. 5	5	1369	0.296
Stream net. 10	10	1061	0.229
Stream net. 25	25	712	0.154
Stream net. 50	50	539	0.117
Stream net. 65	65	455	0.0984

Table 7-1. The drainage densities of the extracted stream networks shown in Figure 3.17.

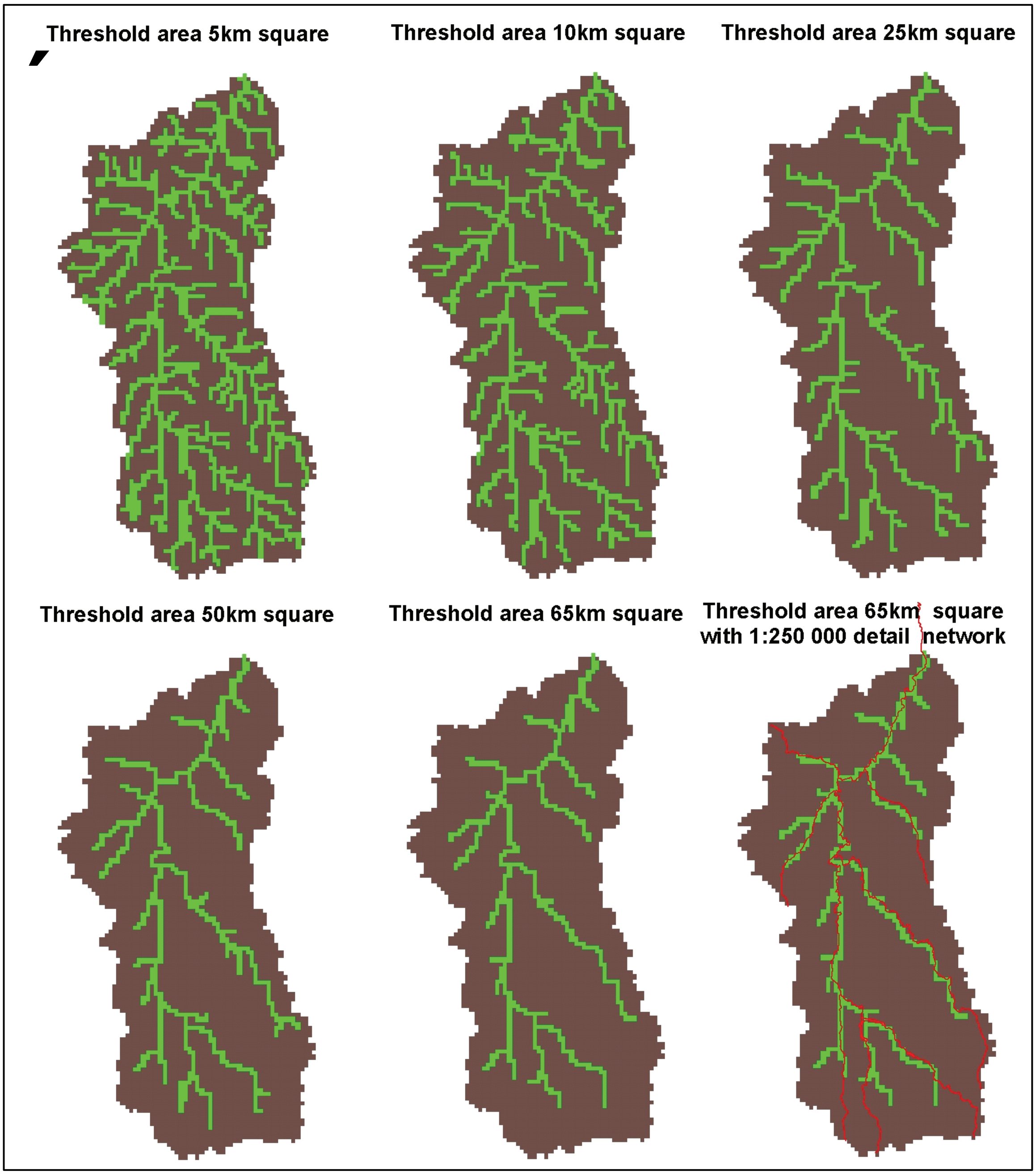


Figure 3.20 The stream networks delineated utilizing five different threshold areas, i.e. 5, 10, 25, 50 and 65km square, on ArcGIS. The superimposition of the 1:250 000 network (from Midgley et al., 1994) on the 65km square network is shown on the bottom right.

Tarboton et al. (1991) state that in "extracting channel networks from digital elevation models, it is important that the networks extracted be close to what traditional workers using maps or fieldwork would regard as channel networks". In their paper, Tarboton et al. present a rigorous method for the extraction of stream networks. They base their methods on the morphometric scaling properties of stream networks as discovered by Horton (1932, 1945), Strahler (1952, 1964) and others since. In particular, they make use of two properties, the constant drop property and the power law scaling property of slope with area, and suggest that the smallest threshold area that should be used be that area for which these scaling properties are still valid.

From Figure 3.17, it is evident, in this instance, that the stream network delineated using a threshold value of 65km^2 corresponds closely to the 1:250 000 detail network in terms of drainage densities (0.098 and 0.095 respectively). However, visually the 1:250 000 detail network does not display as many fingertip tributaries as the 65km^2 threshold network, while the latter network does not extend as far up as the 1:250 000 detail network. The possible reasons for this could be attributed to the season in which the stream network from the topographic map was traced, as some fingertip tributaries may be non-perennial.

In reality though, the 1:250 000 network is too coarse to be regarded as truly representative of the actual network that exists in the Liebenbergsvlei catchment. In order to simplify matters, the network extracted using a threshold area of 25km^2 was taken as representative of the catchment's actual network. According to Todini (2005), stream networks in reality only form about 5% to 10% of the catchments area and that the level of accuracy for this detail is not critical in the TOPKAPI model. The use of a 25km^2 threshold area gives a drainage density of approximately 15%.

3.3.4 Soils map

Figure 3.21 shows a vector-based soils map of South Africa (actually a landtype map with related soils properties) obtained from SIRI (1987). The different soils attributes of the map are represented by the different polygons, where the accuracy of the map (scale of detail) is 2,5km. In order for this map to be of use in this study, it was necessary to be able to identify the soil properties of each pixel. In order to accomplish this, the vector-based soils map of South Africa was converted into raster form using a tool in ArcGIS, called "Feature to Raster". A cell size of 1km square was specified so that the raster-based soils map would be compatible with the other input rasters. It is important to note that although the raster now has a resolution of 1km square, its accuracy is still at the scale at which it was mapped, i.e. 2.5km. A mask of the Liebenbergsvlei catchment was then used to clip the raster-based soils map for the area of interest. These are shown in Figure 3.21.

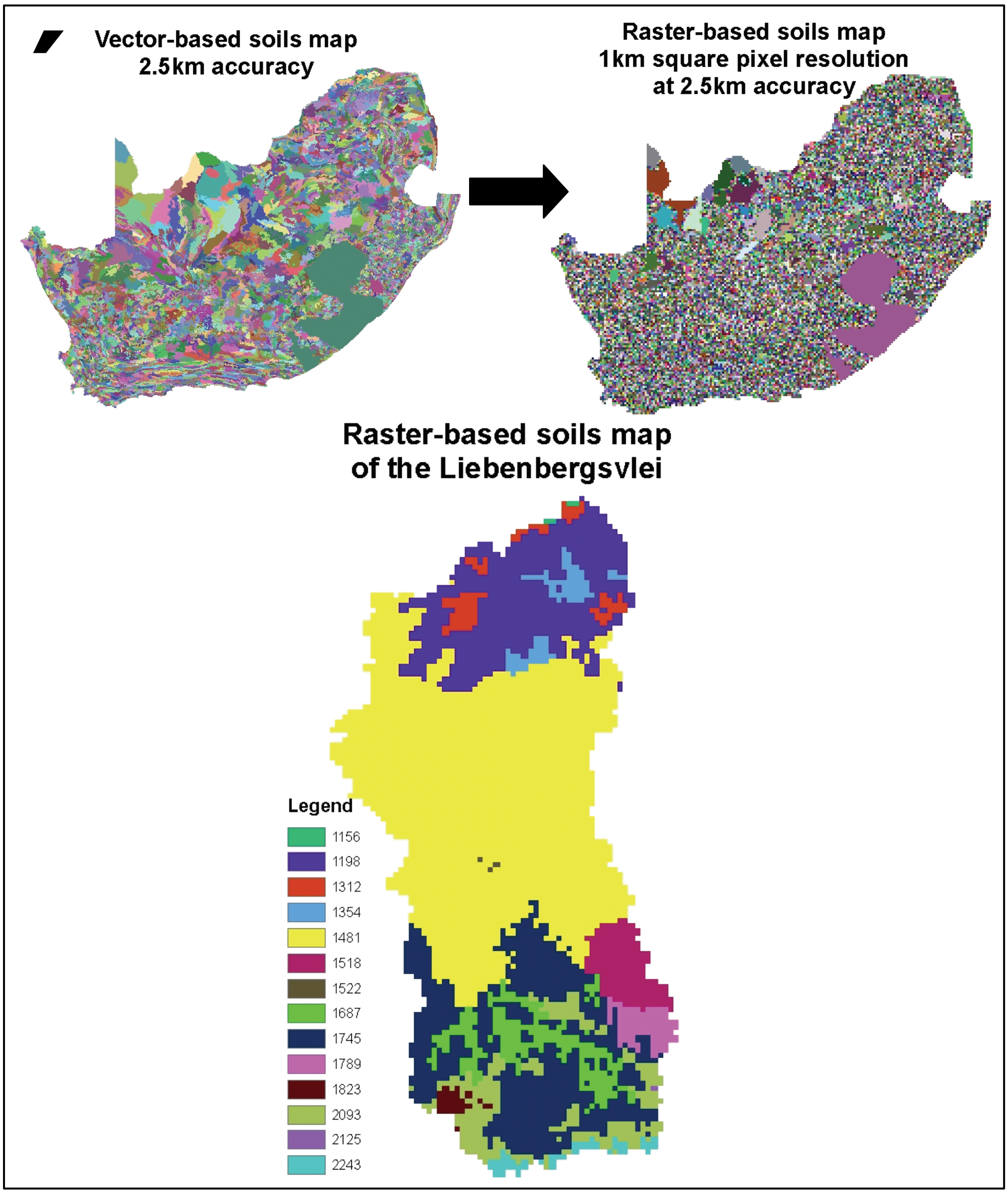


Figure 3.21 A vector-based soils map from SIRI (1987) was converted into a raster with a pixel resolution of 1km square from which the raster-based soils map of the Liebenbergsvlei catchment was clipped.

The legend of the soils map for the Liebenbergsvlei catchment identifies and displays a code, which has related soil properties, rather than actually identifying the soil type. The soil properties given there are inter alia, for both an upper top soil layer and a lower sub-soil layer, depth of layer, wilting point, field capacity, porosity and the saturated drainage rates.

The inputs required by the TOPKAPI model with regard to the soil store are the depth of the surface soil layer, saturated hydraulic conductivity, the saturated moisture content and the residual moisture content. Although the soils parameters related to the map do not explicitly give the latter three input parameters required by the model, it is possible that these may be inferred from the information given. Ideally, a soil types map would be able to identify the particular soil that is found in each pixel. Based on this identification, characteristic soils properties may be found from literature. However, the map used in this research is a landtype map with related soil properties. It is included in this document as it was the only map available at no cost, and for edifying purposes. However, it is felt that a map which identifies the soil type of each pixel would be better suited for the application of the model.

3.3.5 Landuse map

Landuse parameters are required so that Mannings' roughness coefficients may be inferred for, firstly, the hillslope surfaces and then the channel reaches. Figure 3.22 shows a raster-based image of the landuse for each pixel of the continent of Africa at a resolution of 1km square (GLCC, 1997), from which a map of the Liebenbergsvlei catchment may be masked out. This database is one part of a suite of global land cover characteristics (at a resolution of 1km) for all the continents of the world which are freely downloadable from the United States Geological Survey (USGS) website. The coverage characteristics represent averages thereby giving flexibility with regard to seasonal changes in land use.

The legend of the map identifies the landuse type of each pixel which in turn can be used to infer Manning's roughness coefficient for the hillslopes of a catchment. This input is required for the overland store of the TOPKAPI model. The landuse map for the Liebenbergsvlei catchments shows that the catchment's landuse consists predominantly of cropland and grassland. From Chow (1959: 108), typical values of n_o (the surface roughness coefficient) for this coverage type range from 0.020 to 0.050 $m^{-1/3}s$

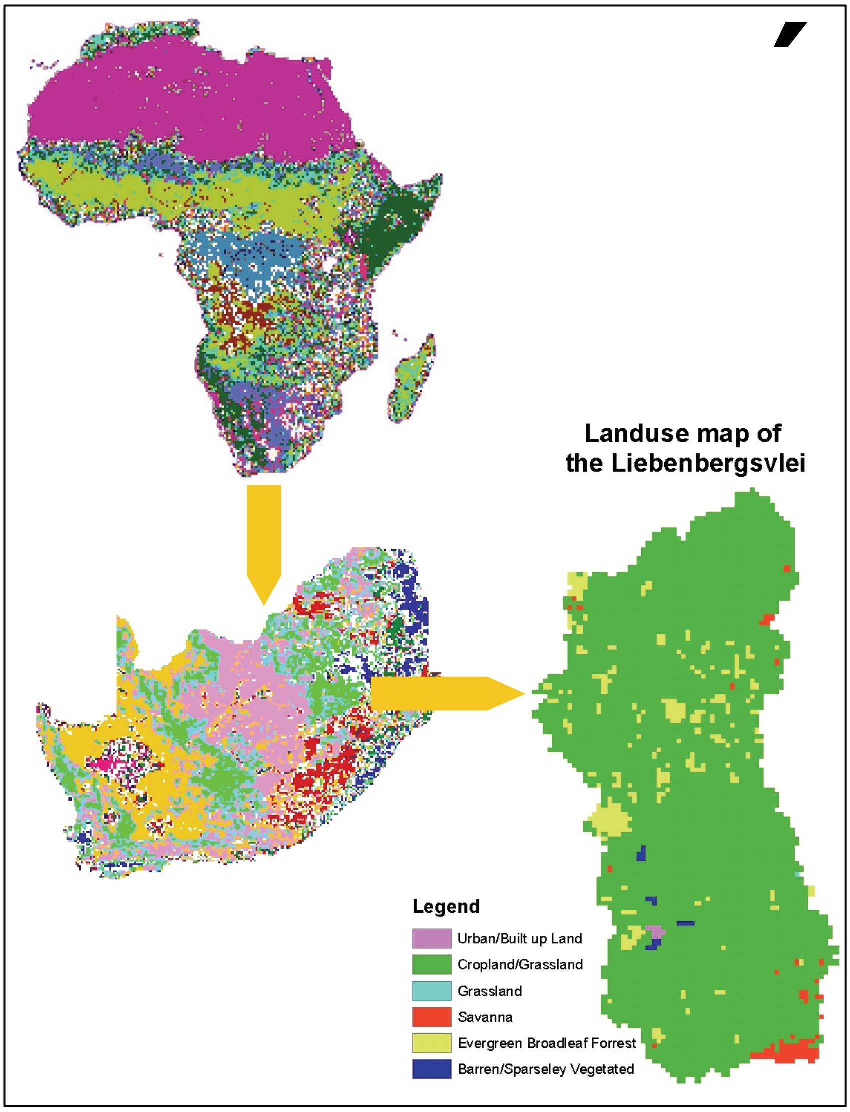


Figure 3.22 A landuse map of Africa, South Africa and the Liebenbergsvlei catchment, all at a pixel resolution of 1km square (GLCC, 1997).

Values of n_c, Manning's channel roughness coefficient, can be estimated from a priori knowledge of the channel reaches in the catchment, using literature such as Chow (1959) or Barnes (1967) for its estimation. If this is not known, the roughness coefficient of the channel reaches in each pixel can be estimated based on the channel order assigned to each reach using the ordering method of Strahler (1964).

3.3.6 Rainfall input

The TOPKAPI model requires distributed rainfall information in real-time for flood-forecasting purposes. The use of remote sensing techniques, such as satellite and radar estimates of distributed precipitation information, is ideal for this application since they provide precipitation estimates in fine spatial detail over a large area and the pixel format of these precipitation estimates is well-matched with the processing grid cells of the model. However there are errors associated with remotely sensed precipitation information and as such rain gauge estimates are used, in combination with the satellite and radar estimates, to condition a "best" merged estimate of real-time distributed precipitation. An example of such a combination technique employed locally is the

SIMAR (Spatial Interpolation and Mapping of Rainfall) project which was jointly undertaken between the South African Weather Service (SAWS) and the University of KwaZulu-Natal (UKZN) under a contract with the Water Research Commission (WRC). The merging process will not be covered here (consult - Kroese, 2004; Deyzel et al., 2004; Pegram, 2004; Pegram et al., 2006), but as a point of example, the attainment of real-time distributed radar estimates of rainfall for input into the model will be explained below (from the S-Band MRL5 weather radar covering the Liebenbergsvlei catchment).

Figure 3.23 shows an instantaneous CAPPI at 2km altitude above ground level (a.g.l.) deduced from a volume scan of radar reflectivity (dBZ), from which the rainfall for the Liebenbergsvlei catchment has been clipped out. The resolution of the rainfall estimate is 1km square. In order for these images to be used as input for the TOPKAPI model, it is worth knowing the rainfall at ground level that occurs over a finite time step (for example an hour). In order to accomplish this, the radar images are Kriged down to ground level from all 18 levels a.g.l. (at 1km vertical spacing) and accumulated over an hour (Pegram et al., 2006). Furthermore, the reflectivity values (in dBZ) are converted into rainfall intensities (in mm/hr) using the Marshall Palmer formula (Marshall and Palmer, 1948). The format of these rainfall estimates make it possible to input the rainfall intensities incident on each grid cell in each time step.

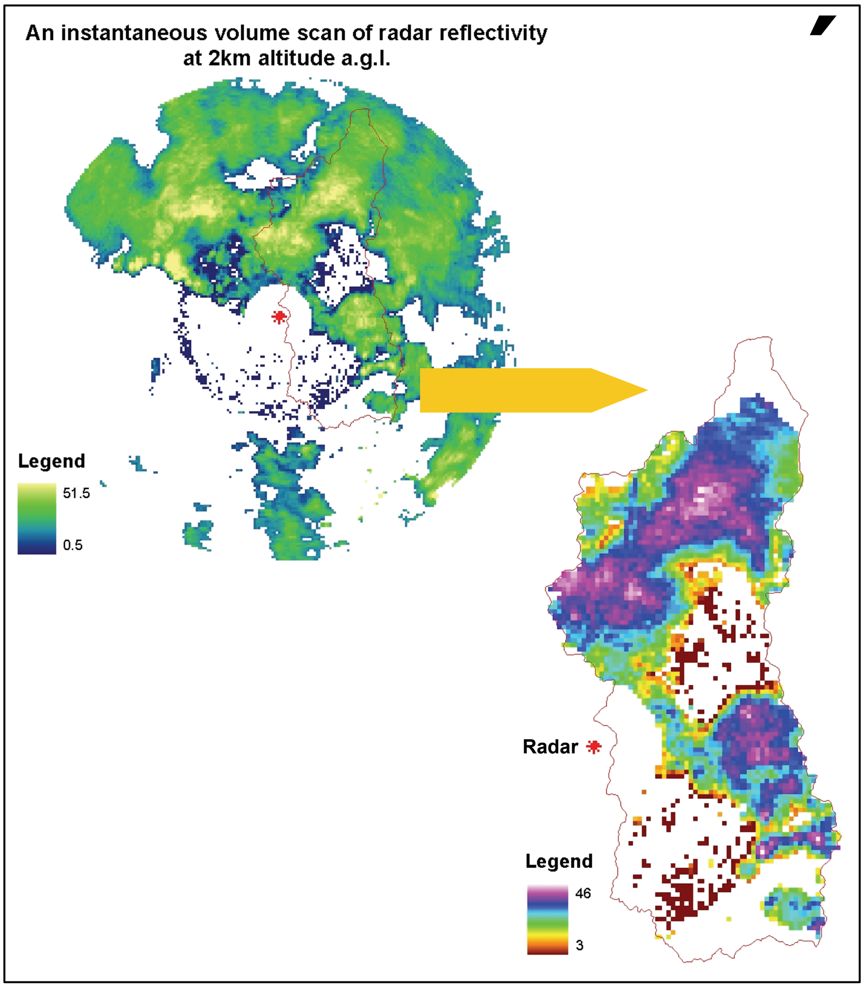


Figure 3.23 Radar reflectivity (dBZ) at 2km altitude above ground level (a.g.l.), from which the rainfall for the Liebenbergsvlei catchment has been clipped out. The resolution of the images is 1km square.

The radar relectivity map (Figure 3.23) comprises a 200 by 200 matrix at a resolution of 1km square, where the image origin is located at the radar centre (in Cartesian coordinates). In order for the rainfall image to be correctly aligned with the Liebenbergsvlei catchment on ArcGIS, which take its origins at the lower left corner, the radar image was given a new origin at the lower left corner by shifting it up and to the right by a distance equal to the radius of the image, i.e. 100km (100 000m in Cartesian coordinates). The rainfall estimate for the Liebenbergsvlei catchment could then be clipped out using a mask of the catchment.

3.3.7 Data alignment

In any work that involves geographically referenced data, it is important that the coordinate systems used are the same, especially when one uses data from different sources. Furthermore, it is also important that the cells of the data are correctly aligned so that the input data match the correct cell which is being modelled. All GIS work carried out in this research made use of the ArcGIS software. A brief explanation of how the data was managed and aligned follows below.

Firstly the combination of data from different sources involved the determination of the geographic coordinate system on which they were based. Secondly it was necessary to establish whether the data was projected or not. A geographic coordinate system (GCS) uses a three-dimensional spherical surface to define locations on the earth. Points on a GCS are referenced by their longitude (which run vertically around the earth) and latitude (which run horizontally around the earth) and are measured in degrees from the earth's centre. A projected coordinate system is defined on a flat two-dimensional surface where locations are identified by x-y coordinates on a grid. A projected coordinate system is always based on a GCS which has been converted (projected) using some method. The GCS adopted for mapping in South Africa at present is the WGS84 global ellipsoid while the projection system used (to cover a limited area of 2° longitude) is a Transverse Mercator Map. Figure 3.24 shows a screen capture of the geographic and projected coordinate system details, from ArcGIS, which has been used uniformly in this research to represent all data covering the extent of the Liebenbergsvlei catchment.

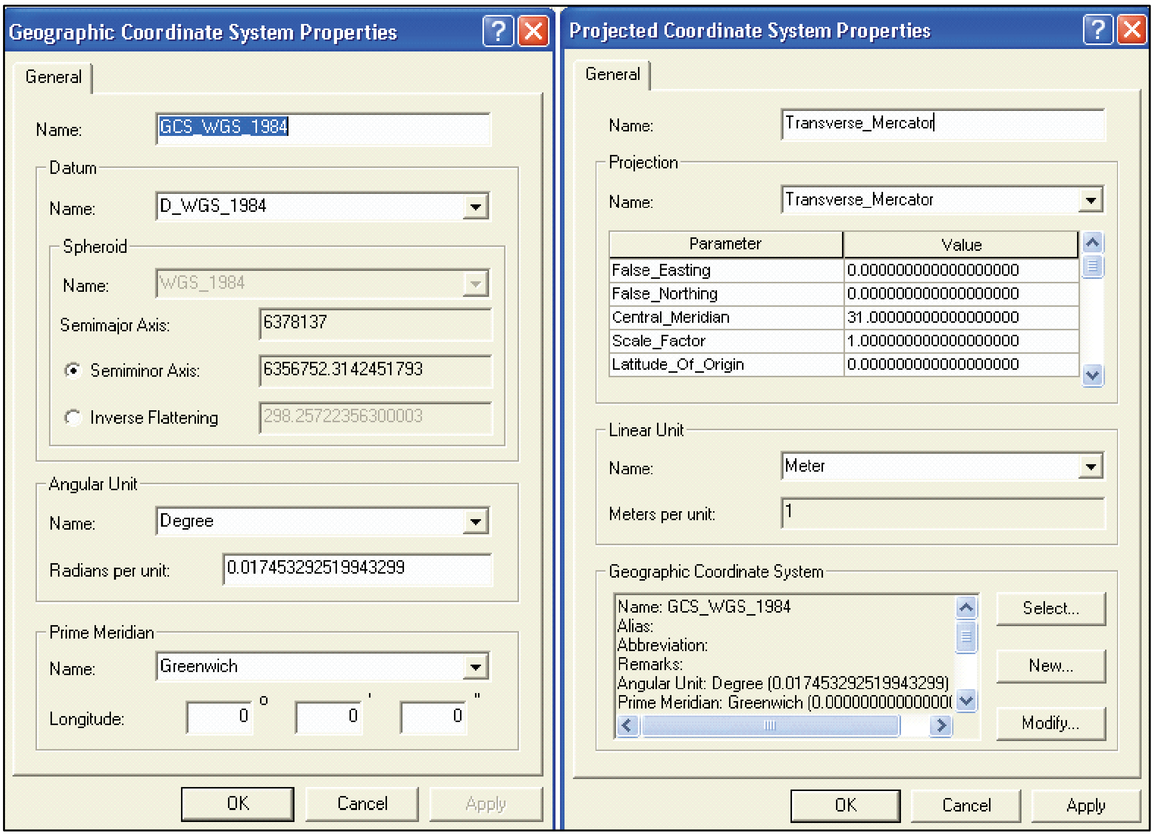


Figure 3.24 A screen capture of the geographic and projected coordinate system details, from ArcGIS, which has been used uniformly in this research to represent all data covering the extent of the Liebenbergsvlei catchment.

Furthermore, in order to align the data "pixel to pixel", a mask of the Liebenbergsvlei catchment representing a matrix of 62 columns and 121 rows at a resolution of 1km square was used to clip and extract all data. The mask was created from the DEM of the catchment and ensures that the clipped data, provided it is at the same resolution, has the same number of columns and rows and is originated at the same point (the lower left corner in ArcGIS). Figure 3.25 shows a screen capture of all the required input data in text-format. These data can be displayed in ArcGIS in raster-format, but are needed in text-format for input into a code to run the TOPKAPI model. It can be seen from Figure 3.25 that all the data have the same origin, number of columns and rows and the same cell size, all of which would ensure "pixel to pixel" alignment.

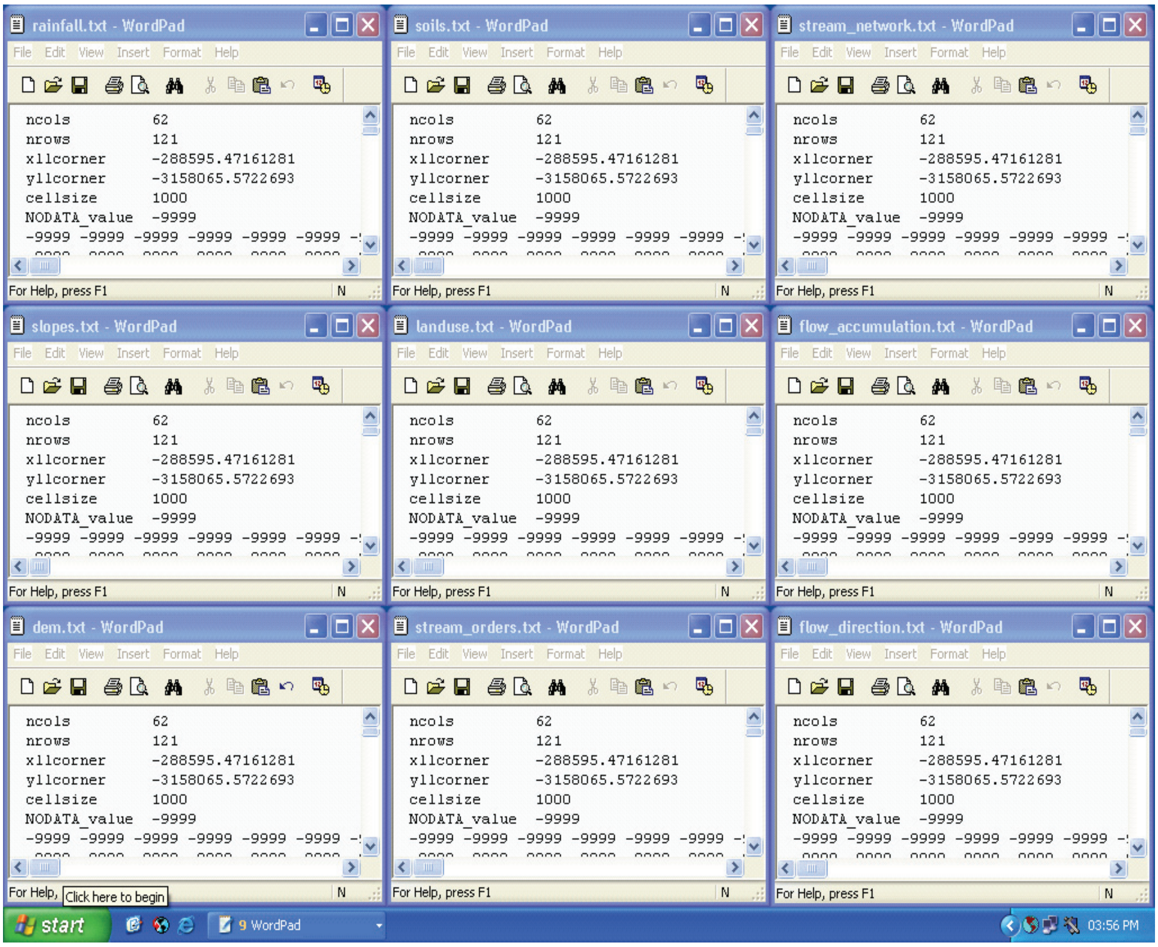


Figure 3.25 A screen capture of the headings of the files of all the input data, in text-format, which describe the properties of each pixel of the Liebenbergsvlei catchment, which is required by the TOPKAPI model. These data can be displayed in ArcGIS in raster-format. The figure shows that all the data consist of 62 columns, 121 rows, are aligned at the lower left corner in a projected coordinate system (see Figure 3.24) and are at a cell size resolution of 1000m square.

3.3.8 Calibration

The TOPKAPI model is a physically based model and as such all input parameters can be obtained directly from field measurements and related literature. This, in theory, requires no calibration. However, Liu and Todini (2002) suggest that the calibration of parameters is still necessary because of the uncertainty of the information on topography, soil characteristics and land cover and also because of the approximations introduced by the scale of the parameters representations. They maintain that the calibration of the model is “more an adjustment” and is achieved through simple trial and error methods. The parameters are calibrated on a continuous sequence of a selected portion of historical precipitation and flow data for the catchment. The parameters are adjusted such that the observed outflow from the catchment mimics the outflow simulated using the model.

3.4 Test application of the TOPKAPI model

The test application of the TOPKAPI model consisted of creating a four cell generic catchment together with establishing the intricate intra- and inter-cell operations. This test was simply created on a standard spreadsheet package using Microsoft Excel. It was hoped that this small-scale application of the TOPKAPI model would test our understanding of the model and form the basis for modelling an entire catchment using a programming language such as C++. This latter task is not accomplished in this research and is left for completion in a follow up study. Instead, the aim of this research was to lay the groundwork in preparation for the establishment of the TOPKAPI model as a fully-functioning real-time rainfall-runoff application for flood-forecasting purposes in the Liebenbergsvlei catchment.

The four cell generic catchment was imagined as follows: Cell 1 flows into Cell 2, which in turn flows into Cell 3, which in turn flows into Cell 4. Channel flow was only initiated in Cell 2 and thus Cells 3 and 4 had channel flow as well. In order to create the intra- and inter-cell operations of the test catchment, it was necessary to model the three fundamental components of the TOPKAPI model in each cell, i.e. the soil, overland and channel (except for Cell 1) stores respectively. The model was then run based on pulsed precipitation inputs (in each time step) and a simple continuity check was used to verify the operations of the test catchment. An explanation of how this was accomplished is detailed in the sub-sections that follow.

3.4.1 Input parameters

The initial values for the input parameters were arbitrarily chosen but were kept within the range of their expected values, which were suggested by Liu and Todini (2002). The initial parameters for each cell, together with their suggested range (shown in parentheses in the second column) are given below in Table 7-2. The parameters that remain unchanged for all the cells of a catchment are the horizontal dimensions of the grid cell, taken as 1000m, the time step, taken as 1 hour (3600s), the non-linear exponents α, which was taken as *3* for the soil stores and $^5/_3$ (from Manning's formula) for the overland and channel stores respectively, and the parameters related to the computation of the channel width (Equation 3.24).

Parameters		**Cell 1**	**Cell 2**	**Cell 3**	**Cell 4**
Soil Store					
Depth of surface soil layer (m)	L (0.1–2)	0.5	0.75	1.00	1.25
Saturated hydraulic conductivity ($m.s^{-1}$)	k_s (10^{-6}–10^{-3})	0.001	0.001	0.001	0.001
Surface Slope	$\tan\beta$	0.09	0.08	0.07	0.05
Residual soil moisture content	θ_r (0.01–0.1)	0.04	0.05	0.06	0.07
Saturated soil moisture content	θ_s (0.25–0.7)	0.45	0.50	0.55	0.60
Overland Store					
Manning's surface roughness coeff.	n_o (0.05–0.4)	0.1	0.2	0.3	0.4
Surface slope	$\tan\beta$	*same as for soil store*			
Channel Store					
Manning's channel roughness coeff.	n_c (0.02–0.08)	0.03	0.04	0.05	0.06
Surface slope	$\tan\beta$	*same as for soil store*			
Constant Parameters for all cells					
Horizontal dimension of cell (m)	X	1000			
Time step (s)	Δt	3600			
Non-linear soil exponent	α_s (2–4)	3			
Non-linear overland exponent	α_o	$^5/_3$			
Non-linear channel exponent	α_c	$^5/_3$			
Max. channel width at outlet (m)	W_{max}	10			
Min. channel width for $A_{threshold}$ (m)	W_{min}	1			
Area required to initiate channel (m^2)	$A_{threshold}$	1 000 000			
Total area drained by catchment (m^2)	A_{total}	4 000 000			
Area drained by i^{th} cell (m^2)	$A_{drained}$	$1x10^6$	$2x10^6$	$3x10^6$	$4x10^6$

Table 7-2. Input parameters chosen for the "four cell generic catchment" for the test application of the TOPKAPI model on Microsoft Excel. The suggested range of the parameters (Liu and Todini, 2002) is given in parentheses in the second column.

3.4.2 Soil store

The soil store of the TOPKAPI model is the regulating store of each cell. The operations of the soil store for the "four cell generic catchment" were formulated on Microsoft Excel as shown in Figure 3.26. An explanation of how some of the key functions of the soil store for Cell 1 operate in each column is listed after the figure.

Cell 1: Soil Store

L	0.5	m
k_s	0.001	$m.s^{-1}$
$\tan\beta$	0.09	
θ_r	0.04	
θ_s (porosity)	0.45	
V_{sm}	205000	m^3
C_s	0.005223	$m^{2-\alpha}/s$
$C_sX/X^{2\alpha}$	5.223E-18	m^3/s

1	2	3	4	5	6	7	8
Time Step	**Begin of Time Step** t_o **(s)**	Precipitation Input		Upstream Inflow $(1-\lambda.W/X).Q^u$ (m^3s^{-1})	Total Input (m^3s^{-1})	Moisture Stored @ t_o $V_s(t_o)$ (m^3)	Outflow @ t_o $Q_s(t_o) = (C_sX/X^{2a})V^{\alpha}$ (m^3s^{-1})
		p (mm/hr)	$p.X^2$ (m^3s^{-1})				
1	0	20	5.556		5.556	5000	0.00000
2	3600	20	5.556		5.556	15000	0.00002
3	7200	20	5.556		5.556	28723	0.00012
4	10800	20	5.556		5.556	44428	0.00046
5	14400	20	5.556		5.556	61242	0.00120
6	18000	20	5.556		5.556	78736	0.00255
7	21600	20	5.556		5.556	96677	0.00472
8	25200	20	5.556		5.556	114929	0.00793
9	28800	20	5.556		5.556	133405	0.01240
10	32400	20	5.556		5.556	152043	0.01836

9	10	11	12	13	14	15	16	17	18	19	20
Quasi-analytical solution to the non-linear differential reservoir equation for the soil store											
$u=y^{-(c-1)}$	$u^{c/(c-1)}$	Fitted parameters β	α	$y^c-\beta y^2+\alpha y=0$	A	B	C	p_1	p_2	$u(t+\Delta t)$	$y(t+\Delta t)$
4.000E-08	8.000E-12	5000	0	0	-55556	0	-1.880E-22	1.371E-11	-1.371E-11	4.444E-09	15000
4.444E-09	2.963E-13	15000	0	0	-166666	0	-6.268E-23	7.917E-12	-7.917E-12	1.212E-09	28723
1.212E-09	4.220E-14	28723	0	0	-319140	0	-3.273E-23	5.721E-12	-5.721E-12	5.066E-10	44428
5.066E-10	1.140E-14	44428	0	0	-493640	0	-2.116E-23	4.600E-12	-4.600E-12	2.666E-10	61242
2.666E-10	4.354E-15	61242	0	0	-680468	0	-1.535E-23	3.918E-12	-3.918E-12	1.613E-10	78736
1.613E-10	2.049E-15	78736	0	0	-874843	0	-1.194E-23	3.456E-12	-3.456E-12	1.070E-10	96677
1.070E-10	1.107E-15	96677	0	0	-1074190	0	-9.725E-24	3.119E-12	-3.119E-12	7.571E-11	114929
7.571E-11	6.587E-16	114929	0	0	-1276991	0	-8.181E-24	2.860E-12	-2.860E-12	5.619E-11	133405
5.619E-11	4.212E-16	133405	-8.77449E-22	0	-1482273	6.57735E-27	-7.048E-24	2.655E-12	-2.655E-12	4.326E-11	152043
4.326E-11	2.845E-16	152043	0	0	-1689369	0	-6.184E-24	2.487E-12	-2.487E-12	3.428E-11	170801

21	22	23	24	25	26	27
End of Time Step $t_1=t_o+\Delta t$ **(s)**	Intermediate Moisture St. $V'_s(t_1)$ (m^3)	Saturation Excess e_o (m^3)	Evapotrans Losses $E_a.X^2$ (m^3)	Actual Moisture St. $V_s(t_1)$ (m^3)	Outflow @ t_1 $Q_s(t_1) = (C_oX/X^{2a})V^{\alpha}$ (m^3s^{-1})	Avg. Outflow over Δt $Q_s(\Delta t)$ (m^3s^{-1})
3600	15000	0		15000	0.00002	9.141E-06
7200	28723	0		28723	0.00012	7.070E-05
10800	44428	0		44428	0.00046	2.909E-04
14400	61242	0		61242	0.00120	8.289E-04
18000	78736	0		78736	0.00255	1.875E-03
21600	96677	0		96677	0.00472	3.635E-03
25200	114929	0		114929	0.00793	6.325E-03
28800	133405	0		133405	0.01240	1.017E-02
32400	152043	0		152043	0.01836	1.538E-02
36000	170801	0		170801	0.02603	2.219E-02

Figure 3.26 The operations of the soil store of Cell 1 for the first ten time steps as modelled using Microsoft Excel.

- **Col. 1:** 75 time steps were created for this model which corresponds to a total storm duration of 75 hours (approximately 3 days).
- **Col. 6:** The total input in each time step is taken as the sum of the incident precipitation (lumped over the time step) and any contributions from the soil and overland stores of an upstream cell. This latter input is derived from the average outflow over the time step from the upstream cell. In this instance, Cell 1 is a source cell with no upstream contributors (and hence Col. 5 is blank), however it is worth noting the partitioning performed with regard to this input, i.e. the partitioning of flow to the channel of a channel cell and to the soil store of the next downstream cell. This is explained in Section 3.4.4.

- **Col 7:** The initial soil moisture stored was set at 5000m^3, which forms approximately 2.4% of the saturated moisture volume V_{sm} (which is 205 000m^3 for Cell 1). In Liu et al. (2005), the initial soil saturation percentage was set at the same value (0.9%) for all the cells of the Upper Xixian catchment (in China) when the calibration for the catchment was performed using the TOPKAPI model.
- **Col 8:** The sub-surface outflow at the beginning of the time interval is a function of the volume stored at the beginning of the time interval, which is computed from the outflow term of Equation 3.17, i.e. $Q_{s_1}(t_o) = \frac{C_{s_1} X}{X^{2\alpha_s}} V_{s_1}^{\alpha_s}$ $\left[m^3 s^{-1}\right]$.
- **Col. 9-20:** These columns are necessary to compute the quasi-analytical solution offered by Liu and Todini (2002), where *y* represents the volume term *V*, *c* the non-linear exponent α, *u* a substitution variable used for the integration and β and α (not to be confused with α from the non-linear exponent) are two variables fitted so as to approximate the non-linear term y^c with a second order polynomial $\beta y^2 + \alpha y$. The variables β and α were fitted by solving the equation $y^c - \beta y^2 + \alpha y = 0$ by iterating β and α such that $\beta = \frac{y^c + \alpha y}{y^2}$ and $\alpha = \frac{\beta y^2 - y^c}{y}$. The solution of this equation is shown in Col. 13 and the variables were fitted in each time step by activating the *iteration* function on Microsoft Excel. Cols. 14-18 are used as intermediary steps to compute *u* (Col. 19) at the end of the time step, i.e. at $t_1 = t_o + \Delta t$. This parameter (*u*) is then back substituted to obtain, in Col. 20, $y(t_o + \Delta t)$ which is the solution of the non-linear soil reservoir equation.
- **Col. 22:** The intermediate moisture storage $V'_s(t_1)$ is the solution of the non-linear reservoir equation for the soil store and is equal to Col. 20 when input is greater than zero. When input equals zero while there is moisture stored in the soil store at the beginning of the time interval, the non-linear differential reservoir equation for the soil store reduces to a decay function and the intermediate moisture storage at the end of the time is computed from equation 3.45. When input and initial moisture storage, $V_s(t_o)$, equals zero at the beginning of the time interval, $V'_s(t_1) = 0$. These switches are achieved using two *if statements* imbedded in each cell of this column on Microsoft Excel.
- **Col. 23:** Saturation excess is the input to the overland store and is activated upon the saturation of the soil store, i.e. when $V'_s(t_1) \geq V_{sm}$. It is taken as an average excess given off during the time step and becomes the input for the overland store of that time step. The switch for this is also achieved using an *if statement*.
- **Col. 24:** Evapotranspiration losses are subtracted as a lumped loss at the end of the time step from the intermediate soil storage. In this exercise, a suitable method to compute this amount has not been implemented and hence the column is blank.
- **Col. 25:** The actual moisture storage at the end of the time step $V_s(t_1)$ results from the subtraction of the saturation excess and evapotranspiration losses from the intermediate moisture storage $V'_s(t_1)$.

- **Col. 26:** The sub-surface outflow at the end of the time interval is a function of the volume stored at the end of the time interval, which is computed from the outflow term of equation 3.17, i.e. $Q_{s_1}(t_1) = \frac{C_{s_1} X}{X^{2\alpha_s}} V_{s_1}^{\alpha_s} \qquad \left[\mathrm{m^3 s^{-1}}\right]$.
- **Col. 27:** The average sub-surface outflow over the time interval Δt is computed simply from the average of the outflow at the beginning of the time interval and the end of the time interval, i.e. the average of Col. 8 and 26. This then becomes the input, for that time step, for the soil store of the downstream cell. If a channel exists in this cell, then the average sub-surface outflow would need to be partitioned between the channel component of the cell and the soil store of the next downstream cell.

3.4.3 Overland store

The operations of the overland store for Cell 1 are shown below in Figure 3.27. The time steps shown are from *time step 1* onwards. However it should be noticed that the overland store is only activated when the soil store becomes saturated during *time step 12*. Initially, it is assumed that there is no water stored on the surface slopes and hence the initial volume is zero. An explanation of how some of the columns operate in modelling the overland store of Cell 1 is listed after Figure 3.27. Explanations of those columns that are not given were deemed to be self-explanatory or have been covered in Section 3.4.2.

Cell 1: Overland Store

n_o	0.1
$\tan\beta$	0.09
C_o	3
$C_oX/(X)^{2\alpha}$	0.0000003

1	2	3	4	5	6	7
Time Step	Begin of Time Step t_o (secs)	End of Time Step $t_o+\Delta t$ (secs)	Saturation Excess e_o (m^3)	Overland Input $r_oX^2=e_o/\Delta t$ (m^3s^{-1})	Moisture Stored @ t_0 $V_0(t)$ (m^3)	Outflow @ t_0 $Q_o(t_0)$ = $(C_oX/X^{2a})V^\alpha$ (m^3s^{-1})
1	0	3600	0	0	0	0.0000
2	3600	7200	0	0	0	0.0000
3	7200	10800	0	0	0	0.0000
4	10800	14400	0	0	0	0.0000
5	14400	18000	0	0	0	0.0000
6	18000	21600	0	0	0	0.0000
7	21600	25200	0	0	0	0.0000
8	25200	28800	0	0	0	0.0000
9	28800	32400	0	0	0	0.0000
10	32400	36000	0	0	0	0.0000
11	36000	39600	0	0	0	0.0000
12	39600	43200	3546	0.984902202	0	0.0000
13	43200	46800	18931	5.258498936	1741	0.0756
14	46800	50400	18931	5.258498936	12930	2.1370
15	50400	54000	18931	5.258498936	18940	4.0374

8	9	10	11	12	13	14	15	16	17
Quasi-analytical solution to the non-linear differential reservoir equation for the overland store									
	Fitted parameters								
y^c	β	α	$y^c-\beta y^2+\alpha y=0$	A	B	C	p_1	p_2	$y(t+\Delta t)$
0.000E+00	1	0	0	-0.0000003	0	0	0.00	0.00	#DIV/0!
0.000E+00	1	0	0	-0.0000003	0	0	0.00	0.00	#DIV/0!
0.000E+00	1	0	0	-0.0000003	0	0	0.00	0.00	#DIV/0!
0.000E+00	1	0	0	-0.0000003	0	0	0.00	0.00	#DIV/0!
0.000E+00	1	0	0	-0.0000003	0	0	0.00	0.00	#DIV/0!
0.000E+00	1	0	0	-0.0000003	0	0	0.00	0.00	#DIV/0!
0.000E+00	1	0	0	-0.0000003	0	0	0.00	0.00	#DIV/0!
0.000E+00	1	0	0	-0.0000003	0	0	0.00	0.00	#DIV/0!
0.000E+00	1	0	0	-0.0000003	0	0	0.00	0.00	#DIV/0!
0.000E+00	1	0	0	-0.0000003	0	0	0.00	0.00	#DIV/0!
0.000E+00	1	0	0	-0.0000003	0	0	0.00	0.00	#DIV/0!
0.000E+00	1	0	0	-0.0000003	0	-3283007.339	1811.91	-1811.91	1741
2.520E+05	0.083125877	0	0	-2.49378E-08	0	-210864901.6	14521.19	-14521.19	12930
7.123E+06	0.042605117	0	0	-1.27815E-08	0	-411413723.9	20283.34	-20283.34	18940
1.346E+07	0.037514825	-2.95026E-13	1.11759E-08	-1.12544E-08	-7.86425E-12	-467237408.3	21615.68	-21615.68	21127

18	19	20	21
End of Time Step $t_1=t_o+\Delta t$ (secs)	Moisture Storage @ t_1 $V_o(t_1)$ (m^3)	Outflow @ t_1 $Q_s(t_1)$ = $(C_oX/X^{2a})V^\alpha$ (m^3s^{-1})	Avg. Outflow over Δt $Q_s(\Delta t)$ (m^3s^{-1})
3600	0	0.0000	0.0000
7200	0	0.0000	0.0000
10800	0	0.0000	0.0000
14400	0	0.0000	0.0000
18000	0	0.0000	0.0000
21600	0	0.0000	0.0000
25200	0	0.0000	0.0000
28800	0	0.0000	0.0000
32400	0	0.0000	0.0000
36000	0	0.0000	0.0000
39600	0	0.0000	0.0000
43200	1741	0.0756	0.0378
46800	12930	2.1370	1.1063
50400	18940	4.0374	3.0872
54000	21127	4.8436	4.4405

Figure 3.27 The operations of the overland store for Cell 1 as modelled on Microsoft Excel.

- **Col. 3:** This is the input into the overland store and results from the saturation of the soil store of Cell 1. Saturation excess from the soil store is computed at the end of each time step, but it is taken as having being exfiltrated during that time step and so becomes the input for the overland store for that time step.

- **Col. 7-16:** These columns compute the quasi-analytical solution to the non-linear differential reservoir equation for the overland store. The explanations of these are similar to those given in section 3.4.2 except that in this instance a substitution variable (for the integration) is not used. For certain time steps in Col. 16, results of *#DIV/0!* are returned by Microsoft Excel because for these time steps the initial volume stored on the surface and the overland input are zero. This does not effect the final result (as seen in Col. 18) since these are still intermediary steps.
- **Col. 18:** This column records the moisture storage at the end of the time step. If the input into the overland store at the beginning of the time step is greater than zero, the value that Col. 18 takes on is equivalent to Col. 16, which is computed using the quasi-analytical solution calculated in columns 7-16. If input and moisture storage at the beginning of the time interval is zero, then the moisture storage at t_1 is zero. However, if the input is zero while there is still moisture stored on the surface at the beginning of the time interval, then the non-linear differential reservoir equation for the overland store reduces to a decay function and the moisture storage at the end of the time interval is computed from equation 3.45.
- **Col. 20:** The average overland outflow over the time interval Δt is computed simply from the average of the outflow at the beginning of the time interval and the end of the time interval, i.e. the average of Col. 6 and 19. This then becomes the input, for that time step, for the soil store of the downstream cell. If a channel exists in this cell, then the average overland outflow would need to be partitioned along with the sub-surface outflow between the channel component of the cell and the soil store of the next downstream cell.

3.4.4 Flow partitioning

Flow partitioning is necessary to split the average outflow from the soil and overland store of a cell between the channel of that cell and the soil store of the next cell downstream cell. This split is proportional to the ratio of the width of the channel of Cell *i* (W_i) to the overall width of the cell. This is seen in section 3.4.2, where the upstream contribution to the soil store of Cell 1 (Col. 5 in Figure 3.24) has been partitioned using the following proportion $\left(1-\lambda\frac{W_i}{X}\right)$. The addition of an extra parameter λ was made in order to create a switch which could either activate or deactivate the channel store of a cell and regulate the amount of flow into it (and hence the flow to the downstream cell as well). This switch is explained in Table 7-3 below.

λ	**Flow to channel** $(\lambda \cdot {}^W/_X)\cdot Q$	**Flow to next cell** $(1-\lambda \cdot {}^W/_X)\cdot Q$
0	0	Q
1	${}^W/_X \cdot Q$	$(1-{}^W/_X)\cdot Q$
${}^X/_W$	Q	0

Table 7-3. The range of values that λ can take when regulating the flow Q to the channel of a cell and to the downstream cell.

It is evident from Table 7-3 that the range of λ is from *0* to $^X/_W$. If λ=*0*, all flow from the soil and overland store of a cell progress to the soil store of the downstream cell (and hence a channel does not exist for that cell). If λ= $^X/_W$, all flow from the soil and overland store of a cell progress to the channel of that cell. This latter scenario can be imagined at the outlet of a catchment where all the outflows from all the stores of a catchment come together.

It was further felt that this value (λ) could be used to either increase or decrease the amount of flow feeding a channel, since in reality the proportion equivalent to $^W/_X$ is very small. In Liu et al. (2005), the values of W_{min} and W_{max} that were chosen for the Upper Xixian catchment (with an area of approximately 10 000km^2) was 1m and 400m respectively. At the 1km square modelling resolution, this forms a partitioning proportion of approximately 0.1% at the point of channel initiation and 40% at the catchment outlet respectively. However, according to Todini (2005), the amount of channel cells in a catchment are approximately 5 to 10% of the total number of cells in a catchment. Thus the use of λ as a tool to increase the proportion of flow to a channel does not make a big difference in the overall modelling of the catchment processes and resultant outflow from the catchment. Hence, for this exercise, the use of λ was limited to a switch and would not take on other values besides *0*, *1* and $^W/_X$.

Figure 3.28 shows the flow partitioning performed for Cell 1 of the "four cell generic catchment". In this case, the width of the channel was computed to be 1m (from equation 3.24, using the parameters given in Table 7-2 above) and λ was set at *0* since Cell 1 does not consist of a channel. The flow that feeds the channel (Col. 8) comprises the sum of the average outflows from the soil and the overland store of that cell (Col. 4 and 5 respectively), which is partitioned in the manner explained above. The remainder feeds the soil store of the downstream cell (Col. 7).

Cell 1: Flow partitioning

W_{max}	10	m
W_{min}	1	m
$A_{threshold}$	1000000	m^2
A_{total}	4000000	m^2
$A_{drained}$	1000000	m^2
W	1	m
λ	0	

1	2	3	4	5	6	7	8
Time Step	Begin of Time Step t_o (secs)	End of Time Step $t_o+\Delta t$ (secs)	Avg. Soil Outflow over Δt $Q_s(\Delta t)$ (m^3s^{-1})	Avg. Overland Outflow over Δt $Q_o(\Delta t)$ (m^3s^{-1})	Total Avg. Outflow over Δt (m^3s^{-1})	Flow to next cell $(1-\lambda.W/X).(Q_s+Q_o)$ (m^3s^{-1})	Flow to channel $(\lambda.W/X).(Q_s+Q_o)$ (m^3s^{-1})
1	0	3600	0.00001	0.0000	9.141E-06	9.141E-06	0.000E+00
2	3600	7200	0.00007	0.0000	7.070E-05	7.070E-05	0.000E+00
3	7200	10800	0.00029	0.0000	2.909E-04	2.909E-04	0.000E+00
4	10800	14400	0.00083	0.0000	8.289E-04	8.289E-04	0.000E+00
5	14400	18000	0.00187	0.0000	1.875E-03	1.875E-03	0.000E+00
6	18000	21600	0.00363	0.0000	3.635E-03	3.635E-03	0.000E+00
7	21600	25200	0.00632	0.0000	6.325E-03	6.325E-03	0.000E+00
8	25200	28800	0.01017	0.0000	1.017E-02	1.017E-02	0.000E+00
9	28800	32400	0.01538	0.0000	1.538E-02	1.538E-02	0.000E+00
10	32400	36000	0.02219	0.0000	2.219E-02	2.219E-02	0.000E+00

Figure 3.28 The flow partitioning operations of Cell 1, where flow is partitioned between the channel store of Cell 1 and the soil store of the downstream cell, i.e. Cell 2.

3.4.5 Channel store

Figure 3.29 below shows the channel store for Cell 2 of the "four cell generic catchment", since Cell 1 did not consist of a channel. An explanation of how some of the columns operate in modelling this store of Cell 2 is listed after Figure 3.29. Explanations of those columns that are not given below were deemed to be self-explanatory or have been covered in the previous sections.

Cell 2: Channel Store

n_c	0.04
$\tan\beta$	0.08
C_c	7.071067812
$C_cW/(XW)^{\alpha}$	2.51018E-05

1	2	3	4	5	6	7
Time Step	Begin of Time Step t_o (secs)	Input from cell $r_cXW = (\lambda.W/X).(Q_s+Q_o)$ (m^3s^{-1})	Upstream Channel Input Q_c^u (m^3s^{-1})	Total Input (m^3s^{-1})	Moisture Stored @ t_0 $V_c(t_0)$ (m^3)	Outflow @ t_0 $Q_c(t_0) = (C_cW/(XW)^{\alpha})V^{\alpha}$ (m^3s^{-1})
1	0	3.033E-08	0	3.03344E-08	22.35	0.00445
2	3600	1.778E-07	0	1.778E-07	13	0.00181
3	7200	6.253E-07	0	6.25252E-07	9	0.00092
4	10800	1.617E-06	0	1.61715E-06	6	0.00054
5	14400	3.433E-06	0	3.43286E-06	5	0.00034
6	18000	6.372E-06	0	6.37161E-06	4	0.00024
7	21600	1.075E-05	0	1.07453E-05	3	0.00017
8	25200	1.687E-05	0	1.68748E-05	3	0.00013
9	28800	2.509E-05	0	2.50885E-05	2	0.00010
10	32400	3.572E-05	0	3.57213E-05	2	0.00009

8	9	10	11	12	13	14	15	16	17
Quasi-analytical solution to the non-linear differential equation for the channel store									
	Fitted parameters								
y^c	β	α	$y^c-\beta y^2+\alpha y=0$	A	B	C	p_1	p_2	$y(t+\Delta t)$
1.774E+02	0.354993004	0	0	-8.91096E-06	0	-0.003404168	0.06	-0.06	13
7.204E+01	0.425091617	0	0	-1.06706E-05	0	-0.016659399	0.13	-0.13	9
3.665E+01	0.486609002	0	0	-1.22148E-05	0	-0.051188217	0.23	-0.23	6
2.139E+01	0.541924701	-1.69628E-15	2.13163E-14	-1.36033E-05	-3.13011E-15	-0.118879594	0.34	-0.34	5
1.370E+01	0.592431093	0	0	-1.48711E-05	0	-0.230841066	0.48	-0.48	4
9.394E+00	0.638890001	0	0	-1.60373E-05	0	-0.397299729	0.63	-0.63	3
6.800E+00	0.681557972	-2.81196E-16	1.77636E-15	-1.71083E-05	-4.12578E-16	-0.628072652	0.79	-0.79	3
5.161E+00	0.720205607	0	0	-1.80785E-05	0	-0.933419833	0.97	-0.97	2
4.100E+00	0.754107981	0	0	-1.89295E-05	0	-1.325365335	1.15	-1.15	2
3.418E+00	0.782081652	0	0	-1.96317E-05	0	-1.81957464	1.35	-1.35	2

18	19	20	21
End of Time Step $t_1=t_o+\Delta t$ (secs)	Moisture Storage @ t_1 $V_c(t_1)$ (m^3)	Outflow @ t_1 $Q_c(t_1) = (C_cW/(XW)^{\alpha})V^{\alpha}$ (m^3s^{-1})	Avg. Outflow over Δt $Q_c(\Delta t)$ (m^3s^{-1})
3600	13	0.00181	0.003130455
7200	9	0.00092	0.001364212
10800	6	0.00054	0.000728539
14400	5	0.00034	0.000440505
18000	4	0.00024	0.000289891
21600	3	0.00017	0.00020325
25200	3	0.00013	0.000150114
28800	2	0.00010	0.000116237
32400	2	0.00009	9.43602E-05
36000	2	0.00008	8.05696E-05

Figure 3.29 The operations of the channel store of Cell 2 as modelled on Microsoft Excel.

- **Col. 5:** The total input for this store results from the partitioning exercise, the result of which is shown in Col. 3, and from an upstream channel outflow (Q_c^u shown in Col. 4). This latter input is the result of the average outflow over Δt from a channel in an upstream cell. Since Cell 1 does not consist of a channel and channel flow is only initiated in Cell 2, this latter input (shown in Col. 4) is zero.

- **Col. 6:** The depth of water in a channel reach is taken to increase linearly with the channel width (Liu et al., 2005). For Cell 2, the channel width (computed from equation 3.24 using the parameters given in Table 7-2 above) is 4.728m. The depth of water was taken as 0.1% of the channel width which corresponds to an initial volume of 22.35m^3.
- **Col. 19:** The moisture stored in the channel at time t_1 is computed using the quasi-analytical solution (shown in columns 8-17) if the input and the moisture stored at the beginning of the time interval is greater than zero. If the input goes to zero while there still remains storage in the channel reach at the beginning of the time interval, than the non-linear differential equation reduces to a decay function for which the solution is given in equation 3.45. If the input and the moisture stored is zero at the beginning of the time interval, then the moisture stored at the end of the time interval remains zero.
- **Col. 21:** The channel outflow, to the channel of the next downstream cell, is computed as an average flow over the time interval. This becomes the input for the downstream cell in that interval. This value is computed by simply taking the average of the outflows at time t_0 and time t_1 (i.e. the average of Col. 7 and 20).

3.4.6 Running the model

The cells of the "four cell generic catchment" were run on Microsoft Excel using the spreadsheet setup explained in the above sections. In each time step, equal rainfall intensities for each cell were input into the soil store and the outflow from each store of each cell was individually modelled using the rainfall-runoff conversion parameters (for the soil store) and routing parameters (for the overland and channel stores), which are given in Table 7-2 above. In order to make certain that the correct setup of the model was implemented, a simple check was undertaken. This check was to ensure that *continuity* was maintained for the catchment as a whole, i.e. to ensure for all the cells that the overall input volume minus the output volume matched the volume that remained behind as storage within the various stores of the catchment. Since at this stage of the model's implementation there are no external moisture losses in the form of groundwater recharge or evapotranspiration, the continuity check was easy to quantify. The result of this exercise is described below and is shown together with a selection of hydrographs of which an explanation follows.

a) Continuity check

The precipitation input used was taken as the same for all cells and specifically chosen to exercise the model over plausible ranges of behaviour. It comprised of the following intensities over the 75 time steps: 20mm/hr for the first 25 time steps, thereafter 10mm/hr for the next 15 time steps, thereafter 5mm/hr for the next 20 time steps and finally 0mm/hr for the remaining 15 time steps. Thus the total input volume to each cell was 740 000m^3 (computed using the *trapezoidal rule*). Examining the volumes, there is a very small discrepancy (a factor of 1.004 of the volume of the input) between what should flow out of the soil store and what was calculated. On careful examination, it was found that the linearization of the non-linear storage equation in Section 3.2.7.(a) introduces a small error. This can be easily absorbed by the evaporation fraction once that has been introduced. The model has thus been successfully adapted to South African conditions.

3.4.7 Summary

This section laid the groundwork for the models implementation by, firstly showing how the data is prepared for input into the model, and then showing how the model works by imagining a small scale example of reality, i.e. the "four cell generic catchment".

The TOPKAPI model is to be used in a new WRC project: K5/1683: Soil Moisture from Satellites: Daily Maps over RSA, which commenced in April 2006. In that project, Soil Moisture (or more usefully a soil wetness index SWI) is to be estimated by three different methods: remote sensing, a network of soil moisture probes and by back-calculation using a distributed hydrological model. The hydrological model of choice in that study is the TOPKAPI model because the pixel resolution matches the data sources detailed above, and in addition, rainfall and SWI. It will be coded in a high level language enabling it to be easily assimilated as an application module in other hydrometeorological systems. The intention is to calibrate the TOPKAPI model on selected test catchments and compare the soil moisture estimates on a daily basis at the pixel scale.

The long term plan is to use this model as the hydrological model in the Flash Flood Guidance system to be acquired by SAWS, as described in Section 4.6 under "Implementation of a National Flood Warning System (NFWS)". It is appropriate to use this model, on catchments affecting the high hazard areas identified in Chapter 2, in the initial stages of the deployment of the NFWS.

4 Conclusion

4.1 A proposed flood forecasting system

The topography of South Africa can be thought of as a plateau bordered on the South and East by a coastal zone about 200 km wide rising to about 1000 m. This geography essentially divides the types of rainfall into: predominantly orographically forced at the coast and predominantly convective in the interior. The catchments in the steep coastal zones have fast response times and relatively heavy annual rainfall. The four major Metros and several other large municipalities on the coast therefore experience fairly frequent flooding and consequent damage. In the interior, the larger catchments are not much affected by convective rainfall, but are responsive to large meteorological systems such as tropical cyclones or cut-off lows which dump large quantities of water over several days. In the case of large catchments, the response times can be measured in days, which means that there is some useful warning time and where they exist, it is possible that gates on dams can be operated to mitigate the effects of the floods. By contrast, in small urban catchments, flash flooding occurs with little warning, often at night and occasionally on weekends, because of the timing of the rainfall.

The large and small catchments thus need to have different mitigation plans: plans for large ones need to be executed by a flood agency which has time to mobilise itself to alert and maintain vigil over several days; the small ones need people to be keeping watch over nights and weekends as well as during working hours. The (somewhat arbitrary) distinction between the two types of catchments is to separate them according to whether their response time is greater or less than 6 hours; in terms of this definition, small catchments would experience Flash Floods. There is of course a spectrum of response times, but generally speaking, the Metros and small towns in Regions are more concerned with flash floods.

This background sets the stage for the most important outcome of the project: the SAWS has accepted responsibility for Flash Flood Forecasting, augmenting its function of issuing Severe Weather Warnings. At the other end of the spectrum, historically, the Flood Unit of DWAF has been involved with floods in big rivers and through dams, and caused by the release of water from dams, such as Vaal, Bloemhof, van der Kloof and Gariep dams, to name a few of the big ones.

Both agencies have contact with Disaster Managers, DWAF through the National Disaster Management Centre, SAWS through the Regional Forecasters to the Regional Disaster Management Centres of the Metros. The latter link is the unexpected beneficial outcome of this project. SAWS weather forecasters are familiar with local climate and are in constant contact with the Disaster managers who are on 24 hour stand-by. This is a natural avenue of communication and is exploited in the proposed way forward summarised at the end of this section.

4.2 The technical background and infrastructure for flood forecasting

In the remainder of this section the various tasks required for flood forecasting are drawn together into a coherent system, which provides a road-map for the implementation of flood forecasting systems in South Africa. Particular emphasis is given to the organizational structures, which will be required to implement such flood forecasting systems. Acquisition, processing and transfer of data are discussed in terms of a prototype system set up for the eThekwini municipality (Sinclair and Pegram, 2004) and shortcomings noted for future improvements.

With the exception of a model for portions of the Orange river and Vaal dam catchment maintained by the DWAF hydrology group, there are no existing flood warning systems in South Africa. This is a dire situation in a country where so many are impoverished and without the means to recover from disasters. The Vaal system model uses the Sacramento rainfall runoff model, calibrated for the region and rainfall data is manually fed into the model during periods of heavy rain. This model is mainly intended to assist with the management of Water Resources and was not designed with disaster management in mind, although it was used successfully to mitigate the effects of a flood in 1996 (Pegram and Terblanche, 1998).

The Vaal Dam catchment has an area of 38500 km^2 and experiences a mixture of stratiform and convective rainfall, most often in the summer months. In mid-February 1996 the reservoir was full and experienced the largest inflow peak on record (4700 m^3/s). Co-operation between the DWAF Hydrology group and SAWS allowed controlled releases from the reservoir such that the peak outflow was attenuated to 2300 m^3/s). Rainfall estimates from the MRL-5 weather radar near Bethlehem, South Africa, were accumulated in hourly intervals for selected sub-catchments of the Vaal and relayed to the DWAF Hydrology group by telephone. The rainfall values were input into the rainfall runoff model and the resulting flow forecasts used to time releases from the reservoir.

Sinclair and Pegram (2004) provide the details of a prototype system set-up for the Mgeni and Mlazi catchments near Durban, South Africa. The implementation provides several of the components of a flood forecasting system shown in figure 4.1 and these are described, along with suggested ways to "complete the puzzle" by implementing the remaining components of the system.

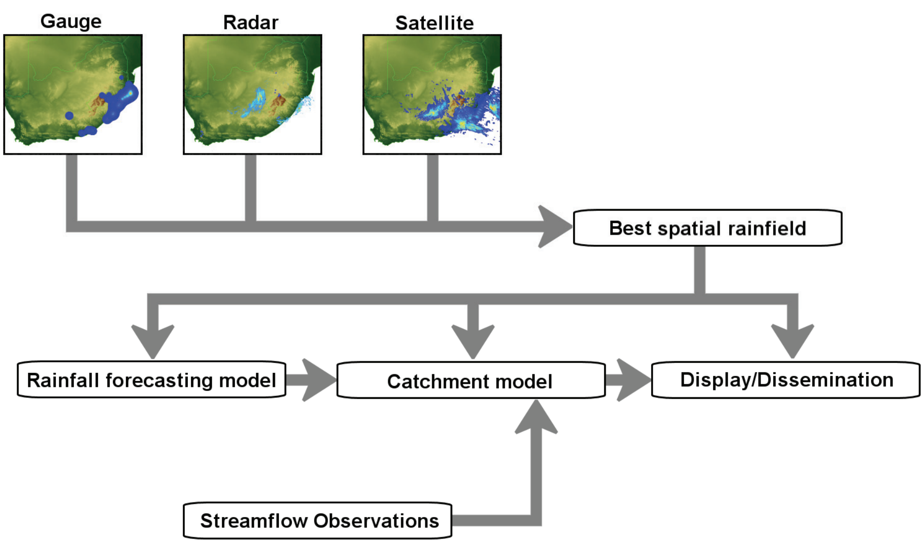


Figure 4.1 A schematic overview of the main components required for a successful flood forecasting system.

4.2.1 Rainfall Estimation

The most crucial input to any flash flood forecasting system is precipitation. In Southern Africa the influence of snow can safely be ignored and the measurement of rainfall becomes the most important factor in determining the system input. There are three measurement devices in South Africa which provide estimates of rainfall at suitable spatial and temporal resolution for flash flood forecasting.

The rainfall estimates produced from rain gauges, weather radar and meteorological satellite may be combined in an optimal way using conditional merging to produce the best spatial estimate of rainfall for the catchment of interest (Sinclair and Pegram, 2005; Pegram et al., 2006). The resulting combined rainfall estimate can be fed into display systems for direct visualization of instantaneous and accumulated rainfall. The estimates are also used as input to catchment models and converted to streamflow, the core output of the flood forecasting system.

4.2.2 Catchment Model

The nature of the catchment model is not dictated here as its implementation and effective use are dependant on the expertise and data which is available. In South Africa the necessary hydrological expertise does not exist in many of the municipal structures which are responsible (by law) for ensuring appropriate flood mitigation strategies, including flood forecasting systems. For useful real-time operation, the catchment models need to be informed by real-time streamflow observations which provide a means of updating the models performance and improving forecasts. A fully distributed model (TOPKAPI), which is suitable for flood forecasting (among other uses) has been described in section 3.

4.2.3 Rainfall Forecasts

To improve the lead-time of streamflow forecasts using current information, rainfall forecasts can prove useful. Short term rainfall nowcasting is dealt with in Sinclair and Pegram (2004) and Pegram et al. (2006). Stochastic nowcasting models can provide the means for extending the information from current best spatial rainfall fields into the future.

4.2.4 Real-time Streamflow Observations

DWAF has instrumented a large number of flow gauging structures with telemetering flow gauges. The data are recorded at short time intervals (12 minutes in most cases) and transmitted to a central server with a frequency of five times daily (on average). In time of high flows the data can be requested on demand at a higher temporal frequency. The data is accessible via DWAF's website and is returned as a rolling buffer of the most recent data in an HTML format. Sinclair and Pegram (2004) developed a Python script to request the web page containing data for a relevant gauge, read and parse the page and extract the relevant flow (or river stage) data. Where dams are used as the gauging structure (and consequently flow rates are not provided by DWAF), additional software is run to convert the dam levels to flows via a rating table. Figure 4.2 gives a diagrammatic representation of the data retrieval process.

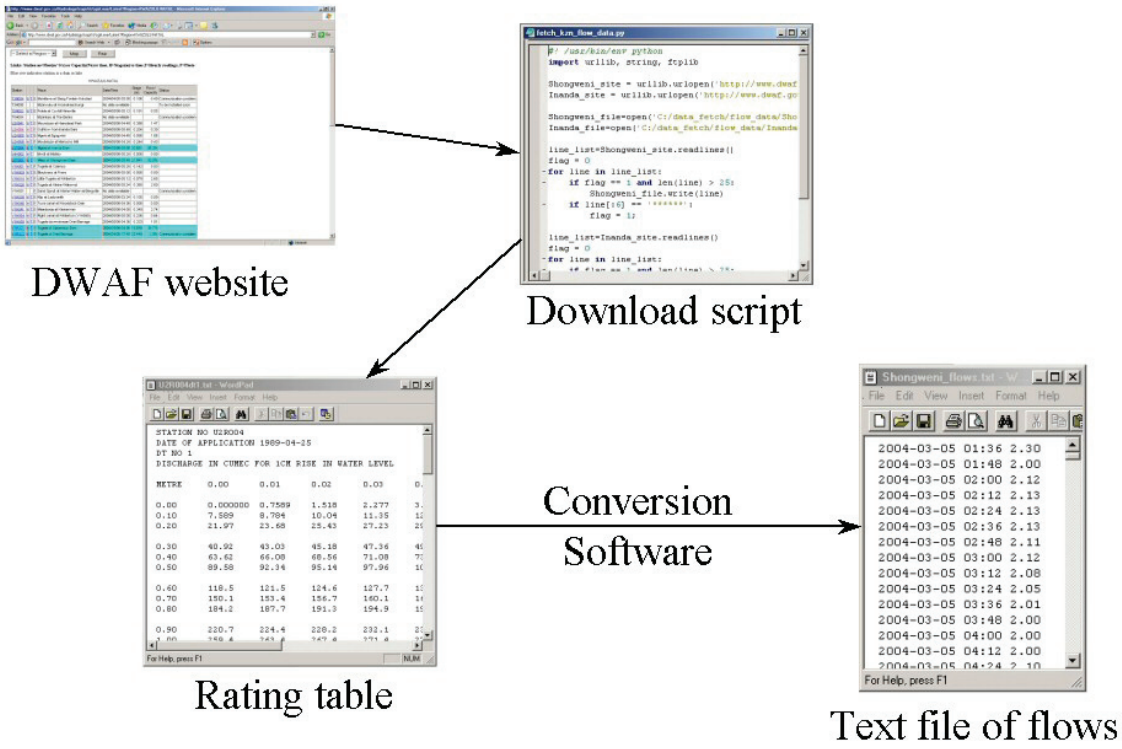


Figure 4.2 An outline of the scripting procedure for downloading and extracting real-time flow records from the DWAF website. The script can be scheduled to run at regular intervals, depending on the application.

The resulting flow record can be used to provide information about current flow conditions as well as feedback (through a suitable filter) for the catchment model. This system has been successfully implemented and run at UKZN and in the eThekwini municipality's disaster management centre. Since the script is easily scheduled to run at any time interval, improved frequency of data collection from gauging stations on selected catchments will make this a reasonably robust and effective method for obtaining real-time streamflow estimates.

4.2.5 Visualizing the Output

The dissemination of outputs refers to the kinds of information presented to the end user of the flood forecasting system, in this case the disaster managers (DMs). The role of the flood forecasting system in the process of disaster management is to provide a warning of the possibility and seriousness of an impending flood event, the actions and decisions taken on the basis of that information are then left up to the relevant authorities. The consultation process yielded two major requirements from the DMs point of view; some warning should be provided ahead of a likely flood and the affected areas should be indicated (preferably in a graphical format). To meet these requirements, the Arcview GIS was chosen as a display tool since the DMs already make use of this system. Images of current and historical rainfall are available for display in the disaster management control room and dynamically selected flood lines may be called up in response to current observed and forecast streamflows.

Integration of the radar rainfall images into a GIS

When radar rainfall images are presented in a spatial context, they can provide an advance warning of heavy rainfall approaching sensitive (flood-prone) catchments.

Figure 4.3 shows an example of an instantaneous radar image of a large convective storm that moved over the Mlazi catchment and the lower reaches of the Mgeni catchment.

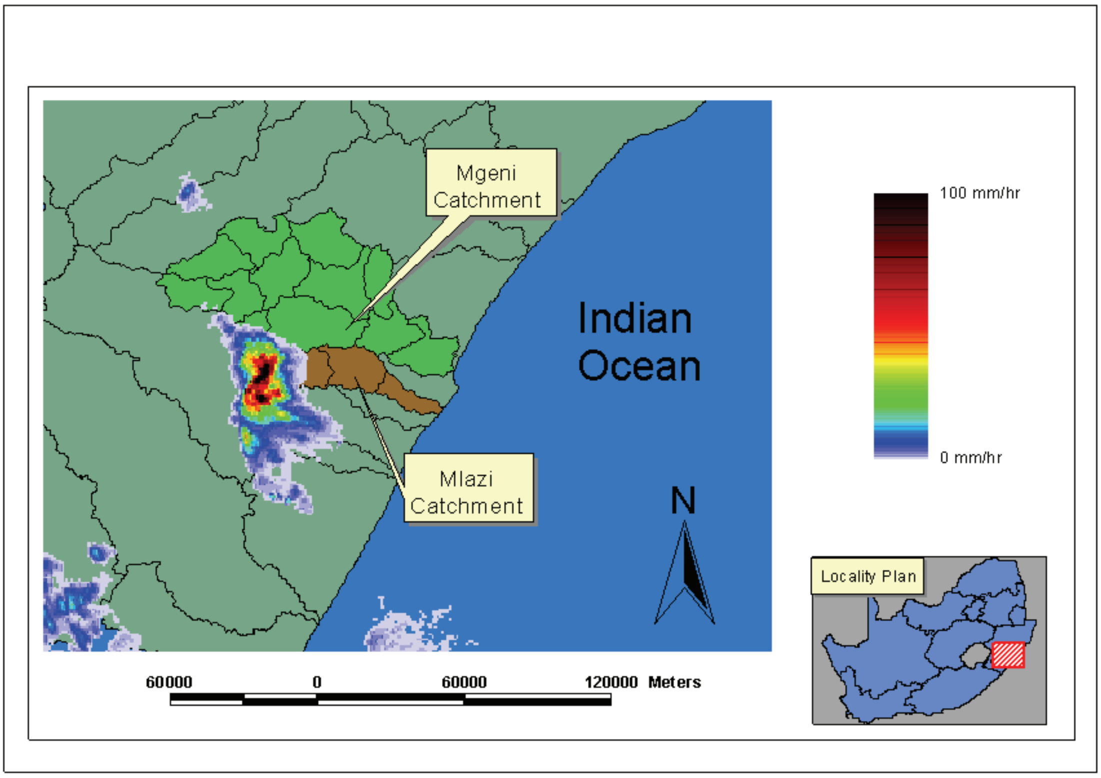


Figure 4.3 Visualization of rainfall in the Disaster Management centre. This figure shows a large convective storm over the upper Mlazi catchment (17 December 2002 at 14:58 SA standard time).

The images are available in an Arcview compatible format at the eThekwini municipality's disaster management centre in near real-time. The data transfer process and relevant software is briefly described in the following paragraphs.

SAWS make use of the "Meteorological Data Volume" (MDV) file format to transfer and archive spatial radar data. In order to make use of this data, it is necessary to have a means of extracting the data from MDV files.

The raw radar data-stream is processed into MDV format at the radar site and transferred to the SAWS server, where data products are published on their web page and archived. The products currently available on the web page do not provide the powerful data analysis capabilities of a GIS. Software developed by Sinclair and Pegram (2004) is run routinely on the SAWS server. The software accepts the MDV format data as input and produces radar rainfall images in a spatially referenced format, which is compatible with the Arcview GIS. The dataset is compressed to reduce its size and stored on the SAWS-METSYS server in a 2 day buffer before deletion. There is no need to preserve this data as the products can be extracted from the archived MDV data if necessary.

Software developed using the Python programming and scripting language retrieves the latest images from SAWS by FTP transfer. The FTP server is queried for new data at frequent intervals and when new data is found it is downloaded to the client machine.

Displaying the flood affected areas in a GIS

There is a need for the DMs to determine which areas they can expect to be affected by floodwaters. A time series of observed streamflows and possible forecasts of the future flows are of no real significance to the DMs, unless the numbers can be interpreted in terms of flood levels, and depths of inundation. The process of translating flows into inundation depth, is dealt with in some detail by Mkwananzi and Pegram (2004).

The computation of floodlines is a fairly laborious process, which, despite the proliferation of model and software packages, requires a large degree of (highly skilled) human interaction. This does not encourage online computation of current and forecast inundation depths as a first choice of modus operandi. Therefore, a simple alternative solution is proposed.

A possible process for producing and using floodlines is as follows: Floodlines at various recurrence intervals can easily be computed offline. Although the flood-wave is dynamic, it is assumed (for steep channels with negligible off-channel storage) that the levels of inundation produced by the flood peak will be closely approximated by the corresponding steady-state peak, whose inundation level is the dynamic wave's upper bound. A Hydraulic model (e.g. HEC-RAS, Brunner, 2001) of the river channel and adjacent flood plains must be produced, using a Digital Elevation Model (DEM) in combination with field surveys. This is a once-off procedure since the same model may be used to model the effects of a range of different flow rates. A typical output from such a steady state model is shown in figure 4.4. The model can also output the flood levels as a set of points in a three-dimensional co-ordinate system as a text file. In order to interpret these points as flood lines and inundation levels, an interpolation between channel cross-sections is required preferably in conjunction with information from a DEM. A polygon can then be produced in a suitable GIS format for viewing in the disaster management centre. In this case an Arcview shapefile like that shows in figure 4.5.

Scripts are easily developed (Sinclair and Pegram, 2004) to select the relevant floodline from within the GIS environment, based on the most recently observed (or forecast) flow rates. This information can be automated and dynamically updated without user intervention.

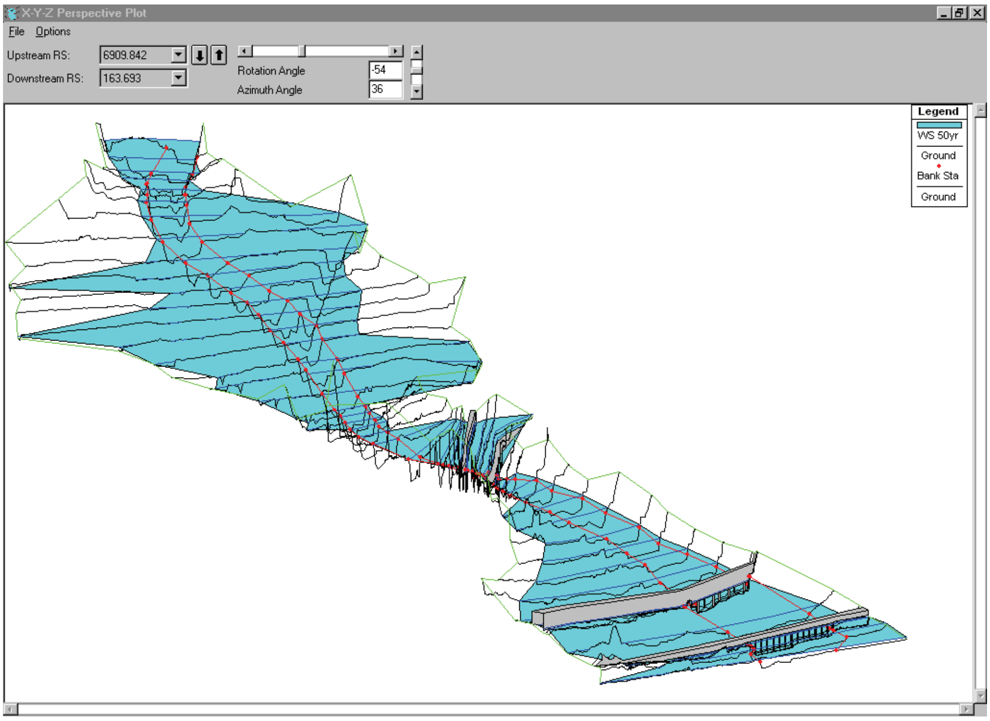


Figure 4.4 HEC-RAS output for the lower reaches of the Mgeni river.

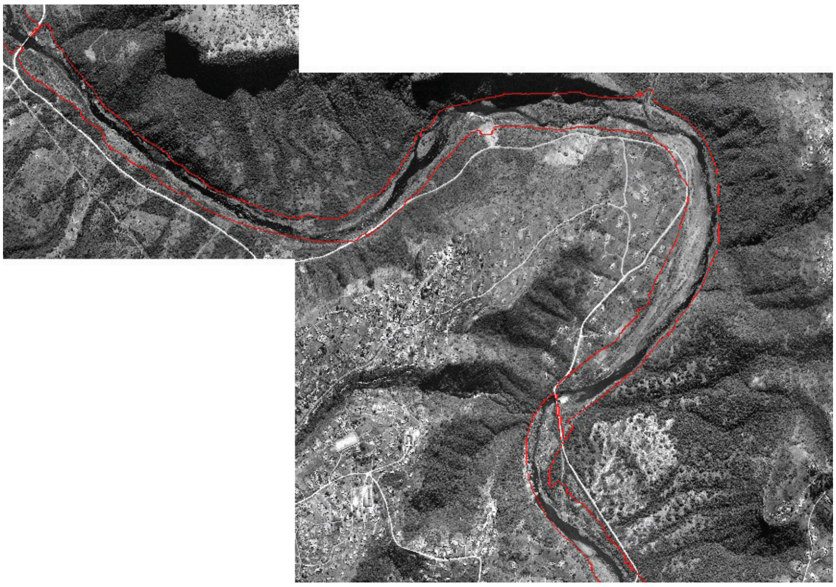


Figure 4.5 A 2\% Annual exceedance probability (50 year Recurrence Interval) flood line: (Mgeni catchment Downstream of Inanda dam).

4.3 Recommendations

The activities performed during the period of this contract have been instrumental in developing the momentum needed to ensure that pragmatic flood forecasting systems are put in place in South Africa. The key role players have begun to work together towards a common goal and it is essential that the process does not stall. Towards this end, there is a strong need to clarify and formalize the roles of key organizations (SAWS, DWAF, NDMC, Municipal DMC's) and most importantly, to establish the supporting tasks for flood forecasting in the job descriptions of the relevant staff members in these organizations if any forward traction is to occur.

Influential factors in the success of flood forecasting in SA will be the availability and access to the relevant data such as rainfall and streamflow data. Great strides forward in this regard have already occurred during recent years. DWAF and SAWS must be commended in particular for efforts in this area. The ancillary data for catchment modelling (DEM's, channel profiles etc.) are already available in some form to the larger vulnerable municipalities; it is up to these municipalities to take the action necessary to serve their residents.

This places decisions taken at a meeting between SAWS and DWAF personnel in Pretoria on 19 June 2006 in context. What follows is the outcome of a recommendation of the Final Steering Committee of the project and is included here for completeness and is a fitting conclusion to this report as it points the way to the future.

Implementation of a National Flood Warning System (NFWS)

Preamble

At the final WRC steering committee meeting on Project No. 1429: "A National Flood Nowcasting System: Towards an Integrated Mitigation Strategy", held at the WRC offices, Pretoria on 21 August 2006, a recommendation was made that a "**National Flood Working Group** be convened, in order to provide continued forward momentum in the area of flood warning". This document is an attempt to provide ideas on a way forward, given the issues identified at the June 19 **meeting at SAWS** (summarized below) and the **Report** on the above project.

June 19 meeting between SAWS, DWAF & UKZN

The participants of the meeting decided that it is important to give input to the Coordinator of the Water Sector Working Group regarding procedures of flood and flash flood management by disaster management structures. The following ***needs*** were identified as being core to development of a strategy:

1. The definition of flood events with a long lead time versus flash floods, with the relevant guidelines associated with each class of event and responsible institution for issuing warnings.
2. Procedures regarding the communication process of warnings for each class of event to the national, provincial and municipal disaster management centres need to be outlined.
3. Since data are critical for effective warnings, municipal and provincial disaster management centres (and CMAs) need to be encouraged to also collect weather and stream flow information where data collection networks of SAWS and DWAF are insufficient for local purposes. Guidelines are needed to set standard criteria and coordination mechanisms with SAWS and DWAF to ensure quality and compatibility of the infrastructure.
4. To effectively implement warning systems for areas vulnerable to flooding, it is important that vulnerability assessments by municipal and provincial disaster management centres be provided via the NDMC to SAWS and DWAF.

5. To avoid confusing warnings from more than one source, flood and flash flood warning systems developed by municipal and provincial disaster management centres for their own use must be coordinated with the systems put into place by DWAF and SAWS. Guidelines are needed on the coordination of warnings issued by SAWS or DWAF with those of the local system, responsibility for warnings issued, and operational running of the local systems.
6. Procedures are needed for warnings of flood events in river basins shared with neighbouring countries.
7. A need was identified for a committee to meet routinely between SAWS, DWAF and NDMC to discuss the entire warning system.

How should the NFWS work? What needs to be done to make this happen & who should do what?

The answer is in three parts:

- the technical hydrological/hydraulic studies turning rain into inundation level and the associated risk
- the responsible organisations associated with the different sizes of river cross-section and flood at the points of hazard
- the lines of communication necessary to ensure an efficient transfer of information during disasters

Technical

- Identify high hazard catchments. High hazard regions are identified in the **Report** (Coastal cities and Gauteng). Metros should perform (some have already completed) flood vulnerability assessments as part of their Disaster Management Plans. Problem catchments needing immediate attention will be identified by this process. It is our understanding that this has already been done in the larger Metros, but there is concern that the information may not be readily available. The vulnerability assessments should include a study of potential inundation depths for areas at risk.
- Determine the Time of Concentration (T_C) on vulnerable catchments to decide between two separate approaches to the flood warning problem.
- For $\mathbf{T_C < 6}$ **hrs**
  - SAWS Flash Flood Guidance System (FFGS) provides warnings when current and/or forecast rainfall will produce “bank full” discharge in a catchment given the current soil moisture conditions.
  - Metros receive warning via SAWS forecasters (or other means to be decided).
  - DMs consult relevant and **readily available** flood inundation maps for the catchments on which warnings have been received to determine where to mobilize. Basically it’s a case of “playing things by ear”.
  - Forecasters keep DMs updated regarding the danger rating for the catchment (yellow alert, orange alert, red alert) based on new

observations and forecasts of rainfall depths. This requires that the FFGS be updated frequently and constantly monitored.

- For **T_C > 6 hrs**
  - DWAF Flood Guidance System (FGS) provides a flood Hydrograph upstream of vulnerable areas using a suitable Hydrological modelling system (e.g. TOPKAPI or other favourite models) and rainfall estimates obtained from SAWS, soon to be augmented by daily soil moisture estimates.
  - Metros/DMs have some system to determine inundation depths from the inflow Hydrograph. In practice this will most likely be using precomputed flood maps, which are a result of Hydraulic modelling carried out offline by engineers.
  - Even though it is feasible to run the Hydraulic model in real-time, the production of flood inundation maps usually requires human intervention since terrain data has limited precision and automatically generated inundation maps may not make sense. This problem can be resolved with better resolution digital elevation models and suitable mapping software, but requires considerable technical skill.
  - Using the peak of the inflow Hydrograph as the equivalent steady-state input gives a conservative estimate of the inundation depths. The reality will likely be less severe (assuming the modelling is good).
  - Steep coastal catchments with little off-channel storage will effectively behave as a channel and experience a Kinematic flood wave (very little diffusion/subsidence of the hydrograph). The inundation levels reached as the peak of this wave passes each point along the channel should match the levels computed from a steady state inflow equivalent to the peak flow rate of the inflow Hydrograph.
  - Hydraulic models can handle unsteady inputs but this may complicate the issue when looking at practical implementation and will only be necessary where off-channel storage is a significant factor.

Responsibility

- Metros need to perform flood inundation analyses if their Disaster Management Plan suggests this is a significant risk. If this has already been done, the relevant information should be readily accessible (not stored in a cupboard or hidden in a GIS database that DMs are unequipped to access).
- Flood risk analyses should enable Metros to identify vulnerable catchments.
- Problem catchments need to be earmarked for i) modelling if T_C is greater than 6 hours or ii) inclusion in the SAWS FFGS if T_C is less than 6 hours. Metros *must* take the lead in this. It is their responsibility to their residents.
- SAWS is responsible for Flash Flood Warning and their senior management is comfortable that they are mandated to do so in terms of the Weather Services Act (Act No. 8 of 2001). They should develop their FFGS and include

catchments on demand so that catchments most at risk are treated with urgency. Extension to other areas will follow in due course.

- It is unclear which department is mandated to handle floods which have a longer lead-time but the Disaster Management Act (Act No. 57 of 2002) mandates Local Authorities to provide for proactive disaster mitigation strategies including early warning systems. Therefore it is our view that the responsibility (but not necessarily the capacity) should lie with Local Authorities and NDMC should facilitate this.
- The reality is that the above is unlikely to happen due to capacity and budgetary constraints at the local/Metro level; therefore we propose that DWAF is best positioned to develop the necessary skills and capacity to do Hydrological modelling of the larger catchments which pose a threat. Although DWAF is best positioned, they appear to lack a mandate to act (and spend) in working to achieve these aims.
- NDMC is mandated in a coordinating role (from our understanding) and not as a provider of skills and services to local Disaster Managers as we envisioned at the outset of the project.
- Improved monitoring of relevant variables is required to reduce modelling uncertainties i.e. rainfall, flow, soil moisture etc. In particular, the SIMAR rainfall field needs improvement, as detailed in Pegram et al. (2006).
- The **National Flood Working Group** (NFWG) must be convened and formalized to develop the guidelines noted in the June 19 meeting and to further refine the suggestions in this document, based on the **Report**.

Lines of Communication

These remain to be agreed on by the members of the NFWG which includes representatives of the three main Government players: DWAF, NDMC & SAWS.

The following two figures which were produced by Eugene Poolman of SAWS are offered as initial proposals:

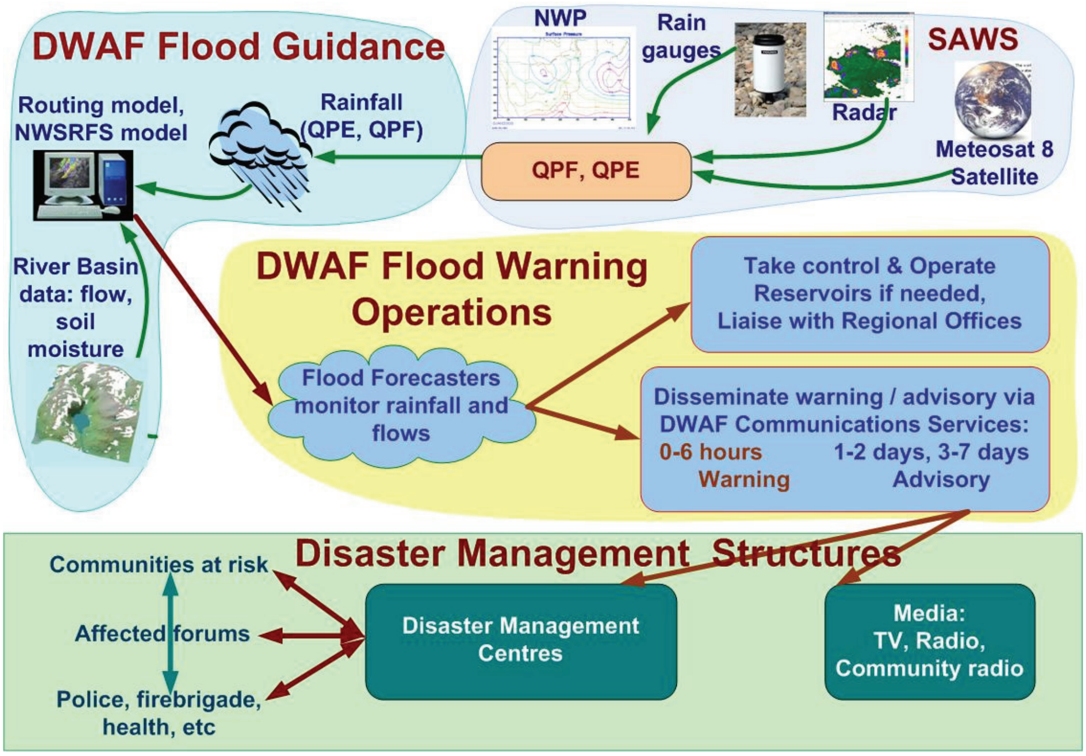


Figure 1. DWAF: Flood warning system: schematic diagram describing the end-to-end warning process from the data input to dissemination of warnings by flood forecasters

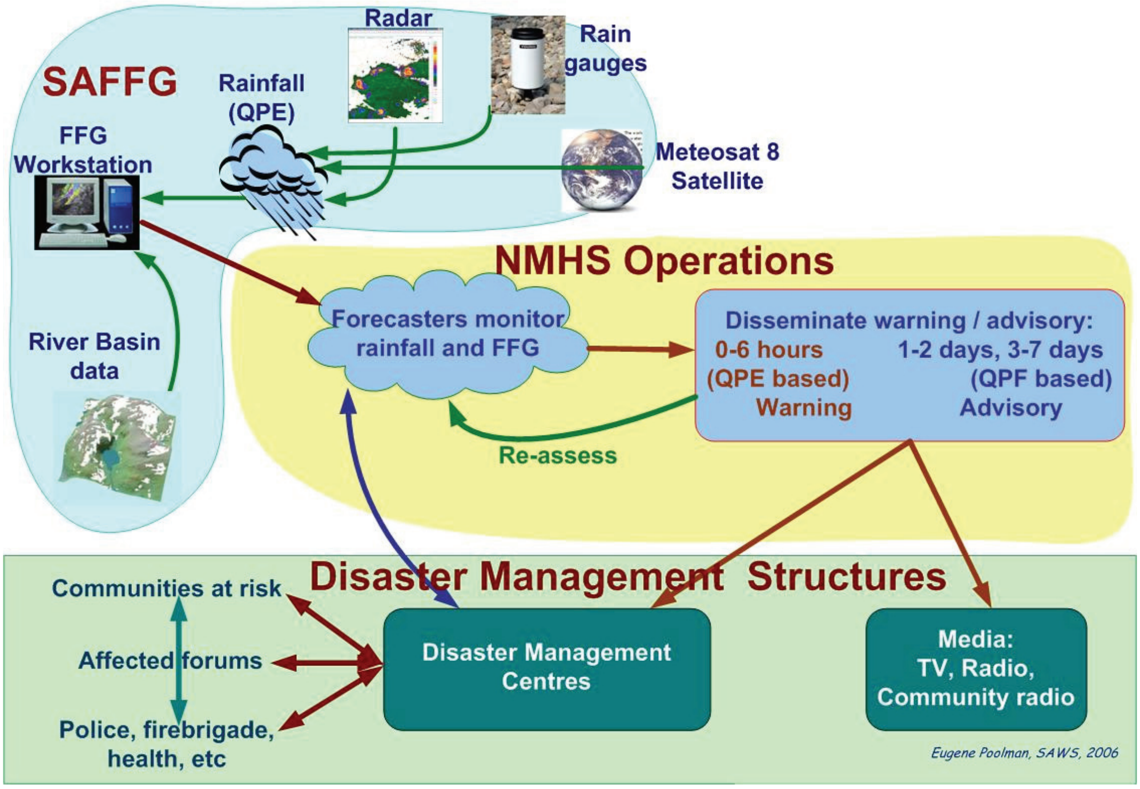


Figure 2. SAWS: Flash Flood warning system: schematic diagram describing the end-to-end warning process from the data input to dissemination of warnings by disaster management centres to their structures and affected communities.

The SAFFG noted in Figure 2 is the Southern African Flash Flood Guidance system offered to SAWS by the University of San Diego California through the WMO. Mr

Eugene Poolman attended the WMO Workshop in Costa Rica in March 2006 to form the necessary links. SAFFG is a system which integrates rainfall, soil moisture, topography, vegetation, soil type and ground cover at the pixel (1 km) scale through chosen distributed or semi-distributed models of the catchment to provide visual warnings of impending floods over the subcontinent. The work of the present project is designed to be imbedded in the SAFFG shell. It a great comfort that SAWS has taken the initiative and responsibility for this product.

References:

Band L.E., Topographic partition of watersheds with digital elevation models, *Water Resources Research*, **22**, 15-24, 1986.

Barnes H.H., Roughness characteristics of natural channels, *US Government Printing Office*, Washington, 1967.

Bartholmes J. and Todini E., A combination of meteorological and hydrological models for flood forecasting applied to the upper river Po-basin, *ACTIF 1st Workshop*, Bologna, 2003.

Brooks R.H. and Corey A.T., Hydraulic properties of porous media, *Hydrology papers*, No. 3, Colorado State University, Colorado, 1964.

Cash J.R. and Karp A.H., A variable order Runge-Kutta method for initial value problems with rapidly varying right hand sides, *ACM Transactions on Mathematical Software*, **16**(3), 201-222, 1990.

Chow V.T., Open-Channel Hydraulics – International Student Edition, *McGraw-Hill*, Tokyo, 1959.

Chow V.T., Maidment D.R. and Mays L.R., Applied Hydrology, *McGraw-Hill*, New York, 1988.

Clothier, A.N. and Pegram, G.G.S., Space-time modelling of rainfall using the String of Beads Model: Integration of radar and rain gauge data, *Water Research Commission, Report No. 1010/1/02*, Pretoria, 2002.

Deyzel, I., Pegram, G., Visser, P., and Dicks, D., Spatial Interpolation and Mapping of Rainfall (SIMAR) Volume 2: Radar and satellite products, *Water Research Commission, Report No. 1152/1/04*, Pretoria, 2004.

Dingman S.L., Physical Hydrology 2nd ed., *Prentice Hall*, New Jersey, 2002.

Dunne T., Field studies of hillslope flow process, *Hillslope Hydrology*, M J Kirkby (ed.), 227-293, Wiley, New York, 1978.

Doorenbos J. and Pruitt W.O., Crop water requirements, *Irrigation and Drainage Paper 24*, U.N. Food and Agriculture Organization, Rome, 1977.

D.L.S.I., A digital elevation model for South Africa, *Directorate of Land Surveys And Information*, South Africa, 1996.

Everson, C., Evaporation from the Orange river: Quantifying open water sources, *Water Research Commission, Report No. 683/1/99*, Pretoria, 1999.

G.L.C.C., Global Land Cover Characteristics, *United States Geological Survey*, 1997. http://edcdaac.usgs.gov/glcc, Accessed 18 February 2005.

Gradshteyn I.S. and Ryzhik I.M., Table of integrals, series and products, A. Jeffrey (ed.), *Academic Press*, Orlando, 1980.

Green W.H. and Ampt G.A., Studies on soil physics, part I, the flow of air and water through soils, *Journal of Agricultural Science*, **4**(1), 1-24, 1911.

Horton R.E., An approach toward a physical interpretation of infiltration capacity, *Soil Science Society American Journal*, **5**, 399-417, 1940.

HYDRO1k, Elevation Derivative Database, *United States Geological Survey*, 1996. http://edcdaac.usgs.gov/gtopo30/hydro. Accessed 18 February 2005.

Jensen M.E., Burman R.D. and Allen R.G., Evapotranspiration and Irrigation Water Requirements, *ASCE Manuals and Reports on Engineering Practice No. 70*, American Society of Civil Engineers, New York, 1990.

Kovacs Z., Regional Maximum Flood Peaks in Southern Africa, *Technical Report TR 137, Department of Water Affairs*, Pretoria, 1988.

Kroese, N., Spatial Interpolation and Mapping of Rainfall (SIMAR), Volume 1: Maintenance and upgrading of radar and rain gauge infrastructure, *Water Research Commission, Report No. 1151/1/04*, Pretoria, 2004.

Liu Z. and Todini E., Towards a comprehensive physically-based rainfall-runoff model, *Hydrology and Earth System Sciences*, **6**(5), 859-881, 2002.

Mark D.M., Network models in geomorphology, Chapter 4, Modelling Geomorphological Systems, M.G. Anderson (ed.), *John Wiley & Sons*, 73-97, 1988.

Marshall J.S. and Palmer W.M., The distribution of raindrops with size, *Journal of Meteorology*, **5**, 165 – 166, 1948.

Martina M.L.V. The distributed physically based modelling of the rainfall-runoff process, *PhD Thesis*, University of Bologna, 2004.

Midgley D.C., Pitman W.V. and Middleton B.J., Surface water resources of South Africa 1990 (WR90), *Water Research Commission, Report No. 298/1/94*, Pretoria, 1994.

Mkwananzi N. and Pegram, G., A Flood Nowcasting System for the eThekwini Metro, Volume 2: Modelling flood inundation in the Mlazi river under uncertainty, *Water Research Commission, Report No. 1217/2/04*, Pretoria, 2004.

Monteith J.L., Evaporation and Environment, *Proceedings of the 19th Symposium of the Society for Experimental Biology*, Cambridge University Press, New York, 205-233, 1965.

MUSIC Final Report, Multi-sensor precipitation measurements integration, calibration and flood forecasting, Section 6, Deliverable no. 1.8, Feb 1st 2001 to July 31st 2004, E. Todini (co-ordinator), 2004.

O'Calaghan J.F. and Mark D.M., The extraction of drainage networks from digital elevation data, *Computer Vision, Graphics and Image Processing*, **28**, 328-344, 1984.

Pegram G.G.S. and Terblanche D.E., Radar Hydrology developments in South Africa, *Proceedings of Radar Hydrology for real time Flood Forecasting: An advanced study course*, University of Bristol, United Kingdom, 24 June – 3 July, 1998.

Pegram, G. and Clothier, A., High resolution space-time modelling of rainfall: The "String of Beads" Model, *Water Research Commission, Report No. 752/1/99*, Pretoria, 1999.

Pegram, G., Spatial Interpolation and Mapping of Rainfall (SIMAR) Volume 3: Data Merging for rainfall map production, *Water Research Commission, Report No. 1153/1/04*, Pretoria, 2004.

Pegram, G., Sinclair, S., and Wesson, S., Daily Rainfall Mapping over South Africa: Mapping, *Water Research Commission, Report No. 1153/1/04*, Pretoria, 2006.

Penman H.L., Natural evaporation from open water, bare soil and grass, *Royal Society of London Proceedings*, Series A, **193**, 120-146, 1948.

Philip J.R., The theory of infiltration: 1. The infiltration equation and its solution, *Soil Science*, **83**, 345-357, 1957.

Richard L.A., Capillary conduction of liquids through porous mediums, *Physics*, **1**, 318-333, 1931.

Sinclair, S. and Pegram, G., A Flood Nowcasting System for the eThekwini Metro, Volume 1: Umgeni Nowcasting using Radar - An integrated pilot study, *Water Research Commission, Report No. 1217/1/04*, Pretoria, 2004.

Sinclair S. and Pegram G., Combining radar and rain gauge estimates using conditional merging, *Atmos. Sci. Let.*, **6**, 19 – 22, 2005.

S.I.R.I., Land Type Series, *Department of Agriculture and Water Supply, Soil and Irrigation Research Institute*, Memoirs on the Agricultural Natural Resources of South Africa, Pretoria, 1987.

Strahler A.N., Quantitative geomorphology of drainage basins and channel networks, V.T. Chow (ed.), *Handbook of applied hydrology*, Sec. 4-11, Mcgraw Hill, New York, 1964.

Shreve R.L., Statistical law of stream numbers, *Journal of Geology*, **74**, 17-37, 1966.

Tarboton D.G., Bras R.L. and Rodriguez-Iturbe I., On the extraction of channel networks from digital elevation data, *Hydrological Processes*, **5**, 81-100, 1991.

Todini E., New trends in modelling soil processes from hillslope to GCM scales, The role of Water and the Hydrological Cycle in Global Change, H.R. Oliver and S.A. Oliver (eds.), *Nato ASI Series: I, Global Environmental Change*, **31**, 317-347, 1995.

Todini E., The ARNO rainfall-runoff model, *Journal of Hydrology*, **175**, 339-382, 1996.

Wood E.F., Sivapalan M., Beven K.J. and Band L., Effects of spatial variability and scale with implications to hydrologic modeling, *Journal of Hydrology*, **102**, 29-47, 1998.

WPDM, White paper on disaster management, *Department of constitutional development*, South Africa, 1998

APPENDIX

A1 Review of deliverables and related actions

The project deliverables are reviewed and related achievements discussed in this section.

Deliverable 1: Establish IT feed to Durban DMC

Description: Port the software currently housed in Umgeni Water and Durban Metro to NDMC/DWAF:PSU and establish the link from the National Office to replicate the existing one. This will be the prototype link for the National system, based on one already successfully operating.

Summary of actions:

To make control and monitoring easier, the prototype data link was set up at the University of KwaZulu-Natal rather than at the Disaster management centre in Durban. All indications are that the system is reasonably robust and can be efficiently replicated at the DM centre. FTP does not currently provide an ideal data transfer mechanism in terms of speed but as South Africa's internet infrastructure improves; this should become less of an issue.

The following has been achieved:

- IP authenticated FTP access to the NDMC server was arranged from a machine housed at the University of KwaZulu-Natal.
- Scripts to automate the extraction of data from the NDMC server and DWAF web server were developed and tested. The scripts were based on the work of Sinclair and Pegram (2004).

Deliverable 2: First round of Training Workshops

Description: Starting with Durban, deliver the first round of flood warning system training workshops. This will include overview and background of system in presentations, followed by hands-on simulated/historical flood events for training and system validation purposes. The feed must come from NDMC.

Summary of actions:

The Training Workshops took the form of interviewing and raising awareness among the Disaster Managers and the Waterways and Drainage Engineers of major metropoles. Four cities were visited in July 2003, a presentation was made to the National Disaster Management Symposium in October 2003 and a further visit was made to the Western Cape Provincial Disaster Manager in November 2003. The description contained in section 3, highlights some of the interaction from the personal viewpoint of Geoff Pegram.

The following has been achieved:

- High level technological knowledge transfer to the main players in the Metros and Regions
- Enablement and focus of their flood mitigation initiatives in line with the National Disaster Management Act.

- An expectation of further up-dates and a willingness to be advised and to collaborate with their peers.

Deliverable 3: Identify High Hazard Flood Areas

Description: In consultation with NDMC, DWAF Flood Centre and DWAF Regional Offices, as well as Metro & City DMs, establish a roster of potentially hazardous (high loss of life, damage to strategic industries) areas. Prioritise these for inclusion in the system.

Summary of actions:

Dusan Sakulski has now established a web site, the URL is: http://edmc1.pwv.gov.za/hazards/. This web page enables one to identify countrywide or local threats and potential hazards. It appears that the most vulnerable areas that need immediate attention, with regards to flood forecasting and warning, are the Metros along the southern and eastern coastline (Durban, East London, Port Elizabeth and Cape Town) and in Gauteng. These have previously been earmarked for attention and personal visits and this study confirms their inhabitants' vulnerability, section 6 provides more details.

The following has been achieved:

- A useful web-site has been established which gives the DMs historical perspective of their problem areas, without requiring extensive data collection.
- The most vulnerable areas have been identified and earmarked for attention.

Deliverable 4: Year end Interim Report

Description: Prepare interim report for first steering committee meeting.

Summary of actions:

The first interim report was produced.

Deliverable 5: Establish Streamflow Monitoring Network

Description: With the cooperation of DWAF and local authorities, instrument key gauges in the high hazard catchments to provide feedback to the rainfall/runoff models for updating and validating forecasts.

Summary of actions:

As the direct result of a previous WRC funded project (Sinclair & Pegram, 2004), two important catchments affecting the eThekwini Municipality were instrumented by DWAF. Although there are still some teething problems with the data transfer, stream flow data is reliably collected from the DWAF web server using the prototype data link described under Deliverable 1. As part of it's mandate DWAF has similarly instrumented many other important catchments in the country and the data is available via the DWAF website in near real-time.

The following has been achieved:

- DWAF has instrumented many gauging stations with near real-time equipment.
- DWAF is making this data freely and easily accessible via it's website.
- Prototype data collection scripts are running successfully at UKZN and would require little effort to be ported elsewhere.

Deliverable 6: Training Workshop

Description: In this round, consolidate on the first year's workshop and travel to newly established centres fed by the National DMC to extend the training program. Possibly travel to potential regional offices to advertise the system.

Summary of actions:

The meeting reported on in section 4 (Minutes of the meeting of SAWS-METSYS, WRC & UKZN Administrators, Scientists and Engineers at Bethlehem, 10 May 2005) has been substituted for this deliverable. The important outcome of this meeting was that SAWS has taken responsibility for Flash Flood forecasting. This puts significant dedicated resources behind the initiative, which will ensure continuity and sustainability after the completion of this project.

Deliverable 7: Model High Hazard Zones

Description: With topographical information and telemetering streamflow gauges in place, calibrate the catchment models for the high hazard zones by priority. Extend the modelling procedure by interpolation to ungauged locations if possible.

Summary of actions:

A fully distributed catchment model (TOPKAPI) has been investigated. The methodology for modelling new catchments using TOPKAPI and readily available data sets has been developed. This work is reported in section 7 (an excerpt from *Mohamed Parak's* MScEng thesis). We have chosen to go the route of applying a fully distributed model that is specifically designed for remote sensing data at the $1km^2$ pixel scale. The model has not simply been imported from its developers in Europe but adapted to South African conditions. Additionally the model has been modified to make sense where it didn't in the original publications. It might beneficially be noted that the Project Leader had extensive discussions on the topic of the TOPKAPI model with its originator, Prof Ezio Todini during the EGU Assembly meeting in Vienna in April 2005. The decision to go this route has not been taken lightly. Globally the use of distributed and remotely sensed data sets is becoming more common; we hope to lay the important groundwork which will ensure that South Africa is in a position to take advantage of the benefits from advances in the accuracy and quality of these data products.

The following has been achieved:

- Significant modelling results have been identified.
- The methodology for modelling new catchments using TOPKAPI and readily available data sets is well developed and reported in section 7 of this document.

Deliverable 8: Interim Report

Description: Prepare report for penultimate steering committee meeting.

Summary of actions:

The second interim report was prepared.

Deliverable 9: Establish Nationwide Information Transfer Links

Description: By now, many Local Authorities' DMC's and DWAF regional offices should have come on board with the system. Efforts will be made to ensure the links are well established and self-sustaining. This will require a large amount of travel and many presentations in order to persuade, encourage, educate and enable people while the system is in the process of being planted. There will be a need to recognize problem areas, ease the transition period, facilitate exchange and transfer of knowledge and co-ordinate deliverables. It will be important to transcend organizational, departmental and regional boundaries to encourage collaboration, then sharing and, most importantly, ownership of the information.

Summary of actions:

A prototype link has been reported on under Deliverable 1. This deliverable has proven very difficult to action in the way that it was originally conceptualised as the immensity of overcoming the skills shortage among the Municipalities proved to be a stumbling block for which we were not prepared. The project team was relying on the enthusiasm of the DMs to provide the necessary momentum for this process. However, it appears that the poorly defined/understood requirements in the act have meant that DMs focus has remained on more traditional areas.

The following has been achieved:

- A prototype link has been implemented.
- The generic framework for a flood forecasting system has been proposed (Section 8.1).

Deliverable 10: Training Workshops

Description: This is the last round of training workshops under the contract. These are designed to educate new personnel and recharge those who are now getting complacent about the system, especially if there have been a few dry years. The road show will probably last the best part of 2 months.

Summary of actions:

The steering committee agreed to substitute the Flash Flood Forecasting workshop, which was held at the University of KwaZulu-Natal on 29 and 30 August 2005. The workshop was arranged by the research group at UKZN and included presenters from the “Observation Research” and “Forecasting and Research” divisions of SAWS. Participants included Researchers, Consultants, Disaster Managers and Weather Forecasters. The timetable and summary of discussions for the workshop is reported in section 5. This initiative resulted in productive knowledge and skills transfer.

Deliverable 11: Final Report

Description: Prepare the final report to the final steering committee meeting.

Summary of actions:

This document is the final report.

A2 Visits to disaster managers at Metros - Report

Professor Geoff Pegram visited a number of centres around the country in order to establish links and to try and determine the available capacity and infrastructure. The report on this process was written in the first person and is included verbatim below.

Report on visits to coastal cities in July 2003

The July trip (1^{st} & 2^{nd}) was an introductory exposure of the new WRC project: "National Flood Nowcasting System" to the Metros of Cape Town, Port Elizabeth and East London.

The presentation was well received in each city (lasted about 2 hours as planned) and I was asked for a copy for distribution. This prompted me to make a short version (without the *.avi files) which will transport over the net. What was a bonus was that I shared some anecdotes about flooding (my first wife Gill's ants predicting the end to the 1987 drought and my second wife Joan's Logan-Utah experience where she watched the burgeoning Mississippi flood of 1993 on the 24 hour weather channel) which seemed to get peoples' attention. The emphasis was on the fact that NDMC have the requirements of the regions in mind with regard to flood forecasting and that what needs to be done is for the Metro DMs to open the dialogue with NDMC regarding the provision of facilities and information. In addition, I emphasized that the WRC initiative (my outreach) was already funded and they were beneficiaries. In all three centres, my contact person and the one who made the arrangements, was an engineer with the Water/Drainage division of the Metro. They took the trouble to arrange a venue, organize a digital projector and most importantly, ensure the participation of the relevant Metro Disaster Manager.

Now to the individual Metros in the order in which I visited them. Note that I landed in Cape Town as a cold front arrived - it dampened me there and followed me to Port Elizabeth (where I experienced some horrendously intense rain on the "disdrometer" outside my door - an aluminium awning - which woke me a t 2, 4 & 6am) and chased me through East London and back to Durban. I feared that I might not be welcome…

In **Cape Town** my host was Barry Wood (021-487 2478) of the Catchment Management Office who had invited Geoff Laskey, the Disaster Manager of Cape Town with several others - 9 in all. This team seems to be well switched on. They do not have as serious a river problem *per se* as many other cities, but have threats to a mixture of people and commercial interests in the following rivers - Lourens, Eester, Salt and Diep. People problems are mainly on the Cape flats where ground waterlogging is a pest. In this context, we discussed the possibility of ground water modelling in conjunction with the daily rainfall map from SIMAR. The prospect of a feed from the NDMC was greeted with enthusiasm tempered by the realistic problem of the slowness of the present communication links. In response to a question as to whether the NDMC would help fund and up-grade, I confessed ignorance, but encouraged them to contact Louis Buys.

As far as equipment is concerned, the radar sited at the airport covers most of the problem areas in the Cape flats - the West of the mountain which the radar can't see is not a flood-problem area and there they have rain gauges. They have a well deployed set of (relatively inexpensive - R 1500 - plastic) tipping bucket rain gauges, most of which are loggers and a few of which are telemetering via a radio link (MOSCAD - shared with Water/Dams dept) at 6 hour intervals. They do have a thought for cell-phone transmission, but their established network is designed primarily as a recording not real-time facility. What is promising for modelling is that they have approximately 30 stream gauges (low to high flow) properly calibrated and maintained with some records going back 30 t0 40 years. What a resource! These data will be very useful for local modelling, should they need it. Flood lines have been developed for the main rivers at high cost by employing consultants to do surveys and modelling. The up side is that this information already exists. However, to augment this information, the promise of a Digital Elevation Model (DEM) on even a coarse grid, would be a welcome addition to the armoury for flood-line determination. They have an informative web-site: www.capetown.gov.za. In an aside, Barry Wood told me that Matt Braun of SRK in Johannesburg/Pretoria did some useful work for Stellenbosch on the WATEES project. These people are keen and ready to go - by the time I get back next year, they should be ready for simulation training.

In **Port Elizabeth** my host was Tony Arthur (041-505 2232) who invited a small group to attend. The DM, Shane Brown was on leave and was represented by his deputy, Hombile Gume. Others were Gustin Esau and Gavin Flanagan. The Mandela Metropolis is currently undergoing restructuring and transformation with some of the negative side effects (uncertainty of the future and frustration) that result from such an exercise. Hombile Gume made the point that there had been a marked lack of dialogue between the engineering division and the DM division of the Metro. I expressed the hope that our meeting gave impetus to the will to open the communication channels.

On the technical side, it turns out that some rivers have been surveyed and modelled - particularly the Sundays. Sadly, after collecting data for 11+ years, rain gauges and stream gauges that the City had installed were recently removed by the authorities, it appears, because they had been vandalized, and because it would have been difficult to maintain them. Tony Arthur was of the opinion that they need to be replaced by something more effective and vandal-proof if they are to conduct flood forecasting; I made the point that it might be prudent to mount an education campaign in conjunction with the DM to help the community understand the value of the gauges. In any event, the available gauged record will be invaluable for modelling purposes. They did not think they would be ready for me next year, but Tony Arthur expects me to contact him within the next 6 months so we can monitor progress. On the positive side, they were delighted at the prospect of the information feed from NDMC.

In **East London** my host was Shaun Peard (an ex student of mine) who had invited the DM Owen Becker (043-743 7118) and two others from Buffalo City Metro: Christo Crafford and Ivor Berrington, together with a Ninham Shand engineer Steve Landolt (who does their dam-break analyses), who provided the projector! Here I was pleased to find that the primary interest and response came from the DM, Owen Becker. It seems that he has already got in place an informal monitoring system in the guise of policemen and/or firemen who will report on the flow-depth in a stream if asked - this on the basis of advanced warning from the local SAWS forecaster in PE with whom he has a working relationship. Things worked better when SAWS had a forecaster in East London who knew the vagaries of the local weather, but that service was discontinued … ! The information feed of satellite and radar information from NDMC would be a welcome boost to the efficiency of their operation. It seems their people problems are primarily due to recent land invasion and this is confined to some of the smaller rivers. The big rivers like the Buffalo are deeply incised and channelled in deep ravines so are not a threat. The group was knowledgeable about modelling procedures like HEC-RAS and are familiar with flood-line determination etc. They look forward with anticipation to the NNDMC feed and to my return visit next year. A small but promisingly dynamic group.

In summary, the walkabout was (from my point at least) a success. The presentation of the Scheme was, not only politely and interestedly but, enthusiastically received. I come away with the knowledge of a message well delivered on which we can build a meaningful future in Flood Nowcasting in this country.

Report on visit to Tshwane city, 16 July 2003

This brief report is a continuation of the previous one on the July 1 & 2 trip to Cape Town, PE and East London. Much of what I said there in the preamble is appropriate here as well.

The contact person in this case was Anë Bruwer (012-310 6402) whose name was given me by Saar van Wyk of NDMC with a strong recommendation. She assembled a group of 9 people who included Pieter Odendaal, the Head of the Roads & Stormwater (SW) division, a GIS person, some consultants and other DM and SW people.

This was a rewarding experience for me on 2 counts – first, I felt more confident of my presentation and secondly, it was very well received. The effect was as if the scales had fallen from their eyes! On being asked how they were to go from there, I suggested they put together a proposal for information transfer (satellite and radar feeds) and approach Louis Buys, the CD of NDMC. They were quite excited by the prospect and I got the impression that the presentation was just the catalyst they needed to realise how easy it was to get going. It was great to see the enabling and empowering effect of the information.

This city is particularly well placed to make a definitive impact on the way the National Flood Nowcasting System develops because they are where Durban was a year ago – they have a small set of telemetering tipping bucket rain gauges, they have done their flood-lines for high risk areas which they have identified, they have got some of the more important rivers (Apies etc) modelled hydraulically with HEC-RAS and they have a keen GIS department ready to put the stuff together. I don't think I could have visited them at a more opportune time and believe they will be calling me soon to help them get detailed focus.

As to the remaining cities, I have been in touch with the President of the Disaster Management Institute of South Africa, Anthony Kesten, and he suggested I present a paper on the System at their International Conference to be held on 9 & 10 October 2003, where I will be able to reach a large number of decision makers and DMs.

I have agreed to do this and call a halt to the propaganda exercise at this stage. I need to make it work with 5 cities to start with and make a success of the system – the rest I'll do on demand.

I am pleased to say that I feel it has been a job well done – what is more, it was very rewarding to me to sense the enthusiasm and response of the people I have met.

A3 Flash Flood forecasting meeting with SAWS - Minutes

MINUTES OF THE **MEETING OF SAWS-METSYS, WRC & UKZN ADMINISTRATORS, SCIENTISTS AND ENGINEERS AT BETHLEHEM 11:00 AM 10 MAY 2005**

Present:

Dr George Green (WRC)	george@wrc.org.za	**083 283 4454**
Mr Nico Kroese (SAWS)	nico@weathersa.co.za	**082 485 2244**
Dr Jonas Mphepya (SAWS)	JonasMphepya@weathersa.co.za	**082 495 5683**
Prof Geoff Pegram (UKZN – Chair)	pegram@ukzn.ac.za	**031 260 3057**
Mr Eugene Poolman (SAWS)	poolman@weathersa.co.za	**012 997 2405**
Mr Gerhard Schulze (SAWS)	schulze@weathersa.co.za	**012 367 6116**
Dr Deon Terblanche (SAWS)	deon@weathersa.co.za	**058 303 5571**

Observers:
Ms Pearl Mngadi, (SAWS - METSYS)
Ms Adalina Nhlapo, (SAWS - METSYS)

In attendance:
Dr Joan Pegram

The meeting opened with a welcome by Dr Terblanche to each person individually recognizing their unique contribution to the work at hand. Dr Terblanche then handed the meeting over to Prof Pegram to chair.

Prof Pegram started by stating that this hydro-meteorological meeting was most important as it set the stage for the future of hydrometeorological research in RSA. He briefly went through the papers attached to the agenda, which had previously been circulated to participants.

Prof Pegram emphasized his 'Vision': of producing a daily updated Soil Moisture (SM) map over RSA at a resolution of 1 km by the year 2008, posted on the web, freely accessible to all, like the SIMAR product. He indicated the ingredients needed:

- ground-truthing of SM;
- hydrometeorlogical data for evapotranspiration estimation;
- NWP model output for spatial interpolation of these;
- distributed hydrological models for back-calculation of SM

He noted the support from potential European collaborators, especially the intention to use Liebenbergsvlei and Oliphants catchments as initial ground-validation sites for remote sensing of SM. In addition, the USDA had been supportive of the deployment of ground validation instrumentation for SM measurement. It was fortuitous that Dr Schulze had been heard to say on television that SAWS needed to take responsibility for Flash Flood Forecasting (FFF), as that set the stage for intense activity in the area of hydrometeorology.

The agenda proper was then addressed by item.

Item 1
The need for SAWS to take responsibility for flash forecasting in RSA.

After a Powerpoint presentation on the WRC project on flood nowcasting by Prof Pegram, points raised included:

- The need to define the role of the National Disaster Management Centre in Flash Flood Forecasting, because meteorology is not their domain of expertise.
- The issue of data collection and increasing the number of reporting rain gauges was raised and it was noted that although an MOU between SAWS and ARC is in the process of development, there is a problem with ARC data, which is collected on an ad hoc basis. This does not meet the needs of SAWS for data collected at standard times and the matter is under negotiation.
- It was emphasized that Severe Weather Forecasting is performed by regional office forecasters, who have sound local knowledge of areas under their control, together with the National Forecasting Centre in Pretoria. The regional forecasters have an understanding of how the weather is likely to develop and therefore are the appropriate people to issue warnings and make decisions in the presence of uncertainty. Through the use of examples the importance of information being routed through the local forecaster to the Disaster manager via telephone, SMS, fax etc was emphasized.
- The discussion expanded to the role of NWP models in giving uncertainty estimates attached to the forecasts. This is done by running ensemble forecasts, to establish probability of events occurring. The missing link is soil moisture, which is a vital parameter, critical to initiating the NWP models, and is likely to become more important in the future.

In answer to the question: Are SAWS prepared to take up the initiative to explore flash forecasting? **It was agreed** that SAWS already has the responsibility for flash flood forecasting in RSA, but lacks the hydrological information to do it effectively, and notes the importance of soil moisture monitoring. There was general consensus that this initiative needed building on the structure already in place for Severe Weather Forecasting. This immediately pointed to the need for the employment of hydrologists and hydrometeorologists within the SAWS structure. This capacity would not be available in the short term but would have to be planned for.

Item 2
The need for reliable sensors and instrumentation.

The issue of radars frequently not operable was raised and this was ascribed to wilful damage, loss of technical staff and the difficulty of their replacement by people of sufficient calibre. As there was a felt need for more rainfall measurement on a real time basis, the issues of networks of small X-band radars in mountainous terrain and an increase of the number of pluviometers was raised, as was the intention to purchase more radars to fill the gaps of coverage over the country. **SAWS is addressing these issues** as was emphasized by Dr Schulze in a presentation of the recapitalization plan.

Item 3
The need for deployment of Soil Moisture probes.

The opinion offered by Dr Green was that single probes are not reliable because their purpose is ground truthing of remote sensing of SM. One rather needs a network of probes suitably sited taking account of soil type, depth, texture etc, governed by an educated decision (informed by a pedologist) as to where to put them to meet scale, variability and representativity requirements. Prof Pegram offered to ask Tom Jackson what he had in mind for ground validation and to report back. **SAWS agreed to deploy** SM probes at suitable automatic weather stations after taking advice.

It was agreed that there was a need to match the range of soil moisture at the pixel scale to the estimates of SM obtained by satellite imagery. Wolfgang Wagner (Vienna) routinely estimates the range of satellite measures of soil moisture over a few seasons at individual pixels and links the observed range of the surrogate measures to soil moisture properties (the difference between field capacity and wilting point). Dr Green made the critical observation that the latter can be calculated off-line for all soils in the country, which are already mapped and available through ARC.

Item 4
NWP Model output in forecast and hindcast mode.

Mr Poolman outlined the limitations of the ETA model currently operated by SAWS. He indicated that SAWS intend to commission the Unified Model from the UK Met Office after the purchase of a super computer in September 2005. The intention is to have local models with higher resolution operating in the regions fed by the central NWP model. It became clear that the **NWP products would be useful** in the interpolation of relevant meteorological variables for the purposes of soil moisture accounting.

Item 5
NWP output in rainfall nowcasting.

The possibility of using NWP models in conjunction with stochastic models for nowcasting up to 6 hours ahead was briefly discussed. It seems that although there is consensus that this is feasible, it is likely that there will be a delay of about 4 years until NWP forecasts have a high enough space resolution and time scale to match the stochastic forecasts after 2 hours.

Item 6
Attendance of UKZN people at WWRP workshop

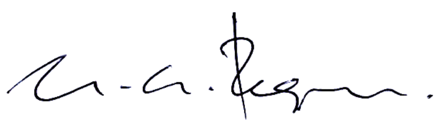
Mr Poolman noted that there was a need for local input and case studies at the workshop, which was intended to be an all African affair for forecasters. Nevertheless **it was agreed that UKZN and METSYS** people would be involved.

Item 7
MOU between SAWS and UKZN

Dr Terblanche noted that this **matter was already in hand** and that it would be the prototype for collaboration between SAWS and other universities/organizations.

The meeting closed at 14:20 after lunch and a presentation of SAWS' Recapitalization Plan by Mr Schulze.

It is accepted that this minute is a true recording of the proceedings



………………………………………..
Chair

Date: 20 May 2005

A4 Flash flood forecasting workshop - Summary

A very successful and well-attended flash flood forecasting workshop was held in Durban at the University of KwaZulu-Natal on the 29th & 30th August 2005. A summary of the discussion and the presentations follows.

TIMETABLE – Monday 29th

Starting Time	Topic	Speakers	Sub-topic
12h00	Lunch and Welcome	Geoff Pegram	
13h00	**Session 1:** Catchment Modelling	Geoff Pegram	Overview
		Scott Sinclair	Semi-distributed Catchment Models - Background
		Mohamed Parak	Fully Distributed Catchment Models - TOPKAPI
14h00	Discussion Period		
14h30	**Session 2:** Rainfield Forecasting, Numerical Weather Prediction	Estelle de Coning	The New MSG Satellite: Nowcasting Abilities
		Scott Sinclair	Stochastic Nowcasting & Advection of Remotely Sensed Rainfall Fields
		Eugene Poolman	NWP Model Capabilities
15h30	Discussion Period		
16h00	**Session 3:** Severe Weather Warning Applications	Deon Terblanche	An Overview of a Historic Flash Flood Event
		Pieter Visser	A Severe Storm Event Over Gauteng on the 27th October 2004
		Eugene Poolman	The Early Warning System in South Africa: Reaching the Disaster Manager
17h00	Discussion Period		
17h30			

TIMETABLE – Tuesday 30th

Starting Time	Topic	Speakers	Sub-topic
09h00	**Session 4:** Meteorological Infrastructure	Nico Kroese	Surface Networks, Radar Networks and Satellite Feeds – Operation and Quality
		Stephen Wesson	Improvement in Radar Measurements
10h00	Discussion Period		
10h30	**Session 5:** Combining Precipitation Estimates	Deon Terblanche	Spatial Characteristics of Rainfall
		Scott Sinclair	Blending Estimates Using Conditional Merging
		Geoff Pegram	Using Radar and Gauges as Validation for Satellites
11h30	Discussion Period		
12h00	Lunch		
13h00	**Session 6:** Prognosis	Pieter Visser	Improvements in Precipitation Estimation
		Ntoko Nxumalo	Remote Sensing of Soil Moisture
		Geoff Pegram	The Future
14h00	Discussion Period		
14h30	Wrap up		
15h00	Adiós		

Attendees

Num.	Name	Organization	Contact Details	
			✉	☎
1	Geoff Pegram	UKZN – SAHG	pegram@ukzn.ac.za	(031) 260 3057
2	Scott Sinclair	UKZN – SAHG	sinclaird@ukzn.ac.za	(031) 260 1077
3	Stephen Wesson	UKZN – SAHG	wessons@ukzn.ac.za	(031) 260 1077
4	Ntokozo Nxumalo	UKZN – SAHG	nxumalon17@ukzn.ac.za	(031) 260 1077
5	Mohamed Parak	UKZN – SAHG	parak@ukzn.ac.za	(031) 260 1077
6	George Green	WRC	georgeg@wrc.org.za	-
7	Nico Kroese	SAWS	nico@weathersa.co.za	(058) 303 5571
8	Pieter Visser	SAWS	visser@weathersa.co.za	(058) 303 5571
9	Deon Terblanche	SAWS	deon@weathersa.co.za	(058) 303 5571
10	Eugene Poolman	SAWS	poolman@weathersa.co.za	(012) 367 6001
11	Estelle de Coning	SAWS	estelle@weathersa.co.za	(012) 367 6015
12	Pearl Mngadi	SAWS	pearl@weathersa.co.za	(058) 303 5571
13	Adelina Nhlapo	SAWS	adelina@weathersa.co.za	(058) 303 5571
14	Mpho M Nekhwalivhe	SAWS	-	073 878 7660
15	Colin Anderson	SAWS	andersonc@webmail.co.za	-
16	W H Pretorius	SAWS	fadnoc@weathersa.co.za	-
17	Jeff Smithers	UKZN – BEEH	smithers@ukzn.ac.za	(0331) 260 5408
18	Mehari Frezghi	UKZN – BEEH	200282337@ukzn.ac.za	-
19	Kershani Chetty	UKZN – BEEH	chettyk@ukzn.ac.za	-
20	Dick Martin	eThekwini Municipality	martindn@durban.gov.za	(031) 300 2237
21	Andrew Mather	eThekwini Municipality	mathera@durban.gov.za	(031) 300 2281
22	Geoff Tooley	eThekwini Municipality	tooleyg@durban.gov.za	(031) 300 2271
23	Billy Keeves	eThekwini Municipality – Disaster Management	keveswr@durban.gov.za	(031) 306 4074 x8310
24	Talita Germishuyse	ARC – ISCW	Talita@arc.agric.za	(012) 310 2580
25	Johan Malherbe	ARC – ISCW	johan@arc.agric.za	(012) 310 2577
26	Craig Schultz	Arcus Gibb	cschultz@gibb.co.za	(012) 348 5880
27	Ans Gerber	Arcus Gibb	agerber@gibb.co.za	(012) 348 5880
28	Chris Swiegers	DWAF – Disaster Coordination	swiegersc@dwaf.gov.za	(012) 336 8437
29	Brink Du Plessis	DWAF – Hydrological Services	brinkdp@dwaf.gov.za	(012) 336-7890
30	Louis Buys	NDMC	cd.dm@ndmc.pwv.gov.za	(012) 334 0726
31	Gawie Jansen van Vuuren	Tshwane (Pretoria) Metro	gawievv@tshwane.gov.za	(012) 358 7788
32	Barry Wood	Cape Town Metro	Barry.wood@capetown.gov.za	(021) 487 2478
33	Allan Rix	BKS	allanr@bks.co.za	(012) 421 3500
34	Matt Braune	SRK Consulting	mbraune@srk.co.za	(012) 361 9821

SUMMARY OF DISCUSSIONS - Monday 29th

SESSION 1: Catchment Modelling

The discussion was largely centred around two topics, distributed catchment modelling using the TOPKAPI model and soil moisture determination by remote sensing.

The issues related to distributed catchment modelling were data availability, calibration and the benefits of using distributed models. The data availability issue was raised by **Matt Braune**, who noted that much of the research reported was based on data from the Liebenbergsvlei catchment. **Geoff Pegram** responded by noting that there is good historical data for the Liebenbergsvlei catchment but that the kind of static data (soils, land-use etc.) required by TOPKAPI are readily available for medium to large sized catchments. In respect of the availability of good real-time rainfall data for operational use, **Deon Terblanche** announced that SAWS plans to increase the rain gauge network by 200 rain gauges per year for the next five years, in addition to adding another 7 weather radars to the radar network. The discussion group felt that land use changes and their effects would be better modelled using TOPKAPI, rather than a spatially lumped model. In particular, soil erosion and evapo-transpiration estimates were noted as useful spin offs, apart from flood forecasting.

The discussion around soil moisture estimates was fairly brief as the topic was scheduled for a presentation on the second day of the workshop. It was established that soil moisture estimate from space were inferred based on the ground heating rate and were therefore only representative of the upper layers of the soil (top 5 cm). It was generally agreed that the most important portion of the soil for flash flood forecasting was that which affects infiltration rate and hence runoff potential.

Combined discussion on SESSION 2: Rainfield Forecasting, Numerical Weather Prediction and SESSION 3: Severe Weather Warning Applications

Note: 1. The discussions for Session 2 and 3 were combined and held at the end of Session 3.

2. Pieter Visser's original presentation for Session 3 (*A severe storm event over Gauteng on the 27th October 2004*) was postponed until Session 6 on the following day (Tuesday 30th August), due to technical difficulties. In place of his original presentation, he presented his Session 6 presentation in Session 3, i.e. *Improvements in Precipitation Estimation*.

The discussion period focussed largely on the responsibility and interaction between various role players involved in the forecasting of floods. The cost and optimum spacing of weather radars was also given some attention. **Pieter Visser** and **Deon Terblanche** of SAWS responded to the question by suggesting that optimum spacing would be between 75 and 120 kilometres, depending on the type of radar.

Chris Swiegers commented that the early warning system (EWS) of DWAF for South Africa is a commendable initiative considering that in the past DWAF was only concerned with the Orange River and selected catchments. He said that floods, unlike droughts, cause great damage to humans and infrastructure, damaging urban developments, service and transport networks. He went on to say that because of the potential impact that damages from floods pose, there needs to be a standard operating procedure when it comes to flood forecasting which should be implemented nationally. This should work within the Disaster Management Act and Framework.

SUMMARY OF DISCUSSIONS - Tuesday 30th

SESSION 4: Meteorological Infrastructure

The discussion began with a considerable period of time spent discussing duplication of data collection and data sharing between the organizations that collect data. The focus was on rain gauge data and this issue has been raised in several other forums. There are already some efforts being made between ARC, SAWS and DWAF to facilitate the sharing and standardization of data. It was agreed that these efforts need to be accelerated and include other organizations, which collect data such as the larger municipalities. **Jeff Smithers** noted that from a user's point of view, the people doing the data collection have to work together. The biggest threat to this process is that no single organization (or more particularly individual) has a clear mandate to drive this process to completion.

The discussion then turned to the responsibility and "standard operating procedure" for the issuing of flood warnings. **Chris Swiegers** raised an important issue, noting that DWAF feels it is not clearly instructed on flood warning and is hesitant to take this up in fear of liability. He emphasized the need for a flood management team consisting of various workgroups i.e. water management, severe weather forecasting etc. Thereafter, the definition of the various roles can be made through consultation with key players.

Louis Buys said he personally welcomed the communication between the weather service and municipalities. But he noted that the problem seems to lie with disaster managers possibly because of the newly established disaster management Act. He also pointed out the importance of the communication link and that this had to be maintained. With regard to the issuing of warnings, he said the NDMC has clear guidelines given in the Disaster Management Act but they still require additional information that is available through the various institutions.

SESSION 5: Combining Precipitation Estimates

The discussion in after this session soon drifted back to the burning issue of poorly defined responsibilities for flood forecasting. The various acts governing the role players, SAWS, DWAF, NDMC etc. do not appear to clearly define the responsibility for flood forecasting. **Chris Swiegers** suggested that it is an obligation of DWAF to integrate these efforts across the entire spectrum and put together a document within the year, which will clarify the responsibilities. He also pointed out the need to establish groups or teams that include disaster managers, agronomists, water managers etc. **George Green** enquired whether this document would provide for the establishment of sector teams and whether consultation with the various role players would be done. **Chris Swiegers** assured him that this was the case and that consultation would be done both proactively and reactively.

The discussion closed with **Louis Buys** noting that he welcomed the idea of such a set of guidelines, as it would take away the pain of guessing where the responsibility for the various activities related to flood forecasting lie.

SESSION 6: A Severe Storm Event Over Gauteng (27th October 2004)

Discussion of the severe storm event centred around the use of radar data by the aviation industry in South Africa and it was established the SAWS radar data is used on a regular basis by the air traffic controllers at most of the country's major airports. There was also plenty of enthusiasm for the radar data correction techniques presented by Stephen Wesson.

SESSION 7: Remote Sensing of Soil Moisture

Most of the discussion focused around whether DEM's were used in the mapping of soil moisture in order to account for the effects of slope and elevation. **Ntokozo Nxumalo** assured the delegates that this was indeed the case. The research presented was met with great interest and high hopes for the usefulness of future developments in aiding flood forecasting efforts.