

EXECUTIVE SUMMARY

Background

The estimation of design floods is necessary for the design of hydraulic structures. The under estimation of design floods will result in the failure of hydraulic structures with consequent economic losses and possible loss of life. The over design of hydraulic structures results in inefficient use of resources. The choice of an acceptable and cost-effective engineering solution is dependent upon having reliable estimates of the frequency of floods, both in terms of peak flows and volumes of water.

Standard techniques for flood estimation have been developed for most countries and procedures for design flood estimation may be broadly categorised as methods based on the analysis of observed floods and rainfall based methods. The situation which faces design engineers and hydrologists most frequently is when no, or inadequate, observed streamflow data are available at the site of interest and then either regional approaches or rainfall-runoff models have to be used for design flood estimation.

In the absence of adequate streamflow data, a number of rainfall event-based approaches are commonly used. In South Africa these include the Rational, unit hydrograph and SCS-SA methods. The procedures for applying the widely used unit hydrograph approach in South Africa were developed in the early 1970s and very little development or refinement has been made since then. Major shortcomings of most event-based methods include the implicit assumption that the exceedance probability of the simulated streamflow is the same as that of the input design rainfall and that antecedent soil moisture conditions prior to large storm events are not accounted for. The limitations of event-based approaches to design flood estimation can be overcome by adopting a continuous simulation approach to rainfall-runoff modelling where the major processes responsible for converting the input catchment rainfall into runoff are explicitly modelled. The use of a continuous water budget ensures that the antecedent conditions prior to each rainfall event are simulated, and the exceedance probability is computed directly from the simulated streamflow and not inferred from the rainfall.

Project Objectives

The objectives of this project were to develop a methodology, using a continuous simulation modelling approach, which could be used for flood frequency estimation in South Africa.

Methodology

The ACRU model was selected as the continuous simulation model as it operates on a daily time step, the simulated streamflow is sensitive to soils and land cover input and the model has been used to estimate design floods in previous pilot studies (Smithers et al., 1997; Smithers et al., 2001). A number of areas were identified in this project where the ACRU modelling system could be further developed or refined for design

flood estimation. These included:

- Investigations into the scale of application and levels of soils and land cover information required to apply the ACRU model for continuous simulation modelling in order to estimate design floods.
- The development and evaluation of a method to disaggregate daily rainfall into hourly totals in South Africa in order to improve the shape of simulated hydrographs and estimation of peak discharge.
- An assessment of procedures used to merge raingauge and radar data and the use of the merged rainfall fields in the development of a methodology to improve the estimation of rainfall falling over a catchment when using historical daily rainfall data.
- An assessment of the stochastic, fine resolution space-time String-of-Beads model to simulate long series of rainfall over a catchment which would enable long series of simulated streamflow to be generated in order to estimate design floods.
- The development and assessment of techniques for flood routing in ungauged catchments.
- In a parallel study, the development and application of adjustments for antecedent soil moisture conditions to Curve Numbers, used in the SCS design flood estimation model, was investigated.
- These developments and refinements to the ACRU modelling system made in this study were incorporated into the ACRU model and the Thukela Catchment was used to assess the use of continuous simulation modelling for design flood estimation.

Scales Issues Related to the Configuration of the ACRU Model for Design Flood Estimation

In the development of a Continuous Simulation Modelling (CSM) system in this study, the spatial resolution at which continuous simulation modelling is implemented is important in order to model the heterogeneous hydrological responses from catchments. It was therefore necessary to investigate the appropriate range of scales at which the CSM system should be applied to identify the appropriate scales of representation of input information. Soil and land cover information play an important role in a CSM as these are the prime regulators of a catchment and therefore directly influence the hydrological response of a catchment. The objective of this component of the study was to investigate the appropriate scale at which the CSM should be configured with respect to levels of spatial disaggregation of a catchment and of soil and land cover information required to give optimum results i.e. to investigate the optimal level of catchment discretisation for the ACRU model used in this study. Simulations at Quaternary Catchment (QC) scale and sub-quaternary scale (sub-QC) with different levels of soils and land cover information were undertaken in the Thukela Catchment.

The methodology adopted to perform this investigation required relatively un-impacted upstream sub-catchments within the Thukela Catchment which had adequate and reliable data. This limited the study as not many catchments are un-impacted and have long periods of flow records. Three QCs were selected with catchment areas ranging from 129 to 544 km². The majority of QCs within the Thukela catchment have catchment areas less than 500 km² and it was thus assumed that the results

obtained for the selected QCs would be valid for all QCs in the Thukela catchment. The results detailed in Section 3.2 indicate that:

- The larger QCs should not be modelled as lumped entities and should be discretised to hydrological response units (HRUs) as the best simulations were obtained using HRU scenarios.
- The use of area weighted and not modal soils information resulted in the best simulations.
- Modelling using more than one driver rainfall station per sub-QC yielded better results in QC 59 than when a single driver rainfall station was used, but the use of additional rainfall stations in QC 72 did not make much difference to simulated results. This could be attributed to the limited number of reliable representative rainfall stations in QC 72.

The recommendations from these results are that the optimum level of catchment discretisation in the Thukela catchment should include sub-quaternary catchments where appropriate, and all sub-catchments should be modelled using HRUs with area weighted soils information and, where possible, more than one driver rainfall station per QC should be used to represent the rainfall in the sub-catchments which constitute the QC.

Temporal Disaggregation of Daily Rainfall

The temporal distribution of rainfall, viz. the distribution of rainfall intensity during a storm, is an important factor affecting the timing and magnitude of peak flow from a catchment and hence the flood-generating potential of rainfall events. Rainfall disaggregation refers to estimating high temporal resolution rainfall values which can be aggregated to give values equal to observed coarser-scale totals.

Prior to this study, the ACRU model utilised four fixed regionalised synthetic temporal distributions to disaggregate daily rainfall. This suggests that a single distribution can be used to represent the temporal distribution of rainfall for a particular region. This, however, is not realistic and analysis of rainfall data shows that at a given location there are several temporal patterns ranging from nearly uniform rainfall to highly variable rainfall. Furthermore, the peak intensity can occur during any hour of the day, adding to the variability of temporal rainfall patterns. In order to account for the variability of temporal patterns of rainfall, a regionalised stochastic approach to daily rainfall disaggregation was developed in this study, as described in Section 3.3.

The daily rainfall disaggregation model developed is capable of producing 480 different temporal patterns with ranging levels of uniformity. The methodology was assessed independently at 15 sites in South Africa and both moments and statistics and extreme rainfall events were analysed. The results indicate that the disaggregation model reproduced the general distribution of rainfall relatively well, both when observed short duration data are available as well as in the absence of such information, but that the structure (sequencing) of the disaggregated rainfall requires additional refinements.

Spatial Distribution of Rainfall

Rainfall is highly variable in space and time and is the major driving hydrological force. Hence it is crucial to obtain an accurate estimate of rainfall in a catchment

when modelling the hydrological response from a catchment. Raingauges measure rainfall directly and rainfall depth accumulated over the period of interest is measured with a high degree of accuracy at points where the gauges are located. However, raingauge networks are too sparse to capture the spatial variability of rainfall. Radar, on the other hand, measures a volume-averaged reflected signal which is converted into rainfall and captures the spatial distribution of rainfall but needs to be calibrated using gauged rainfall. Merged rainfall fields, derived from radar and raingauges, are

The objective of this component of the project was to improve the estimation of real and stochastic rainfall in a catchment. This was achieved by assessing a methodology to merge raingauge and radar data. Based on the premise that the merged rainfall fields are the best estimate of catchment rainfall, the short periods of available radar data were used to develop relationships between the merged rainfall fields for a catchment and data from a selected raingauge. This relationship can be used to adjust the much longer record of historical gauged rainfall data to better represent rainfall in the catchment. The String-of-Beads-Model (SBM) (Pegram and Clothier, 2002), which is a detailed space-time stochastic rainfall model, was also assessed for application to generate long sequences of rainfall over a catchment for use in a CSM. The Liebenbergsvlei Catchment was used as a study site as both radar and rainfall data from a dense network of gauges were available.

The merging technique was validated against data from tipping bucket raingauges used in the conditioning of the radar images. The conditional merging technique is intended to retain the rainfall depths used in the conditioning of the radar images in the merged rainfall field. The results obtained indicated that gauged rainfalls at the conditioning raingauges were not always retained, as the merging technique developed by Sinclair (2004) masks the area where the radar did not register any rainfall, even though raingauges in this area may have reported rainfall. This was done to avoid false rainfall in other parts of the area. When the masked values were removed from the comparison, a nearly perfect relationship was obtained between the conditioning raingauge data and the merged pixel rainfall values located at the conditioning raingauge. With the exception of the masked rainfall, the merging algorithm was determined to be correct.

The merging technique was independently verified using daily raingauges which were not used in the conditioning of the radar images. For most sub-catchments reasonably good verifications were obtained, with $R^2 > 0.70$. It was noted that the raingauges selected to represent the areal rainfall of the sub-catchments generally over-estimated the mean areal merged rainfall values of the sub-catchments by between 5% and 50%. The methodology developed can be used to provide improved estimates of average historical catchment rainfall for use in modelling and other hydrological studies, until such time as the period of record of the merged rainfall fields is adequate for hydrological studies.

The assessment of the SBM indicates that the model reproduced the observed statistics at a daily time scale reasonably well and better than at monthly or annual time scales. This result was not unexpected as the SBM is a short duration rainfall model designed to mimic rainfall values at a detailed temporal and spatial resolution and small errors at 5 minutes durations accumulate over longer durations to the errors evident at the daily and longer time scales. Spatially, the SBM reproduced the statistics of the selected raingauges used in the study. Therefore, it is concluded that

an appropriately calibrated SBM may be used in rainfall-runoff modelling which requires rainfall at detailed spatial and temporal resolutions and could be used as input to a CSM system in order to estimated design floods.

Flood Routing in Ungauged River Reaches

Hydrographs are lagged and attenuated as they flow down river reaches and through dams. In a CSM it is necessary to model the changes to hydrographs as they are routed through a catchment.

The Muskingum-Cunge method for flood routing is implemented in the ACRU model. In ungauged catchments, the user is required to specify the cross-sectional shape and dimensions of the reach, in addition to the slope and roughness coefficient for the reach. This input information is then used to estimate the depth : discharge relationship for the reach. In this study it was shown that the computed outflow hydrographs generated using the Muskingum-Cunge method, both with empirically estimated variables and variables estimated from cross-sections of the selected rivers, resulted in reasonably accurate computed outflow hydrographs with respect to peak discharge, timing of peak flow and volume. Hence, it is concluded that the Muskingum-Cunge method, with variables estimated using empirical relationships, can be applied to route floods in ungauged catchments in the Thukela Catchment and it is postulated that the method can be used to route floods in other ungauged rivers in South Africa.

Application of a Climate Classification System for Regional Adjustments of SCS Curve Numbers

The SCS method is a design event based approach to design flood estimation and has been adapted for use in South Africa (Schmidt and Schulze, 1987). The refinements to the SCS method for South Africa include the development of techniques to account for typical soil moisture status prior to large storms. Stormflow response is highly variable and researchers have proposed procedures to adjust Curve Numbers (CNs) according to a soil water budget provide more realistic estimates of stormflow and peak discharge than when using only accumulated antecedent rainfall depths. However, the direct application of soil water budgeting procedures requires long and accurate daily rainfall and evaporation records, in order to estimate the change in soil moisture storage, ΔS , prior to runoff producing storm events. The problem then arises of how to estimate the values of ΔS in regions where only limited hydrological and very basic monthly climatological information is available.

The objective of this component of the study was to approach the soil water status of a catchment as a climatologically driven variable by assuming that changes to CNs due to Antecedent Soil Moisture (ASM) are similar internationally for similar climatic regions, and that climatic regions may be represented by a standard climate classification, such as the Köppen classification system, which was selected for use in this study. It was further hypothesised that within a specified Köppen Climate Class (KCC), ΔS was likely to be a function of the distribution of Mean Annual Precipitation (MAP) for major soil/vegetation combinations.

The concept of estimating ΔS from MAP for each KCC and specified soil/vegetation combinations was termed the ACRU-Köppen method. The approach is conceptually

sound, computationally simple, complies with hydrological fundamentals and does not move beyond the original intent of the SCS technique. A major strength of the approach is that it is a relatively simple technique, does not require a high level of expertise and is not data demanding for application. The use of the ACRU-Köppen method of CN adjustment was found to work well in a catchment in Eritrea and it is postulated that the method could be used in other data sparse catchments for the same KCC and similar soil/land cover characteristics to improve modelling of stormflow volumes and peak discharges from small catchments in developing regions, where adequate and accurate hydro-meteorological information are often not available.

Application of the CSM in the Thukela Catchment

The above developments and refinements were incorporated into the ACRU model and the Thukela Catchment was used as a case study. The application of the model proved challenging in an operational catchment where the observed data are not perfect, the network of daily raingauges is relatively sparse, transfers of water between catchments occur, irrigation is developed over time and other land cover changes occur.

Some challenges to modelling and design flood estimation which were noted during the project include the following:

- The problems associated with estimating rainfall over a catchment using a single rain gauge were evident in some results when the simulated and observed streamflow did not correspond for some events. However, even though there may not be a one-to-one correspondence between simulated and observed events, it is necessary for design flood estimation that the distribution of the larger events is similar.
- A thorough investigation into the reliability of the observed streamflow data indicated that the data from many flow gauging stations were not suitable for verification studies. The importance of using a physically-based, conceptual model is highlighted by the unreliability of the flow data from a number of the gauging weirs. The direct calibration of a model to these data would result in erroneous simulations.
- The stages recorded at many of the flow gauges exceeded their rating tables during larger events, which are the focus of this study. The moderate extension of the rating tables performed in this study is believed to add to the uncertainty of the accuracy of the observed flow data.
- The annual maximum series (AMS) extracted from the primary flow data generated using the extended rating tables generally corresponded well with AMS supplied by Van Bladeren (2000), although in some cases the AMS from Van Bladeren exceeded the extracted values.
- No detailed information which could be used in a daily time step model was obtained on the transfers of water between catchments, which limited the number of catchments which could be used for verification of the simulations.
- The areas irrigated in the sub-catchments were derived from the Water Use Licencing, Registration and Revenue Collection database (WARMS). Without detailed information on irrigation management practices, two irrigation schedules were simulated and the results obtained indicate that the simulated volumes are not sensitive to different, but reasonable, irrigation scheduling. The

peak discharges obtained from the two irrigation schedules simulated were different as a result of the stochastic disaggregation of the daily rainfall.

- The development of irrigation in some sub-catchments impacted significantly on the streamflow simulated. This was evident in the results obtained from a number of catchments by good correspondence between accumulated observed and simulated runoff in the early part of the record when irrigation was not simulated, and in the latter part when irrigation was simulated.
- The use of a static land cover in the simulations, which does not reflect changes over time of land cover in a catchment, resulted in better simulations closer to the date of when the land cover information used in the simulations was captured.
- Despite the above issues, the distribution of simulated volumes generally compared well with the distribution of the observed data, over the range of catchment areas considered in this study (approximately 100 - 2000 km²). The distribution of the simulated peak discharges generally compared well with the observed distribution for the smaller catchments (< 150 km²), but were usually not as good for larger catchments. The results for the simulated design peak discharges reflect the results for the distribution of peak discharges, but are deemed to be reliable and consistent enough for use in practice.

Conclusions

A number of conclusions regarding the results from this study with respect to the application of the ACRU modelling system for use in design flood estimation can be made. These include:

- In order to realistically model the hydrology of the larger quaternary catchments at a daily time step, it is necessary to delineate the quaternary catchment into sub-catchments and, where appropriate, model each sub-catchment as a number of HRUs.
- The use of area weighted, and not modal, soils information is recommended.
- The accurate estimation of catchment rainfall is crucial to modelling the correct hydrological responses and the merging of raingauge and radar data is the best estimate of the true rainfall field.
- The use of historical rainfall from raingauges to estimate catchment rainfall can be improved by using relationships developed between the short record of merged rainfall fields and corresponding data from a selected raingauge.
- The SBM model holds much potential to generate detailed space and time stochastic rainfall values which can be used as input to a CSM system.
- The method of disaggregating daily rainfall developed in this project introduces a stochastic element into the ACRU model and the disaggregation procedures can be used by other hydrological studies where the disaggregation of daily rainfall is required.
- The use of the ACRU model for design flood estimation was shown to produce distributions of simulated daily volumes which generally reflected the observed distribution in catchments for a range of catchment areas.
- The distribution of the daily simulated peak discharges generally reflected the observed distribution in smaller catchments (< 150 km²). In larger catchments the good simulation of the distribution of streamflow volumes did not consistently translate into good distributions of daily peak discharge.

- The advantage of continuous simulation modelling to provide consistent and reliable estimates of design floods have been highlighted in this study. This approach avoids calibration against observed flow data which may be erroneous and is able to reflect current and future conditions in the catchments in the estimation of design floods and thus avoid any non-stationarity which may be present in the observed flow data.
- This study has emphasised the need to improve the estimation of historical rainfall, irrigation and land cover changes in a catchment in order to realistically simulate observed hydrological responses.
- The difficulty in translating a flood volume into a realistic hydrograph with the correct peak, particularly on larger catchments, is evident from the results obtained.

The results from this study have shown that the use of the ACRU model as a CSM can simulate the hydrological responses from an operational catchment, despite the challenges related to data and operations in the catchment. The output from the CSM has been shown to produce reasonable and consistent estimates of design floods, particularly in smaller catchments.

Recommendations for Future Research

In order to refine and improve the CSM for design flood estimation, the following recommendations are made:

- The method of adjusting historical raingauge data to estimate catchment rainfall should be applied for all catchments where radar data are available.
- The use of the merged rainfall fields created from the radar and raingauge data should be used as input to hydrological models where possible.
- In order to simulate historical flow data, the use of a time series of land cover information should be generated where possible and a database of changes to land cover should be captured and maintained for future use.
- An analysis of the hydrographs generated by the CSM should be made to further assess the performance of the model for design flood estimation.
- The translation of the runoff volume into a hydrograph and associated peak discharge requires further refinement. This may involve investigating the estimation of catchment lag and further investigation into the performance of flood routing algorithms for application in ungauged catchments.
- A more detailed study is required to assess the significance on the simulated performance of the stochastic disaggregation of daily rainfall.
- The SBM should be refined to be user friendly and easily calibrated against raingauge data and the SBM should be used as input to a CSM to generate long sequences of streamflow for design flood estimation.
- The methodology for the temporal disaggregation of daily rainfall requires further refinement. It is recommended that the methodology used be applied on discrete ranges of daily rainfall i.e. for smaller and larger events. It is further recommended sequencing of the disaggregated hourly rainfalls be refined in order to improve the simulation of the structure of the rainfall, as measured by the lag autocorrelations, number of events and event durations.

Knowledge Dissemination

Technology transfer has taken place in various forms during the course of the project. Conferences have been attended, papers have been published, guest lectures have been presented and MSc and MSc Eng dissertations have been completed. Below is the list of publications and dissertations produced, conferences attended and lectures presented by members of the project team.

Publications

- Chetty, K., Smithers, J. C. and Schulze, R. E., 2003. Towards a Continuous Simulation Modelling Approach for Design Flood Estimation in South Africa, 2nd IWRM Symposium. IAHS Red Book Series, Stellenbosch, South Africa, pp. 16.
- Chetty, K. T. and Smithers, J. C., 2005. Continuous Simulation Modelling for Design Flood Estimation in South Africa: Preliminary Investigations in the Thukela Catchment. *Physics and Chemistry of the Earth*, 30: 634-638.
- Frezghi, M. F. and Smithers, J. C., 2005. Merged rainfall fields for continuous simulation models, Proceedings of the Twelfth South African National Hydrological Symposium. SANCIAHS, Pretoria, RSA.
- Knoessen, D. M. and Smithers, J. C., 2005. The development and assessment of a daily rainfall disaggregation model for South Africa, Proceedings of the Twelfth South African National Hydrological Symposium. SANCIAHS, Pretoria, RSA.
- Schulze, R. E. and Ghile, Y. B., 2004. SCS-LHI: Background and User Manual on the Application of SCS-Based Techniques for the Estimation of Design Floods from Small Catchments in Regions with Limited Hydrological Information ACRU Report No. 52, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, RSA.
- Smithers, J. C. and Chetty, K. T., 2005. Design flood estimation using a continuous simulation modelling approach, Proceedings of the Twelfth South African National Hydrological Symposium. SANCIAHS, Pretoria, RSA.
- Tewolde, M. H. and Smithers, J. C., 2006. Flood routing in ungauged catchments using Muskingum methods. *Water SA*, 32(3): 379-388.

Dissertations

- Frezghi, M. S., 2005. The development and assessment of a methodology to improve the estimation of the spatial distribution of rainfall. MSc Eng. Dissertation Thesis, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, South Africa.
- Ghile, 2004. An adaptation of the SCS-ACRU hydrograph generating technique for application in Eritrea. MSc Dissertation Thesis, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, South Africa, 167 pp.
- Knoesen, D. M., 2005. The Development And Assessment Of Techniques For Daily Rainfall Disaggregation In South Africa. MSc Dissertation Thesis, School of

Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Tewolde, M. H., 2005. Flood routing in ungauged catchments using Muskingum methods. MSc Eng Dissertation Thesis, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Conferences attended and guest lectures

- IAHS 2nd Integrated Water Resources Management Symposium held in Stellenbosch, SA, 2003. (Ms Chetty)
- British Hydrological Society Symposium held in England, June 2005. (Prof Smithers)
- Guest Lecture, Centre for Ecology and Hydrology (CEH), Wallingford, UK, 2005 (Prof Smithers)
- Waternet Conference held in Namibia, November 2004 (Ms Chetty)
- Guest Lecture, Water Resources Development and Training Centre, University of Roorkee, India, January 2005 (Ms Chetty)
- SCS design flood estimation course, SAIAE Continuing Professional Development (CPD) Events: 2004, 2005 and 2006 (Prof Smithers, Prof Schulze and Ms Chetty)

Capacity and Competency Building

Capacity building has been practiced and successfully achieved throughout the duration of this project. The project employed Ms Chetty as the principal researcher on the project and has enabled her to complete her studies towards an MSc degree in Hydrology. The project also employed Mr Owen Wilson as a research assistant as part of a broader capacity building internship programme within the School of Bioresources Engineering and Environmental Hydrology at the University of KwaZulu-Natal. Mr Wilson subsequently successfully completed his Honours degree in Hydrology. Both Mr Wilson and Ms Chetty are from previously disadvantaged communities.

Four students, Mr Mehari Frezghi (MSc Eng), Mr Darren Knoesen (MSc) and Mr Mesfin Tewolde (MSc Eng) and Mr Yonas Ghile (MSc), have completed their postgraduate degrees at the University of KwaZulu-Natal while working on components of the project.

Both Ms Chetty and Professor Smithers, the project leader, teach Hydrology and Bioresources Engineering modules at undergraduate and postgraduate levels and the students employed on the project tutored modules at undergraduate level. Currently over 70% of these classes comprise of students from previously disadvantaged backgrounds.