Assessing Flood Hydrology in Data Scarce Tropical regions: a Congo (ROC) case study

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Abstract A robust hydrological assessment can be a challenging task in regions where a lack of data, of sufficient quality, is available to fully validate analysis. This level of uncertainty is heightened in studies of flood hydrology for tropical regions, where spatio-temporal variation in rainfall can be significant and the associated timing of flooding can be challenging to determine.

The Tchivouba catchment, situated within the Republic of Congo, was used as a basis for the study of flood hydrology in the tropics, and the methods presented in this paper aim at reducing uncertainty in instances of data scarcity in similar settings.

Introduction

The focus for this study was to provide a robust assessment of the flood hydrology for a proposed mine development, situated in the Republic of Congo (RoC). The location of the progressive open pit would require significant river engineering works, with construction of multiple dams and river diversions proposed to enable progression of the pit and safeguard the mine operatives. A detailed study of both the regional and local climate and hydrology was therefore commissioned to ensure production of the most efficient, reliable and cost effective engineering design solutions for surface water systems.

Estimation of flood flows is challenging in many parts of the African continent, but particularly so in the RoC where hydro-meteorological data is so scarce that development of suitably robust statistical methods to estimate flood flows has not been possible. For example, use of statistical methods, such as regional analysis or flood frequency curve development, is not possible given the lack of data to feed into the analysis. Regional analysis is conventionally done through either 'pooling' data from catchments with similar hydrological characteristics to make predictions such as that in the Flood Estimation Handbook (CEH 1999) or fitting regression lines to the large sets of data (McKerchar and Pearson 1989), to develop a relationship for prediction of flood flow in each region within the country of study. Where data is only available for a limited number of catchments, often at a regional scale, (catchment sizes in excess of 500 km^2), with insufficient temporal resolution in the frequency of measurements, combined with records often of insufficient length (<20 years), development of such regional relationships, or even a single site flood frequency curve, is extremely challenging.

In the absence of these alternate, more data reliant and statistically robust methods, hydrologists working within industry often resort to making flood predictions using simplified event based rainfall-runoff models. The tendency within a consultancy environment in the mining industry, is to adopt the simplest and most efficient method that produces the most conservative flood discharge. Using methods such as the Rational or SCS Runoff Curve Number (CN) method, this allows for uncertainties associated with a lack of data and incorporates an allowance for risk within the engineering design.

Though the methods themselves are robust when applied correctly, some only produce a single flood peak, making them unsuitable for input to design of flood control structures (dams) and their 'lumped' nature means they fail to properly account for the variable physical characteristics of a particular catchment (soils, vegetation cover, topography) and result in more uncertain flood predictions. A subsequent result is often excessive over designed solutions for surface water infrastructure.

Adequately representing the spatial and temporal variation of rainfall within a model presents additional challenges to a hydrologist working in data scarce regions of the world. It is often common practise to use a hyetograph developed elsewhere that shares similar meteorological conditions to the study catchment, such as the SCS dimensionless distributions. The problem with these solutions is that these are now significantly outdated, were developed using averaged data from very large regions in the United States of America (USA) that have regionally different ratios between short duration and long duration rainfall values, and are no longer recommended for use in the USA by the NRCS, let alone elsewhere. Where sufficient site-specific data is available, nested storm patterns can be generated to produce a hypothetical storm, however temporal resolution issues often hinder the development of reliable statistics.

This study applied a bottom up approach, with the baseline hydro-meteorological monitoring network reviewed and improved, to establish a stronger representation of rainfall-runoff response in the area. A detailed review of climatic influences, both at a regional and local scale was performed, with remotely sensed TRMM data used to support the analysis. A hydrological model was built utilising the HEC-HMS platform and the ModClark transform and SCS-CN loss methodologies, requiring the development of design hyetographs, using a time-distribution method, which allowed determination of the most adequate shape for the hyetograph. Further refinement of the model resulted from validation of simulated outputs in response to measured events, utilising a stage monitoring device installed during the study period. Model outputs were used directly as inputs to a 1D-hydraulic model, which considering the semi-braided planform typology presented multiple challenges.This paper aims to emphasize that selection of the most appropriate methods of analysis and modelling, taking into account project specific constraints, is critical to understanding flood hydrology. This must be underpinned by a local scale baseline monitoring network with adequate spatial coverage and temporal resolution, quality controlled data and a clear understanding of the regional and global scale factors which impact local conditions.

It should be understood that the aim of this paper is not to critique or pass judgement on the work of others, nor is it to present a perfect methodology for industry based hydrologist to follow. Rather it presents one solution that may be useful in some instances and outlines the approach taken to understand the unique climate and hydrological setting of the study area and the methods applied to overcome the uncertainty in flood flow estimation associated with limited data.

Case Study Location and Background

The 113 km^2 Tchivouba catchment within the Republic of Congo was used as a basis for the study of flood hydrology in tropical regions. Located in the south-west of the ROC within the coastal plain, a narrow strip of land between the Mayombe Mountains and the Atlantic coast, the Tchivouba is a tributary of the Loémé river, which drains approximately 3,199 km^2 into the Lakes of Cayo and Louafouleba before discharging into the Atlantic Ocean, see Figure 1.

In broad terms, the climate in the RoC is strongly influenced by the movement of the Inter-Tropical Convergence Zone (ITCZ). The warm 'pseudo'-monsoon flux of south-westerly moist air from the Atlantic produces a large zone of convective clouds. The behaviour of the ITCZ from year to year is deemed the primary factor in precipitation variability across the region in which the Tchivouba Catchment is situated. However, a paucity of high quality long-term climate datasets of sufficient spatio-temporal resolution prevent deeper understanding and quantification of rainfall variability (Todd & Washington 2004; Washington et al. 2013, Nicholson and Grist 2003).

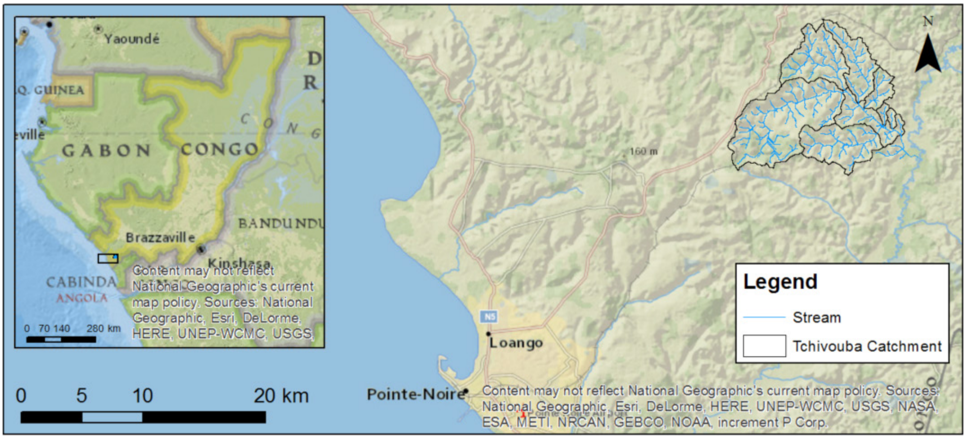

***Figure 1**: Project location*

Methods

A detailed climate and catchment characterisation study was completed, to determine both the quantity and spatial variability of rainfall falling within the Tchivouba catchment, and the catchment characteristics that influence the interception, storage, losses and propagation of storm runoff response throughout the catchment.

Long-term regional rainfall data was collected to support site-specific short-term rainfall records collected at four project rain gauges installed within the catchment. High-resolution satellite-based precipitation estimates derived from the Tropical Rainfall Measuring

Mission (TRMM) precipitation radar were utilized, demonstrating the significant spatial variability in rainfall resulting from the large-scale convection system influenced by the movement of the Inter-Tropical Convergence Zone. A long-term synthetic rainfall time-series was developed for the catchment, based on regression analysis between the local stations and the regional climate station records and design storm rainfall depths calculated utilising the annual maxima method with the Gumbel extreme value distribution and the Cunnane plotting position formula. Individual storm events measured within the project area were analysed and dimensionless mass curves developed following the Huff (1967) methodology, to determine the temporal distribution of each design storm event defined for use within the model.

To better understand the natural runoff regime within the project area, a hydrometric station was installed within the upper reaches of the catchment where well-defined channels and in-bank flow was evident. Downstream, the project was inundated wetland, resulting in difficulties accurately obtaining hydrometric measurements of the runoff hydrograph in these areas. Although limited, this upstream location provided a validation point for subsequent modelling, and considering water management infrastructure for the mine would be located at sub-catchment outlets in the form of diversion channels and attenuation dams prior to the low-lying floodplain, allowed for some degree of confidence in subsequent design flood flows.

Detailed catchment topography, vegetation and land use mapping had been obtained through a LiDAR survey within the lower floodplain regions of the catchment. These were supplemented in the outer reaches by satellite imagery and digital elevation data obtained via the Shuttle Radar Topography Mission (SRTM). A regional soil map and field investigations using infiltration tests and soil definition were used to define the soils and shallow subsurface conditions in the area.

To determine design flood response at various locations throughout the project area, a detailed rainfall-runoff model was required that would provide the flexibility to characterize and define the variable rainfall-runoff relationship throughout the catchment. Utilising site specific data, an improvement on lumped, catch all methods such as the Rational Method was sought, to better simulate the spatial variability in runoff response within the local area using a method more appropriate for the catchment size and location. A HEC-HMS model was constructed, utilising a gridded SCS-Curve Number (CN) loss methodology and Mod-Clark transformation to provide a quasi-distributed rainfall-runoff model. By discretizing the catchment domain into a uniform grid, a linear quasi-distributed transformation method was utilised that has the ability to account for spatial variations in rainfall and losses using the grid. Rainfall excess was determined for each grid cell and routed through a linear reservoir accounting for catchment storage effects. The runoff travel time for each grid cell was calculated and scaled to overall catchment time of concentration based on the travel time to the catchment outlet. The SCS curve number loss method was then utilised and spatial variation within the catchment included within the grid. By utilising a relatively fine grid resolution, this method used a discharge-weighted approach to determining the overall runoff from the catchment as opposed to a weighted CN, providing a more accurate representation of runoff response, particularly considering the considerable spatial variation in topography, land use and sub-surface saturation. The gridded CN were calculated using a land cover and soil map for the catchment alongside a table relating land use to curve numbers for each hydrologic soil group in the catchment area using reference hydrological soil-cover complexes.

An initial abstraction ratio, (the initial rainfall amount in mm that is retained before runoff commences), plays an important role in the calculated runoff depth, the hydrograph peak and the temporal distribution of runoff. It is for the most part dependent on climatic conditions and arguably the most ambiguous of the parameters defined within the modelling process, investigated in many studies (Jiang 2001; Hawkins et al. 2002 and Mishra and Singh 2004) with determined values ranging between 0.01 and 0.3. Due to the obvious ambiguity, a sensitivity analysis was performed to provide the best understanding of sub-catchment response to variations in this parameter.

The boundary of the modeled area was defined as the outline of the entire Tchivouba catchment; which incorporates all contributing streams and rivers upstream from the final outlet into the River Loémé in the SE part of the project area. The catchment has been split into a number of sub-catchments, each defined in relation to specific junctions within the main Tchivouba network that represent the confluences of incoming tributaries. These channels are all slow moving owing to the fact they are densely vegetated and have shallow channel slopes. The relatively shallow cross-sectional channel profiles of these watercourses, together with debris deposited within them, results in regular 'out of bank' flow.

An unsteady state 1D hydraulic model was constructed using HEC-RAS to incorporate approximately 9.4km of the Tchivouva river, from its confluence with the Loeme River to a point 1.5 km upstream of the proposed open pit. Cross-sectional information was obtained directly from LiDAR survey information, with site access and the swamp conditions of the lower regions preventing the collection of detailed in-channel geometries. Given the shallow nature of the flood plain channels, this approach was determined to at least provide a conservative approach to flood line determination, with cross sectional topography at worst underestimating the conveyance potential of the channel due to the LiDAR reflectance from the water surface. A sensitivity analysis was performed to assess the sensitivity of the model to changes in key input parameters. The results indicate the model is not particularly sensitive to change in input parameters. However, there was clearly a need to identify roughness values for the model which are representative of those in reality as high values of n, mean higher predicted water levels, albeit minor ones in this study. Land-use and vegetation mapping, aerial photography, assessment of obstruction and in channel sampling allowed representative n-values to be incorporated into the model.

Results and Discussion

Utilising detailed rainfall analysis, design rainfall depths and design hyetographs were developed that adequately represented the local magnitude and temporal distribution of design storm rainfall, see Figure 2. The derived design hyetograph, developed from analysing all the significant storms in the available monitoring record, has a temporal distribution typical of a convective storm, with the majority of rainfall falling in the second quartile. A clear understanding of the large scale processes driving the localized rainfall distribution, coupled with an understanding of what convective storm hyetographs should look like in terms of the cumulative mass distribution in time, provided confidence that the hyetograph developed for input to the model, which subsequently strongly influences the rainfall-runoff relationship within it, would be representative of the study catchment.

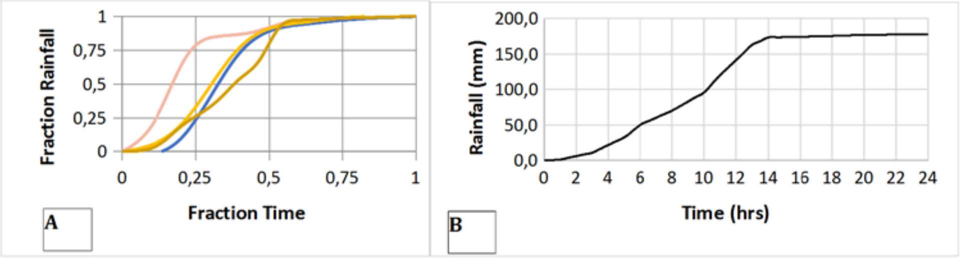

Figure 2: Nested storm analysis (A) and subsequent 100 year 24-hour design hyetograph (B).

Utilising the measured flow data available within the upper catchment, the model was refined in a simple calibration to increase confidence in the selection of an appropriate Initial Abstraction ratio (IaR). Individual storm events were modelled and IaR adjusted to produce the best fit between the measured and simulated hydrograph, see examples in Figure 3. An IaR of 0.165 was defined for use in the model.

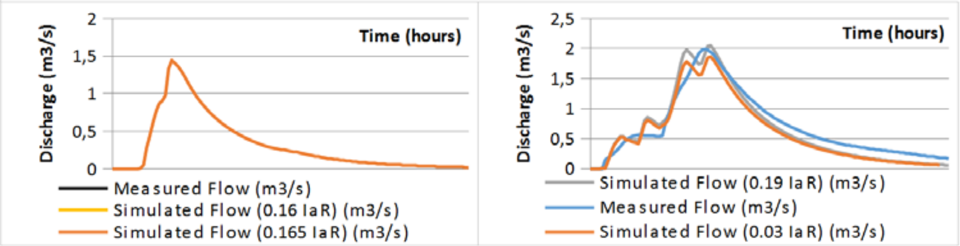

Figure 3: Sample of 'calibration' runs – two individual storm events in this example.

The ModClark model was then utilised to simulate the rainfall loss and runoff response across the Tchivouba catchment, with Figure 4 demonstrating the runoff hydrograph within the Upper Tchivouba sub-catchment for the 1 in 10 and 1 in 100 design storm. This achieved a key aim for the study, which was to use more detailed methods of assessing the hydrology, than those in previous studies of watercourses in this catchment in order to arrive at more representative flood flow estimates. These improved estimates then provide appropriately conservative engineering design inputs and ultimately result in the most cost effective and sustainable design solutions for water management infrastructure.

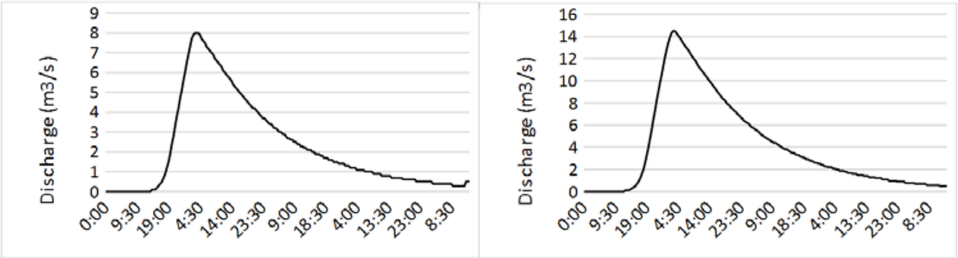

Figure 4*: 24 hour design storm runoff hydrograph; 1 in 10 year (A), 1 in 100 year (B).*

Confidence that the lower estimates provided by the ModCLARK model were representative of the catchment in flood conditions was provided by the model calibration process. Model outputs matched well with the time to peak and magnitude for the observed storm events selected for the calibration process.

The model hydrographs were utilised in a 1D HEC-RAS model to simulate the expected flood levels within the catchment and future mine area, to highlight the at risk areas and inform future design and mitigation measures.

The length of record available for both stage and flow within the lower catchment only allowed development of a preliminary rating curve, and one which is particularly sparse at the upper end, so full calibration of the hydraulic model outputs was not possible.

Conclusions

In order to reduce uncertainty in flood predictions, this study utilised high resolution TRMM data in unison with a network of rain gauges to increase understanding of the spatial distribution of rainfall across the Tchivouba catchment and allow development of a representative design rainfall hyetograph for input to hydrological modelling.

The choice of a quasi-distributed hydrological model allowed better representation of catchment response to rainfall events, reducing the uncertainties associated with use of lumped models with little parameterisation, used in prior studies of the project area.

Uncertainty in predictions was also reduced in the modelling process through event based calibration of the hydrological model, and through detailed sensitivity analysis of both the hydrological and hydraulic models to changes in key parameters. Installation of an automatic stage monitoring device in a suitable reach within the catchment allowed development of a preliminary rating curve for model calibration. Prior to this, no reliable continuous measurements of river stage and discharge had been collected.

Whilst every effort was made to isolate the uncertainty within the hydrological model, using observed data to calibrate the rate of initial abstraction, the number of observed events from which calibration was performed was limited, both in terms of total number and in terms of the magnitude of events. Further improvement could be made in future as more extensive climate and surface water records are collated, allowing for updated flood predictions. These datasets would refine the outputs of the hydrological model and produce a better rating curve with which to calibrate hydraulic models.

In conclusion, this study has advanced knowledge of the hydrological and hydraulic flood behaviour of the project, through extension to the baseline monitoring network, data collection and quality assurance, appropriate choice of modelling software and model calibration and sensitivity analysis. By its very nature flood prediction is uncertain, but by applying each of these steps even when under significant constraints, the authors have found during the course of this study that these can be significantly reduced.

Acknowledgements

The authors thank Cominco Resources Limited for giving us the opportunity to conduct this study and present this paper using their data. Also for their collaboration in what has been a challenging and highly rewarding study to have worked on.

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