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Uncertain hydrological modelling: application of the Pitman model in the Great Ruaha River basin, Tanzania

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Abstract Uncertainty analysis has become the standard approach to hydrological modelling, but has yet to be effectively used in practical water resources assessment. This study of the Great Ruaha River basin in Tanzania is based on the use of regional estimates of mean runoff, groundwater recharge and three flow points on flow duration curves (FDCs) to constrain ensemble outputs from the Pitman monthly model using Monte Carlo parameter sampling. The constraint bounds were quantified from gauged data available for 26 sub-basins together with assumptions about the spatial variations in hydrological response using limited physical sub-basin property and climate data. The results are encouraging in that the simulated FDC ranges bracket the observed curves at two gauging stations downstream of many ungauged sub-basins that are important sites for water resources development decision making. Further work is required to refine the constraint bounds, the input parameter sets and climate data and achieve a more robust model of the basin.

Key words uncertainty; hydrological modelling; southern Africa; hydrological constraints

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1. INTRODUCTION

Some form of uncertainty analysis has become the de facto standard approach for almost all scientific hydrological modelling studies, although the exact nature of the uncertainty approach varies between individual studies (Beven and Binley, 1992; Wagener ***et al.,*** 2003; Vrugt ***et al.,*** 2003; Kavetski ***et al.,*** 2006; Abbaspour ***et al.,*** 2007; Kapangaziwiri et al., 2012). The International Association of Hydrological Sciences PUB (Predictions in Ungauged Basins) decade achieved a great deal in establishing much of the philosophy and many of the techniques required for uncertainty analysis in hydrology (Hrachowitz, 2013). However, these techniques have not been widely used within practical water resources assessments (Pappenberger and Beven, 2006) and many such studies remain based on traditional model calibration approaches despite the fact that the study participants recognise the uncertainties in the methods and data that they are using.

The nature of the sources of uncertainty in hydrological modelling are well recognised and include uncertainties in the model structure (Gupta et al., 2012), parameter uncertainty (Wagener and Wheater, 2006), the input climate data (Younger et al., 2009), the observed flow data used for model evaluations (Westerberg et al., 2013), as well as in the impacts of water abstractions (Hughes and Mantel, 2010). From a practical modelling perspective the choice of model is often constrained by convention and model familiarity and therefore structural uncertainties play a limited role and arguably can be considered part of parameter uncertainty. In a model that has been demonstrated to include components that cover most of the known hydrological processes likely to occur within a region, the dominance of different processes in specific sub-basins will be reflected by different parameter sets (Hughes, 2013). The major issue then becomes getting the right

answers with the most suitable parameter sets (Kirchner, 2006), something that can only be achieved if a thorough understanding of the dominant processes is available (Uhlenbrook and Sieber, 2005, Banks et al., 2011). Unfortunately, such knowledge is frequently not available in large scale practical water resources assessment studies and we are often faced with using limited information to develop behavioural models (Beven, 2012). One of the lessons learned from the PUB decade is that models can help to improve our understanding of prevailing hydrological processes (Fenicia et al., 2008; Blöschl et al., 2013).

Arguably, the most important aspect of any uncertainty approach to hydrological modelling is not the method of generating uncertainty ensembles, but the method used to evaluate those ensembles and to decide which can be considered behavioural (Beven, 2012) in the face of uncertain observed data, or no observed data, for comparison purposes. Various contributions have suggested several approaches that involve regional indices of hydrological behaviour (Wagener and Wheater, 2006; Yadav et al., 2007), regional flow duration curves (Westerberg et al., 2013) or constraints linked with ***a priori*** parameter estimation using physical basin characteristic data (Kapangaziwiri and Hughes, 2008; Kapangaziwiri et al., 2012).

This paper presents part of a comprehensive modelling study of the hydrology and water resources of the Great Ruaha River basin in Tanzania, East Africa. The model used is the Pitman monthly time step conceptual model that has been applied extensively in the southern African region for both scientific and practical studies (Hughes, 2013). Parallel studies involve the use of the MIKE-SHE (Vansteenkiste, 2014) and SWAT (Ndomba et al., 2008) models and the ultimate aim of the whole programme is to provide science-based tools for water resources decision making within the basin.

2. STUDY AREA

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The Great Ruaha River (GRR) is an upstream tributary of the Rufiji River Basin within Tanzania and covers an area of 86 000 km^2. The basin is drained by four main tributaries (Figure 1); the Upper Great Ruaha (ug24 and upstream), the Kisigo (1ka42 and upstream), the Little Ruaha (1ka31 and upstream) and the Lukosi (1ka37 and upstream). Figure 1 illustrates that 48 sub-basins have been defined for this study, 26 based on the available stream flow gauging stations (the sub-basins labelled 1ka** In Figure 1) and 22 that are ungauged (sub-basins labelled ug**). The majority of the runoff is generated from the Chunya escarpment to the west, the Kipengere ranges in the south west and the Poroto Mountains in the south central parts of the region (Figure 1). The runoff generated feeds the alluvial and seasonally flooded Usangu plains (including the Ihefu perennial swamp) located in 1ka71 and 1ka27a. The GRR then continues through the Usangu game reserve and Ruaha National Park and supplies the Mtera Dam (1ka5a) and Kidatu hydroelectric plants. The majority of the irrigation water use in the basin is located where the headwater sub-basins drain into the Usangu plains. One of the key water resources development issues is competition for water between the upstream abstractions for irrigation, the environmental water needs of the national park and the hydroelectric power generation needs of Mtera Dam (Lankford et al., 2009).

The GRR basin is characterized by major variations in topography, climate, soil and vegetation. The elevation ranges from approximately 109 to 2 962 metres above mean sea level (mamsl), while the topographic characteristics are strongly related to erosion cycles which have prevailed over the continent since the late Jurassic. The soils and hydrogeology are also closely linked to the geomorphological landforms. The African Zone is an extensive part of the basin with relatively flat topography that includes most of the semi-arid northern tributaries, the Little Ruaha and some of the western headwaters (ug3, 5 and 18). The infiltration capacity of the surafce soils is generally high, but may be restricted in deeper layers of clay filled saprolite derived from the underlying granites (CCKK, 1982). The Post-African Zone mostly occupies the lower parts of the Upper Great Ruaha (ug24, 1ka59, 1ka33 and ug2) and is characterised by a relatively young and unstable land

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surface subject to soil erosion. Borehole profiles of this zone show a layer composition similar to that of the African Zone (CCKK, 1982). The Gondwana and Post Gondwana Zone is located in 1ka37 and sub-basins 1ka8a and 1ka9. These areas have steep topography with considerable depths of saprolite on plateaus but thin saprolite on the valley slopes. These areas have relatively high baseflow regimes, particularly 1ka37 that is underlain by limestones. The Rungwe Volcanic Zone is characterised by very different geology compared to the other upland zones and is dominated by a mixture of basalts, ash and pumice. Previous studies have identified a considerable amount of ground water storage and ground water fed base flow during the dry season (CCKK, 1982). The Scarp Zone is located mainly along the southern and western sides of the Usangu Plains and refers to the steep scarp faces with rapid runoff and frequent presence of springs (CCKK, 1982). The Alluvial Fans Zone borders the Scarp and the Post-African zones and is important due to its groundwater potential related to relatively permeable geology and recharge from the surrounding mountain areas (SMUWC, 2001). The Lake Deposits Zone is located mainly within 1ka71a and 1ka27 and consists of heterogeneous buried river channel and floodplain deposits, which are generally less permeable than the surrounding alluvial fans.

The climate is largely controlled by the movement of the Inter-Tropical Convergence Zone (ITCZ). The rainfall regime is unimodal with a single rainy season from December to May/June but with a high degree of spatial variability strongly correlated with altitude. The mean annual rainfall ranges form 1 800 mm yr^{-1} in the highlands to less than 600 mm yr^{-1} in the semi-arid parts of the basin in the north west. Minimum and maximum average monthly winter and summer temperatures vary from 5 °C to 13 °C and 22 °C to 27 °C, respectively in the higher altitudes and from 15 °C to 24 °C and 28 °C to 30 °C, respectively in the lower parts of the basin. Evaporation ranges from 1 800 mm yr^{-1} in the semi-arid part of the basin to less than 800 mm yr^{-1} in the wet highlands

3. MODELLING METHODS

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The model used in this study is a modification of the original Pitman (1973) monthly time-step, rainfall runoff model. The version of the model used and it's history of development and application are discussed in Hughes (2013), as well as additional sources cited within that paper, and the full details of the model are not repeated here. The main modification to the original structure, designed to simulate natural hydrology, was associated with the inclusion of an explicit surface-groundwater interaction function (Hughes, 2004), but further additions include functions to simulate water use and wetland impacts (Hughes et al., 2013), both of which are relevant to the GRR basin. The model is semi-distributed with independent parameter and climate inputs used for each sub-basin defined by the user (see Figure 1 for the GRR setup). The methods used to establish uncertain, but behavioural (Beven, 2012), parameter sets for both natural and impacted conditions have been adapted from the uncertainty framework proposed by Kapangaziwiri et al. (2012).

The approach that has been adopted involves two main steps. The first step only simulates the incremental contribution of each sub-basin (i.e. no downstream routing), only treats some of the 15 natural hydrology parameters as uncertain (using uniform or normal distributions) and is designed to generate at least 2 000 behavioural parameter combinations based on ranges established for 6 constraints. The constraints used in this study are the 1) mean monthly runoff volume (MMQ; $m^3 * 10^6$), 2) mean monthly groundwater recharge (MMR; mm), 3), 4) and 5) runoff volume at the 10^{th} , 50^{th} and 90^{th} percentiles of the flow duration curve (Q10, Q50 and Q90) divided by MMQ, and 6) the percentage of months with zero flow (%). The assumption is that the constraint values would be quantified from observed flow data or any available regional information on natural hydrological behaviour and that the constraint boundaries should reflect the uncertainty in this available information (Yadav et al., 2007; Westerberg et al., 2013). The model is run for each sub-basin up to 100 000 times with simple independent Monte Carlo sampling of the parameter distributions. An ensemble is considered behavioural if the simulated characteristics fall within all 6 constraint bounds and these parameter sets are saved for use in step 2. The process is illustrated in Figure 2A and the model stops when 2 000 parameter sets are saved or until the maximum number (100

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000) of test ensembles has been reached. It is clearly important that the constraint bounds are compatible with each other and with the parameter uncertainty bounds.

Figure 2B illustrates an extreme case where no behavioural ensembles are generated because the constraint bounds are not compatible. This may occur, for example, if the MMR constraint is high, but the Q90 constraint is low. High groundwater recharge simulations would pass the MMR constraint test, but would fail the Q90 test. Figure 2C illustrates an extreme case where the parameter uncertainty bounds are not compatible with the constraints. An example might be setting the recharge and soil water drainage parameters of the model to relatively high values for a semi-arid ephemeral sub-basin that has very low (or zero) Q10 values and a high percentage of zero flows. Between these two extremes are many other possibilities that might result in less than 2 000 behavioural results. The relatively high degree of equifinality present within the model precludes a simple approach of setting high ranges for initial parameter uncertainty as experience suggests that the initial cloud of possible outputs is then too dispersed to allow 2 000 behavioural ensembles to be found. A post-processing utility program is used to identify improved parameter uncertainty bounds when less than 2 000 behavioural parameter sets are found.

The second step in the process uses all the model components (including those used to quantify water use or land use change effects) and the full model is run with all sub-basins linked to generate cumulative stream flow volumes. The natural parameter values are sampled from the 2 000 saved behavioural sets (i.e. the full set of saved values), while the other parameters are sampled independently from their defined distributions. The perceived advantage of this approach is that we can be certain that all of the simulated sub-basin incremental stream flow ensembles are behavioural relative to the constraints used in step 1. The outputs from step 2 can be compared with any observed stream flow data (either located in headwater, or downstream sub-basins) and further constraints used to limit the final ensemble set or to re-evaluate some of the water use parameters and their uncertainty.

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In this study the model results evaluations were based on four objective functions. The first two are the Nash-Sutcliffe coefficient of efficiency (Nash and Sutcliffe, 1970) using both un-transformed data (CE) and natural log transformed data (CE{ln}). The other two are the percentage bias of the simulated mean monthly flow volume relative to the observed mean using no data transformation (%Bias) and a natural log transformation (%Bias{ln}).

4. APPLICATION TO THE GREAT RUAHA RIVER BASIN

4.1 Quantifying the climate inputs and the observed flow data

The details of how the climate inputs were generated for the basin, over the total modelled period of January 1960 to December 2009, are not included in this paper. No warm-up period is typically needed for this model when simulating strongly seasonal climate regimes and when the model is initiated at the end of the dry season, as is the case in this study. The methods used for the rainfall data inputs are discussed in Stisen and Tumbo (2015) and were based on merging the limited available rain gauge data with satellite data (CPC-FEWS) developed specially for the African continent and which has previously been demonstrated to be useful for similar hydrological modeling applications (Stisen and Sandholt, 2009). The available rain gauge data are interpolated using a regression based method with the spatial patterns of variation taken from the satellite precipitation data (Stisen and Tumbo, 2015). The spatial variation in annual potential evaporation was partly based on data from only three stations, one each located in the extreme north and south of the basin and a further station in the central area. Additional information was downloaded from the International Water Management Institute (IWMI) online climate service portal (http://wcatlas.iwmi.org) and these data are based on Penman-Montieth evapotranspiration estimates. It is likely that there will be a high degree of uncertainty in the model inputs for evaporation demand.

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Daily flow data were acquired from the Rufiji Basin Water Office (RBWO). Historically, stream flows in the the GRR basin have been monitored by 33 river gauging stations. Most of the 33 stations were reported to be currently operational, but a large number of them are not. For this study, data from 26 gauging stations were available including both currently operational and non-operational stations (Table 1 and Figure 1), however many of them have long periods of missing data. The details of the hydraulic calibration data and the station rating curves were also provided by the RBWO for most of the stations.

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4.2 Uncertainty analysis Step 1: Quantifying the constraints

The constraint ranges for all the sub-basins of the GRR were quantified on the basis of the available observed stream flow data, as well as some assumptions about the response characteristics of the un-gauged sub-basins. All 48 sub-basins were allocated to one of 6 regional groups that were assumed to have internally similar response characteristics (Table 2). The observed stream flow data were first of all screened for periods when the data appeared to be erroneous (excessive high flows, low flows inconsistent with other parts of the record, etc.) and these were removed. The rating curves were also assessed and assigned 'Poor', 'Moderate' or 'Good' quality ratings. 'Poor' ratings were allocated when the rating relationships showed large scatter or where the ratings did not extend to the highest flows. The flow constraints (MMQ, Q10/MMQ, Q50/MMQ, Q90/MMQ and % Zero flows) were then calculated for all headwater gauges and used to guide the development of the regional constraint ranges (Figure 3). Apart from potential errors in the rating curves, it was assumed that additional uncertainty in the observed data would be derived from stage observational errors, short periods of record not adequately representing longer-term mean values of the constraints as well as the effects of abstractions. These were not explicitly quantified (Westerberg et al., 2013), but were subjectively allowed for in the quantification of the regional constraints shown in Figure 3.

The MMQ constraint is plotted in Figure 3A as the runoff ratio to enable comparisons to be made across sub-basins and while all of the gauges are used in this plot, it should be noted that the downstream gauges do not reflect incremental flow conditions from those sub-basins. All the constraints are plotted against the aridity index of mean annual values of potential evaporation demand divided by rainfall. The constraint ranges plotted are for all of the sub-basins within the groups, while the ranges for most of the individual gauged sub-basins were smaller. Group 1 contains the majority of the headwater gauges, is characterised by the lowest level of aridity and has relatively narrow constraint bounds that are largely based on an assumption of ±20% error in the observed data constraint estimates. It also has the highest runoff ratios of all groups. The constraints for Group 2 were more difficult to determine as there are fewer gauges and they mostly represent a mixture of headwater and foothill runoff responses. However, the range of uncertainty is similar to group 1, with the exception of Q10/MMQ. It is likely that the estimate of this range was adversely affected by some poor observed high flow data. The lower bound of the Q90/MMQ constraint for both groups 1 and 2 is very uncertain due to the effects of some abstractions in the headwater areas. Group 3 represents a more diverse set of conditions than the previous two groups and different constraint ranges were used for sub-sets of this group, which is why the ranges are shown as much wider than the previous groups. The main differences within the group are in the recharge and Q90/MMR constraints. The headwater areas (1ka22 and 1ka37) in the east are underlain by limestones and have very high recharge and baseflows. The extent to which these also occur downstream (1ka21, 1ka2a and 1ka31) is more difficult to determine. Groups 4 to 6 represent the more semi-arid parts of the GRR, while they are only represented by a single headwater gauge (1ka41) and therefore valid constraint values are difficult to quantify. This is reflected in Figure 3 by a high level of uncertainty, particularly in Q10/MMR and Q50/MMR.

The recharge constraint was difficult to establish and therefore the ranges were typically quite large. However, they were aligned as far as possible with the Q90/MMR constraint such that most

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of the Group 1 values were quite high (5 to 12 mm month^{-1}), Group 2 generally lower (2 to 12 mm month^{-1}), Group 3 very variable (10 – 15 for 1ka37, but 2 to 10 mm month^{-1} for downstream sub basins) and groups 4 to 6 also variable in the range of 0.5 to 5.0 mm month^{-1}. Similarly, the % zero flow constraint was variable but always zero for groups 1 to 3 and within a range of 10% to 60% for the other groups.

4.3 Uncertainty analysis Step 1: Establishing the ranges of the natural hydrology parameters

Approximate parameter value ranges were initially obtained through some trial manual calibrations of the model against the available stream flow data. The full details of the parameter uncertainty ranges are not provided here, largely because of space limitations (these details will be available within the Rhodes University PhD thesis of the first author, expected to be finalised by the end of 2014. See http://www.ru.ac.za/library/resources/theses/rutheses/). Some of the ground water geometry and outflow parameters (drainage density, storativity and transmissivity) were aligned to the topography and geology, evaluated from the trial calibrations and were not set as uncertain. The ranges of the interception and evapotranspiration parameters were mostly the same for all sub-basins, although the riparian ground water evapotranspiration parameter was set to higher values for the drier and flatter downstream areas than for the steeper headwater sub-basins. The parameters of the triangular distribution function (ZMIN and ZMAX mm month^{-1}) for catchment absorption that is used for surface runoff calculations were generally lower (more runoff) for the steeper headwater areas (ZMIN: 10 to 60; ZMAX: 200 to 600 mm month^{-1}), high for the flat wetland and downstream sub-basins ((ZMIN: 100 to >200; ZMAX: 800 to 1 200 mm month^{-1}) and between these limits for other areas. The uncertainty ranges for the maximum unsaturated zone storage parameter (ST mm) varied over 200 to 500 mm for headwater areas, 600 to 1 000 mm for the foothill sub-basins and 600 to 1 400 mm for some of downstream flat sub-basins. The maximum monthly interflow (FT mm month^{-1}) and ground water recharge (GW mm month^{-1}) parameter ranges generally reflect the patterns of variation of the Q90/MMQ constraint. For the wetter areas

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of group 1, FT varied from 10 to 40 mm month^{-1}and GW from 8 to 35 mm month^{-1}. For group 2 the equivalent values were 5 to 20 and 8 to 20, while for groups 4 to 6 FT was set at 0 to 8 mm month^{-1} and GW at <5 to 10 mm month^{-1}. GW for 1ka37 (limestone) was set to be within 15 to 55 mm month^{-1}. The interflow and ground water recharge estimations are based on non-linear power functions of the current level of storage in the unsaturated zone. The ranges of the power parameters of the two equations (POW and GPOW) were assumed to be the same for all sub-basins.

The top part of Figure 4 illustrates the ranges of the mean monthly recharge (MMR) and low flow (Q90/MMQ) constraints, while the lower part shows the ranges of the two main parameters determining low flow response (FT and GW) for some selected sub-basins. The grey blocks represent the full input ranges, while the black blocks are the ranges of the final 2 000 behavioural outputs from stage 1 of the modelling process. There are a number of cases where the output ranges are substantially lower than the input ranges and this occurs particularly in group 2, where the regional uncertainty is quite high. Part of this result is related to differences in the climate inputs to the model across sub-basins that were assumed to have broadly similar responses. Thus the first 6 sub-basins (group 1) all have the same FT and GW parameter ranges, but have quite different responses in terms of MMR and Q90/MMQ. The GW graph indicates that the full input range of this parameter was not represented in the 2 000 outputs for some of the sub-basins, and neither was the full range of constraints. This could either suggest that the upper constraint bounds are too high or that both the upper and lower GW parameter bounds are too low. While there is too much uncertainty in the available stream flow data to fully resolve this issue, it has been concluded that the upper bounds of some of the constraints have been set too high for some catchments. This conclusion is supported by the fact that the Q90/MMQ results mostly cover the full range of input constraints, which can be more reliably quantified than the recharge constraint. Despite the fact that the upper MMR bounds are not fully consistent with the Q90/MMQ constraint bounds, step 1 of the modelling process has still managed to generate the required 2 000 behavioural outputs.

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4.4 Uncertainty analysis Step 2: Quantifying the water use and other parameters

The impacts of water abstractions are inevitably included in the observed data and therefore have to be simulated before the model can be evaluated against the observed flows. While some of the abstraction effects are small, the major irrigation areas in the upper parts of the Usanga Plains are expected to be quite large, particularly with respect to the low flow regime. The water abstractions have been assumed to consist of relatively small domestic abstractions for village communities located along the south western borders of the basin (mostly groups 1 and 2), together with large scale irrigation schemes at the base of the foothills zones from the tributaries that flow into the Usangu Plains (mostly group 2). Table 2 lists the main water use parameters and identifies the main rice growing areas. These data were obtained from previous reports and population census data (SMUWC, 2001; URT 2012) but are recognised to be highly uncertain. The rice irrigation water use was based on an annual demand of 1 070 mm with a high return flow fraction (0.33). The other irrigation areas used an annual demand of 475 mm with lower return flow fractions of depending on the topography (0 in flat areas, 0.2 in steeper sub-basins). While the water use data can be input as uncertain ranges in step 2 of the modelling process, they were input as fixed values to avoid confusion between different sources of uncertainty. Water use uncertainty will be added at a later stage in the water resources assessment of the GRR.

In addition to the water use parameters, afforestation parameters were included in sub-basin 1ka32a, transmission losses (from the channel to ground water) in the downstream arid areas (e.g. 1ka42, 1ka59, ug24 and 1ka5a) and wetland parameters (Hughes et al., 2013) in 1ka71a and 1ka27, representing the Usangu Plains. The wetland parameters were included after an initial run of the model and an evaluation of the results against observed stream flow data at 1ka59. The wetland parameters were manually calibrated but within realistic parameter limits based on the documented characteristics of the two main wetland areas (WWF Tanzania Country Office, 2010).

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5. MODELLING RESULTS

Figure 5 presents the full uncertainty range and the output range after step 1 for an index based on the model's potential to generate moderate to low flows. This index is the maximum monthly interflow depth (FT) divided by the power parameter (POW, always > 1.0) of the relationship with moisture storage and added to the equivalent ratio for ground water recharge (GW/GPOW). This set of four parameters represents one of the main sources of equifinality (Beven, 2006) in the model. Figure 5 illustrates that the use of constraints to filter the total parameter space has resolved some of the uncertainty in the input parameter space in that very high and very low combinations of the index are not accepted as behavioural. However, there are still many different combinations (equifinality) of interflow depth and ground water recharge depth that can reproduce the observed low flow regimes of the sub-basins.

The main simulation results, compared to the observed flows, are presented in Figures 6 to 8, as well as Table 4. Before discussing these results several factors have to be emphasised:

- All of the results are based on uncertain natural hydrology parameters that were derived using the step 1 constraint analysis. There was no other form of 'calibration' used except for the parameters of the wetland function for 1ka71 and 1ka27a.
- The results are based on fixed but approximate values for the water abstractions. These are certainly not stationary throughout the observed data periods. In some cases the earlier (irrigation not established) and later (irrigation restricted to decrease downstream impacts) periods would reflect lower abstractions.
- The results are compared with very uncertain observed data that are affected by the historical patterns of abstractions, possible non-stationary rating curves and rating curves that do not include the full range of high flows in the observed time series records. This makes it very difficult to evaluate the results using conventional objective functions.

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Despite the comments made above about the value of the observed flow data, Table 4 includes the ensemble ranges of the objective function values for some of the gauged sub-basins. Where the maximum CE and CE{ln} values are greater than 0.5 these have been highlighted to illustrate the number of situations where conventional model evaluations would have suggested that at least some of the uncertainty ensembles could be considered acceptable compared with the observed data. Some of the poor CE results are certainly affected by the limitations of the observed rating curves for high flows making it very difficult to reliably quantify the surface runoff parameters of the model. Figure 6 suggests that these impacts are likely to be at FDC % points lower than 10% and would not have been constrained during step 1 of the uncertainty approach. The extreme high flow simulations may also be affected by uncertainties in the input rainfall data. At the other end of the flow range, it is equally difficult to resolve the uncertainties in water use (either as a model input or as possible impacts on the observed flows) and the impacts on low flow simulations. Table 4 (the CE{ln} column) indicates that the best ensemble simulations for many of the sub-basins have acceptable fits to the observed moderate to low flow regimes, but the very large range of %Bias{ln} and the minimum ensemble values for CE{ln} are indicative of high uncertainty.

Despite these rather negative observations, the model has generated results at the key gauging station downstream of the wetlands (1ka59) that at least bracket the frequency characteristics of the observed flow data after the wetland impacts are included (Figure 7). These results have been achieved after some manual calibrations of the wetland parameters for sub-basins 1ka71a and 1ka27 (Table 5). The documented understanding (WWF Tanzania Country Office, 2010) of the dynamics of these wetland areas is not sufficient to confidently state that the parameter values used are physically representative, but they are believed to be within reasonable bounds of possibility. For example, the zero value for QCap and high value for QSF reflect the fact that the main channel of the GRR disappears within the downstream part of the wetland within 1ka27, while a major channel feature is evident throughout the upper wetland area within 1ka71a. The addition

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of the wetland functions certainly improved the overall results at the outlet of 1ka59. Figures 7 and 8 indicate that while the FDC results are generally adequate and the model is able to reproduce the patterns of inter-annual variability, the simulations of individual monthly flow volumes are not very good. This is quite a typical result in regions where there are likely to be large spatial variations in rainfall, but where there are not enough data to quantify the variability at the model time scale of 1 month. While the use of satellite rainfall data may be useful to fill some of the gaps, satellite rainfall data are not sensitive to orographic controls on rainfall and therefore cannot be expected to completely make up for deficiencies in ground-based observations in topographically diverse regions (Sawunyama and Hughes, 2008).

The assessments of the validity of the ensemble simulations relative to the observed data at the outlet of 1ka5a (Mtera Dam: and the available data pre-date the dam construction in 1984), the other critical site from a water resources management perspective, yielded similar conclusions as those reached for 1ka59. There are ensembles that can be considered acceptable representations of the observed data, although there are many with some months of apparently excessive high flows. Most of these are generated within the Kisigo River sub-basins upstream of 1ka42 and are difficult to ascribe to any obvious model parameter or rainfall errors.

6. CONCLUSIONS, LESSONS LEARNED AND THE WAY FORWARD

The first conclusion must be that this study is not complete. The model results suggest that the evaluation of the observed flow data needs to be more thorough (Westerberg et al., 2013) which may contribute to reducing the uncertainty in those sub-basins where the data can be considered more reliable. The existence of large amounts of missing data within the observed stream flow data makes it difficult to evaluate the model results consistently across the basin and adds to the uncertainty in adequately simulating inter-annual variability. The study has largely ignored the potential uncertainties in the input rainfall and evaporation demand data and more attention needs

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to be given to the volumes and seasonal distributions of the water use data. However, all of these additional analyses would have been extremely difficult and might have been largely meaningless in the absence of the basin scale context of the spatial and temporal variations in simulated hydrological response. The uncertainty version of the Pitman model that has been established through this study provides that context and will be further supported by the results from the MIKE-SHE and SWAT models when these become available and are compared with the Pitman model results presented here. These three models have different structures and inter-model comparisons (Vansteenkiste, 2014) of both the parameter sets and the results, together with the observed stream flow data, should help to improve all three model configurations. The GRR basin can be considered quite well gauged from an African perspective. However, despite the existence of 26 stream flow gauges, there remains a great deal of confusion about the spatial variability in hydrological response. Part of this is related to un-resolved uncertainties in the stream flow data. Further assessment of the results for the Pitman model and comparisons with the other models should also contribute to resolving some of these uncertainties and to a better understanding of the basin scale processes (Fenicia, 2008).

The 2-step uncertainty analysis approach using regional constraints on hydrological response adopted in this study has proved to be very useful in organising a substantial amount of uncertain information into a coherent model of the whole basin. That there are some parts of the basin where further improvements can be made is undeniable (Table 4). However, the results for many parts of the basin, and particularly those downstream sites (1ka59 and 1ka5a) that are critical for water resources assessments and decision making, are very encouraging. Without pre-supposing the outcomes of the comparison with the other models, it is already possible to identify some areas that warrant further attention:

- A re-evaluation of the observed flow data to identify the more reliable records (or parts of some records) so that the constraint ranges for these sub-areas can be reduced.

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- An evaluation of the high flow simulations in some parts of the basin (notably the arid north west sub-basins) to identify if these are related to excessively high rainfall inputs or some deficiencies in the existing parameter sets (e.g. too low maximum storage parameter values).
- An assessment of the sensitivity of the model results to changes in the water use parameters and whether or not any information (SMUWC, 2009) about the historical patterns of irrigation management practices are reflected in changes in the observed low flow regimes.
- An overall re-evaluation of the spatial variations in low flows (linked to the previous point) that includes assumptions about surface – groundwater interactions.
- The inclusion of simulations of Mtara Dam and the downstream hydropower scheme to assist in identifying the key components of the upstream flow regimes that are likely to affect power production. This information would be valuable to provide focus for further model improvements and uncertainty reduction.

There are also some parts of the model that will remain highly uncertain in the absence of additional observed climate, stream flow and water use data. One of these is the transition of hydrological response characteristics from the relatively well gauged headwater sub-basins in the extreme south west of the basin to the lower elevation foothill sub-basins (ungauged) and into the Usangu Plains. Another is the transition from the same headwater areas northwards through the ungauged basins forming the western boundary of the basin to the semi-arid gauged sub-basin 1ka41. These are not only ungauged with respect to stream flows but they also contain no rainfall stations. Amongst the 9 gauged sub-basins in the south western headwaters (Figure 1) there are substantial differences in the observed response characteristics. Some of these can be attributed to known geological and topographical differences, but by no means all of them. Within parts of this area there are large populations of rural communities and their impacts on the hydrological

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regimes remain un-investigated and largely unknown. The possible impacts could include direct abstractions for domestic and garden irrigation purposes (already included in the model), as well as changes to vegetation cover and infiltration characteristics. Including these impacts in the model is likely to remain extremely uncertain.

The overall conclusion is that the uncertainty approach that has been adopted for this study is appropriate in terms of the type of data that are available, the need to improve the scientific understanding of the basin scale hydrological response characteristics and from the perspective of providing integrated information for practical water resources management. It therefore has the potential to make a substantial contribution to the new IAHS scientific decade (Montanari et al., 2013), specifically with respect to the 'science in practice' theme. The authors have learned a number of lessons about the application of this type of approach to uncertain hydrological modelling through the GRR basin study that can contribute to the design and implementation of similar future studies in other large African basins.

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Acknowledgements Dr Simon Stisen of Geological Survey of Greenland and Denmark is thanked for rainfall data inputs to the model, and we are grateful to the Rufiji Basin Water Office (RBWO) for providing the stream flow data.

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Table 1 Available stream flow data

Station ID	River	Start	End	Area (km^2)	% Missing data	Status
1ka2a	Little Ruaha	1954	2009	2 896	30	Operational
1ka5a	Great Ruaha	1957	1980	69 386	58	Closed
1ka7a	Chimala	1962	1992	169	52	Closed
1ka8a	Great Ruaha	1954	2009	783	34	Operational
1ka9	Kimani	1954	2009	446	17	Operational
1ka10	Mlomboji	1956	1983	233	25	Closed
1ka11	Mbarali	1955	2009	1 600	17	Operational
1ka12	Halali	1956	1983	807	20	Closed
1ka15	Ndembera	1956	2010	1 221	12	Operation
1ka16a	Lunwa	1964	1994	75	58	Closed
1ka21	Little Ruaha	1957	2009	2 619	10	Operational
1ka22	Mtitu	1957	2009	461	3	Operational
1ka27	Great Ruaha	1965	1979	20 746	36	Closed
1ka31	Little Ruaha	1957	2010	5 195	21	Operational
1ka32a	Little Ruaha	1957	2009	838	11	Operational
1ka33	Ndembera	1957	2009	1 839	52	Closed
1ka37	Lukosi	1957	2010	3 064	6	Operational
1ka39	Little Ruaha	1957	1980	1 681	58	Closed
1ka41	Kisigo	1957	1974	4 368	55	Closed
1ka42	Kisigo	1957	1994	25 097	66	Closed
1ka50a	Mswiswi	1958	1976	102	68	Closed
1ka51	Umrobo	1960	1994	38	32	Closed
1ka56	Ruaha	1961	1989	182	12	Closed
1ka59	Great Ruaha	1963	2010	23 285	15	Operational
1ka61	Great Ruaha	1965	1976	79 906	77	Closed
1ka71	Great Ruaha	2001	2008	12 514	52	Closed

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Table 2 Regional sub-basin groups, the sub-basins within them and a description of their hydrological response characteristics.

Group	Sub-basins	Characteristics
1	1ka7a, 1ka8a, 1ka9, 1ka16a, 1ka50a, 1ka51, ug15, ug16, ug17	South west headwaters, all with assumed high rainfall and runoff, relatively high recharge and baseflows.
2	1ka10, 1ka11, 1ka12, 1ka56, ug1, ug2, ug4, ug6, ug20, ug21, ug22	Foothills of the south west, as well as some of the larger gauged sub-basins extending from the headwater areas. Lower rainfall and runoff ratios than Group 1.
3	1ka2a, 1ka15, 1ka21, 1ka22, 1ka31, 1ka32a, 1ka33, 1ka37, 1ka39	A mixed group representing the central headwater sub-basins and some in less elevated areas. Some of these are dominated by limestone geology with high recharge and baseflow contributions.
4	1ka41, 1ka42, ug3, ug5, ug7, ug8, ug9, ug10, ug18	The more arid western sub-basins with much lower rainfall, high evapotranspiration and low runoff ratios with some zero flow periods.
5	1ka27, 1ka71, 1ka59, ug24	Central sub-basins with low topography, low rainfall and assumed very low incremental contributions to flow.
6	1ka5a, 1ka61, ug11, ug12, ug13, ug14	The lower sub-basins of the GRR with similar incremental flow contributions as Group 5.

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Table 3 Water use data used in the model (some small uses in group 4 sub-basins have been omitted).

Group 1			Group 2			Group 3		
	Irrigation area (km^2)	Domestic use ($m^3 * 10^3 y^{-1}$)		Irrigation area (km^2)	Domestic use ($m^3 * 10^3 y^{-1}$)		Irrigation area (km^2)	Domestic use ($m^3 * 10^3 y^{-1}$)
1ka7a	21	341	1ka11	84	472	1ka2a	0	66
1ka8a	54	815	1ka12	0	900	1ka15	61	737
1ka9	37	409	1ka56	0	49	1ka21	0	93
1ka16a	0	65	ug1	126	557	1ka22	0	386
1ka50a	0	26	ug2	146	157	1ka31	0	219
1ka51	0	8	ug4	(Rice)47	151	1ka32a	0	352
ug15	0	54	ug6	(Rice)30	55	1ka33	76	413
ug16	0	74	ug20	(Rice)10	152	1ka37	0	590
ug17	0	48	ug21	0	40	1ka39	0	147
			ug22	0				

Table 4 Sample summary of objective function results after step 2 with water use and wetlands (the bold CE and CE{ln} values highlight those above 0.5).

Sub-basin	Range of objective functions across all 10 000 ensembles			
	CE	CE{ln}	%Bias	%Bias{ln}
1ka51	-0.61 : -0.04	-0.10 : 0.27	-2.4 : 26.7	-17.9 : 25.5
1ka8a	**0.58** : **0.75**	-0.44 : **0.53**	-21.9 : 14.8	-51.5 : 8.71
1ka11	-0.76 : 0.31	-2.45 : **0.52**	-36.5 : -3.2	-70.9 : -16.0
1ka56	0.39 : **0.54**	0.04 : **0.80**	-29.1 : 7.8	-44.4 : 33.4
1ka33	-2.64 : -0.77	-3.69 : -0.41	-17.4 : 32.1	-70.1 : -16.0
1ka39	-1.13 : **0.57**	0.37 : **0.82**	1.1 : 53.7	-21.1 : 50.7
1ka21	-0.68 : 0.49	0.03 : **0.76**	-14.8 : 31.2	-32.8 : 18.1
1ka22	-2.39 : 0.29	-1.37 : **0.58**	-20.9 : 18.5	-41.8 : 4.5
1ka31	-0.47 : 0.41	0.39 : **0.71**	-22.1 : 22.2	-32.5 : 22.9
1ka37	-1.95 : 0.16	-0.14 : 0.49	-6.2 : 15.4	-13.1 : 14.5
1ka41	0.32 : **0.68**	-0.87 : 0.30	-60.4 : 7.3	-28.6 : 145.5
1ka27a	**0.58 : 0.73**	0.45 : **0.74**	4.4 : 42.7	-12.1 : 71.0
1ka71	0.29 : **0.69**	-0.29 : **0.80**	-24.1 : 35.4	-32.3 : 54.7
1ka59	0.46 : **0.53**	0.20 : **0.66**	-15.9 : 19.4	-10.2 : 83.3
1ka5	-0.84 : **0.57**	-0.6 : **0.84**	25.5 : 95.9	-21.7 : 106.8

*CE=Coefficient of Efficient, CE (ln)=Coefficient of Efficient Log transformed, %Bias= Percentage Bias , %Biasn (ln)=Precentage bias log transformed.

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Table 5 Parameters of the wetland function used for sub-basins 1ka71 and 1ka27

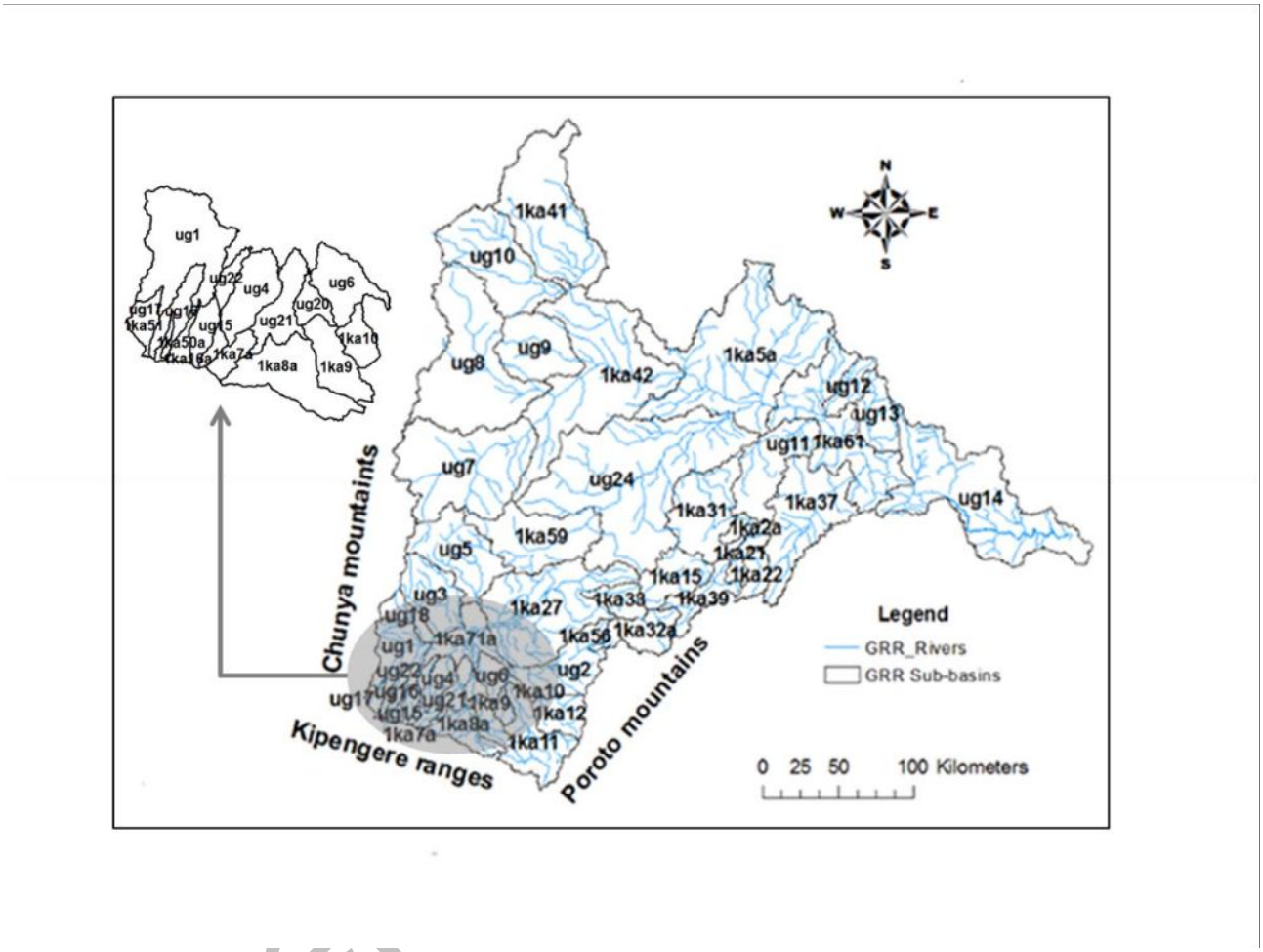
Parameter	1ka71	1ka27
Maximum wetland area (km^2)	800.0	600.0
Residual wetland storage (RWV, $m^3 * 10^6$) below which there are no channel returns.	40.0	80.0
A & B in the wetland area (WA)-volume (WV) relationship: $WA = A*WV^B$	1 000 : 0.8	2 000 : 0.8
Channel capacity (QCap) before spill to wetland occurs ($m^3 * 10^6$)	10.0	0.0
Fraction of channel flow (>QCap) that spills onto wetland (QSF)	0.1	0.8
RFC and RFP in the wetland to channel return flow function: Return flow fraction, $RFF = RFC * (WV / RWV)^{RFP}$ ($RFF \leq 0.95$) Return flow volume = RFF * (WV – RWV)	0.2 : 0.6	0.1 : 0.8

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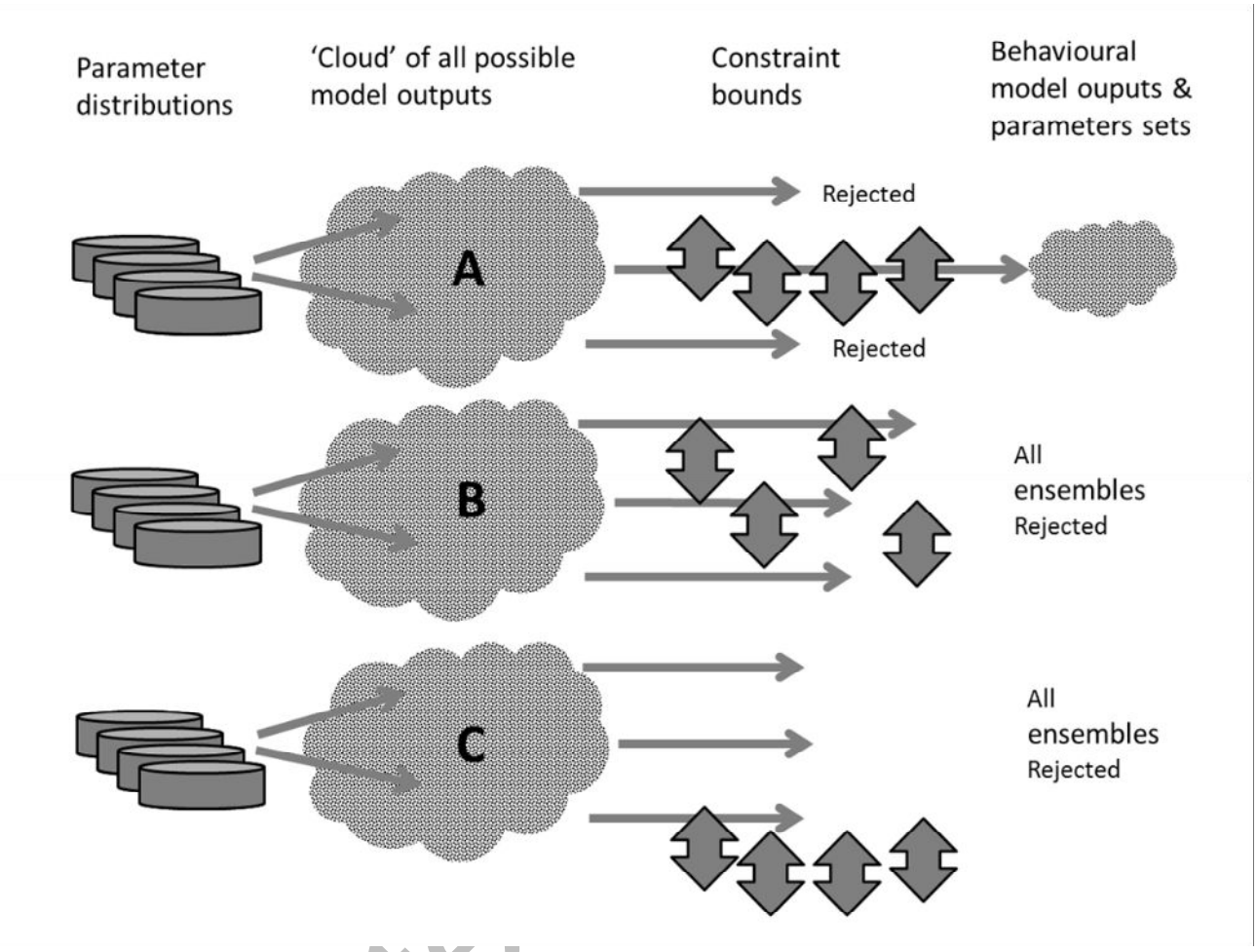
Figure 1 The Great Ruaha River basin and the sub-basins used in the modelling study (the insert shows the south western sub-basins in more detail). The locations of the available raingauges are given by Stisen and Tumbo (2015).



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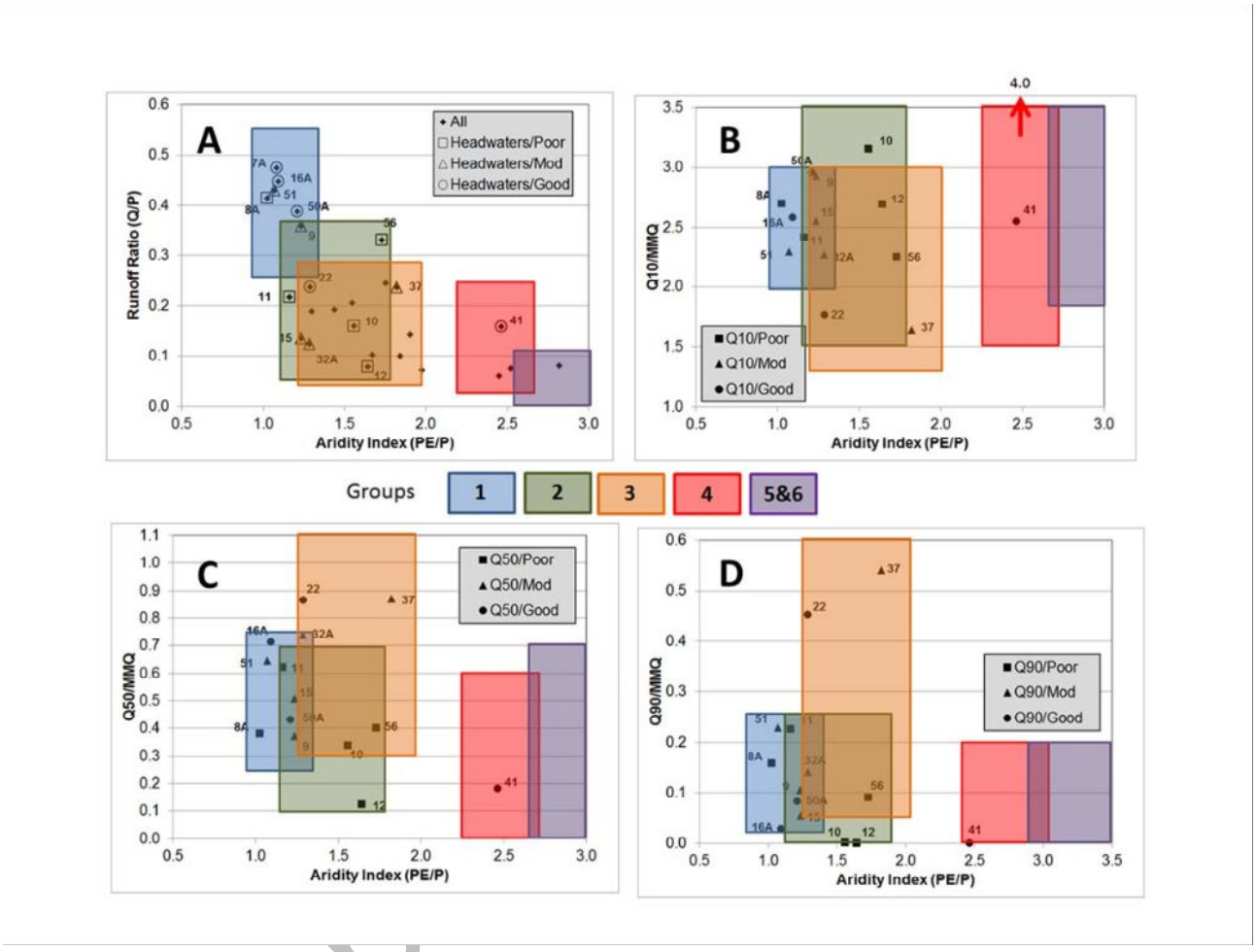
Figure 2 Conceptual diagram of Step 1 in the modelling process designed to identify 2 000 behavioural parameter sets using regional constraint ranges.



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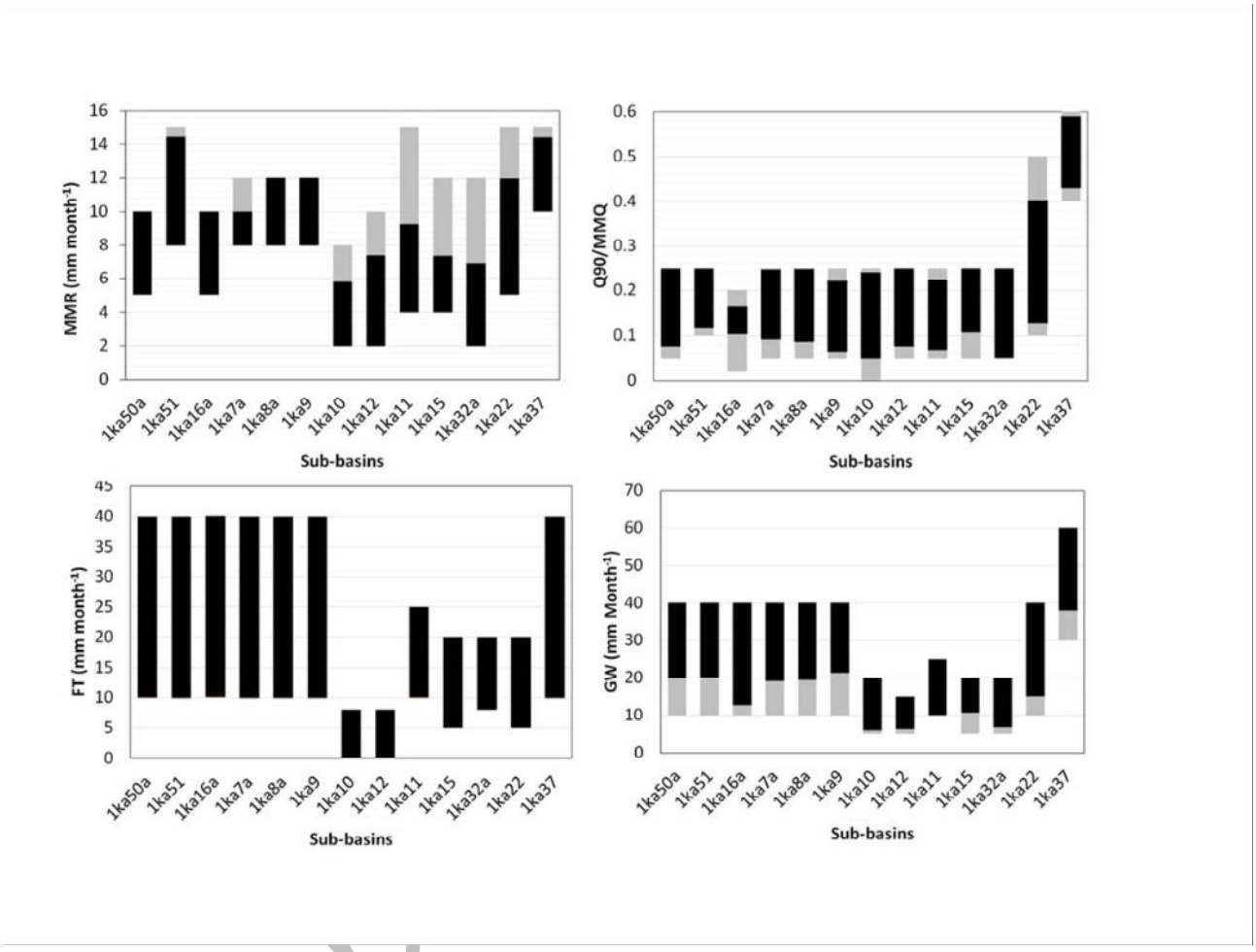
Figure 3 Observed stream flow constraints and regional constraint ranges for runoff ratio (used to determine the MMQ constraint), Q10, Q50 and Q90 (all relative to MMQ). The number labels represent the headwater gauges but excluding the '1ka' prefix. The regional groups are defined in Table 2.



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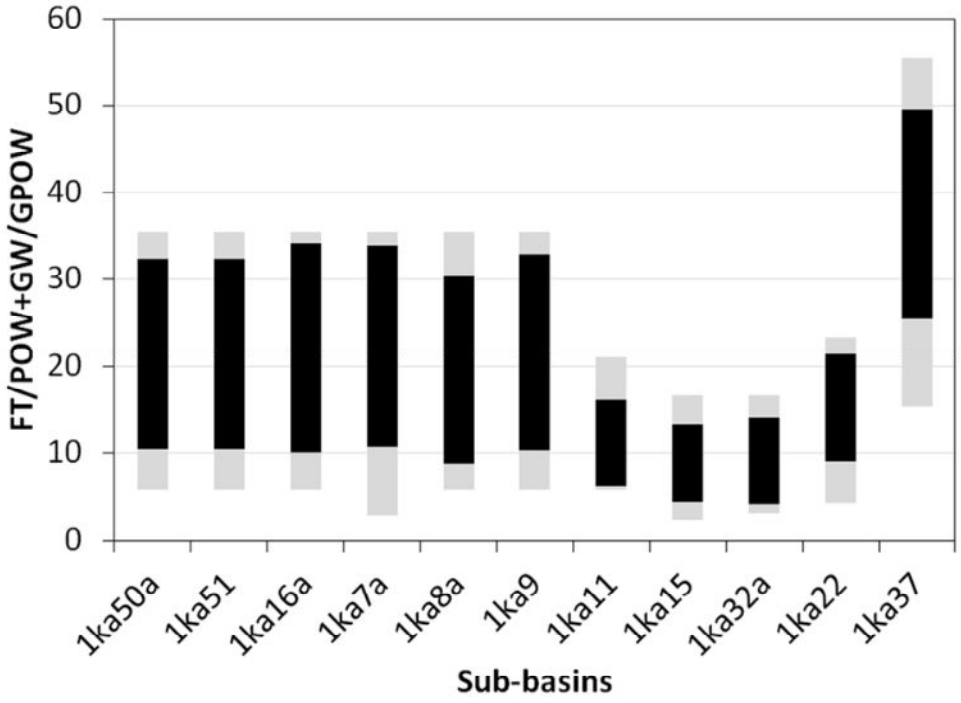
Figure 4 Range of MMR and Q90/MMQ constraints as well as parameter FT and GW uncertainty ranges. The grey bars represent the input ranges and the black bars the behavioural ranges output from step 1 of the modelling process for natural flow conditions.



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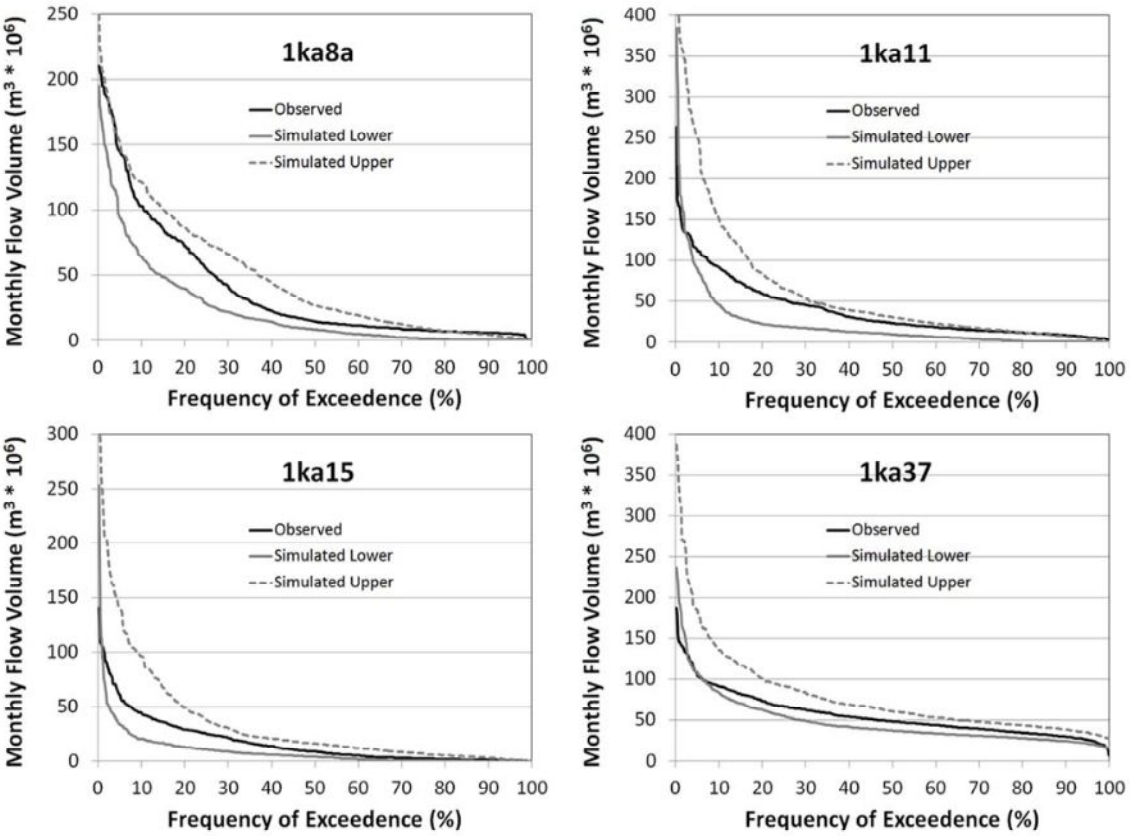
Figure 5 Range of input and output (after step 1) values for an index of potential low flow generation using FT/POW + GW/GPOW.



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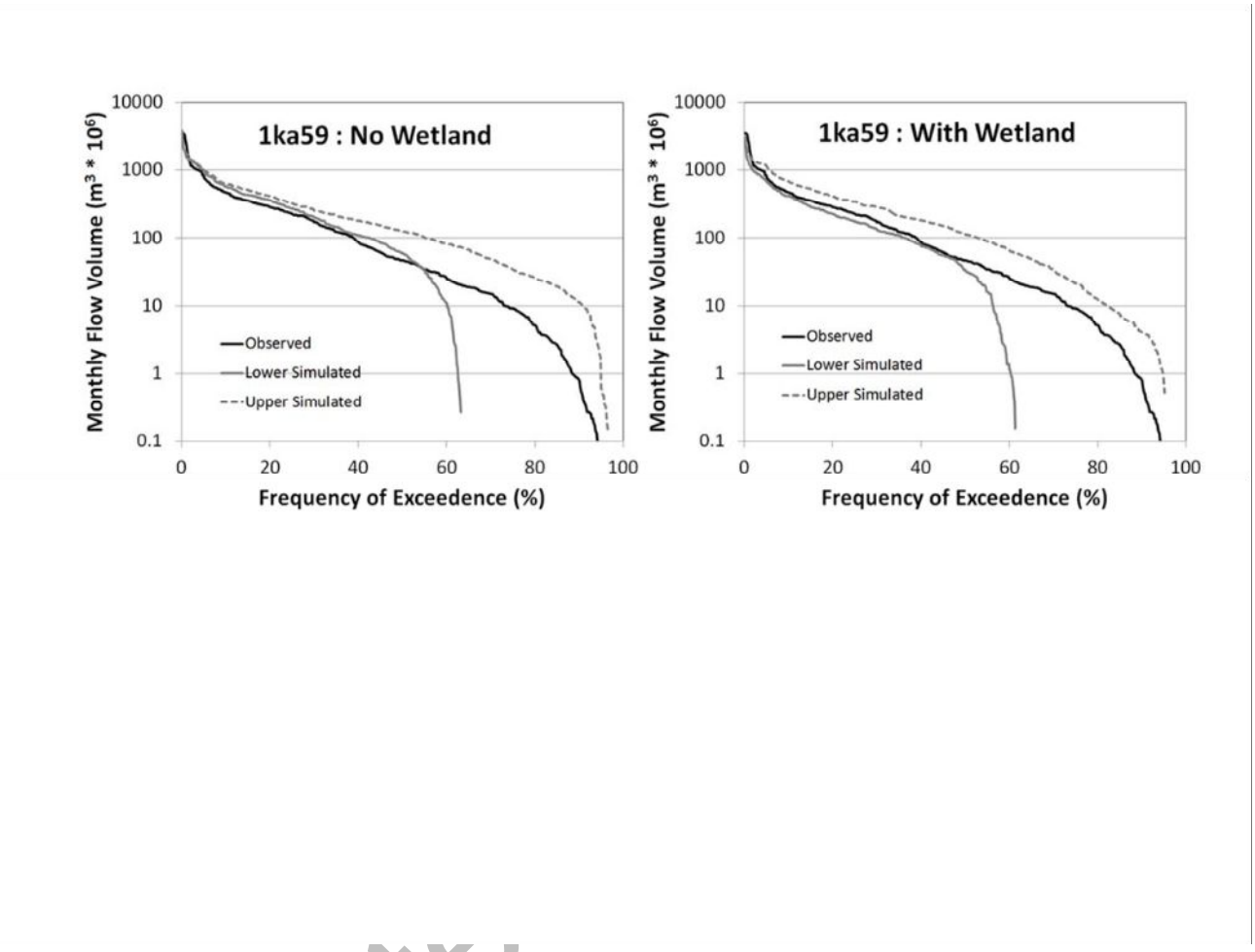
Figure 6 Flow duration curves of simulated bounds and observed data for selected sub-basins. The results are after step 2 and include water use.



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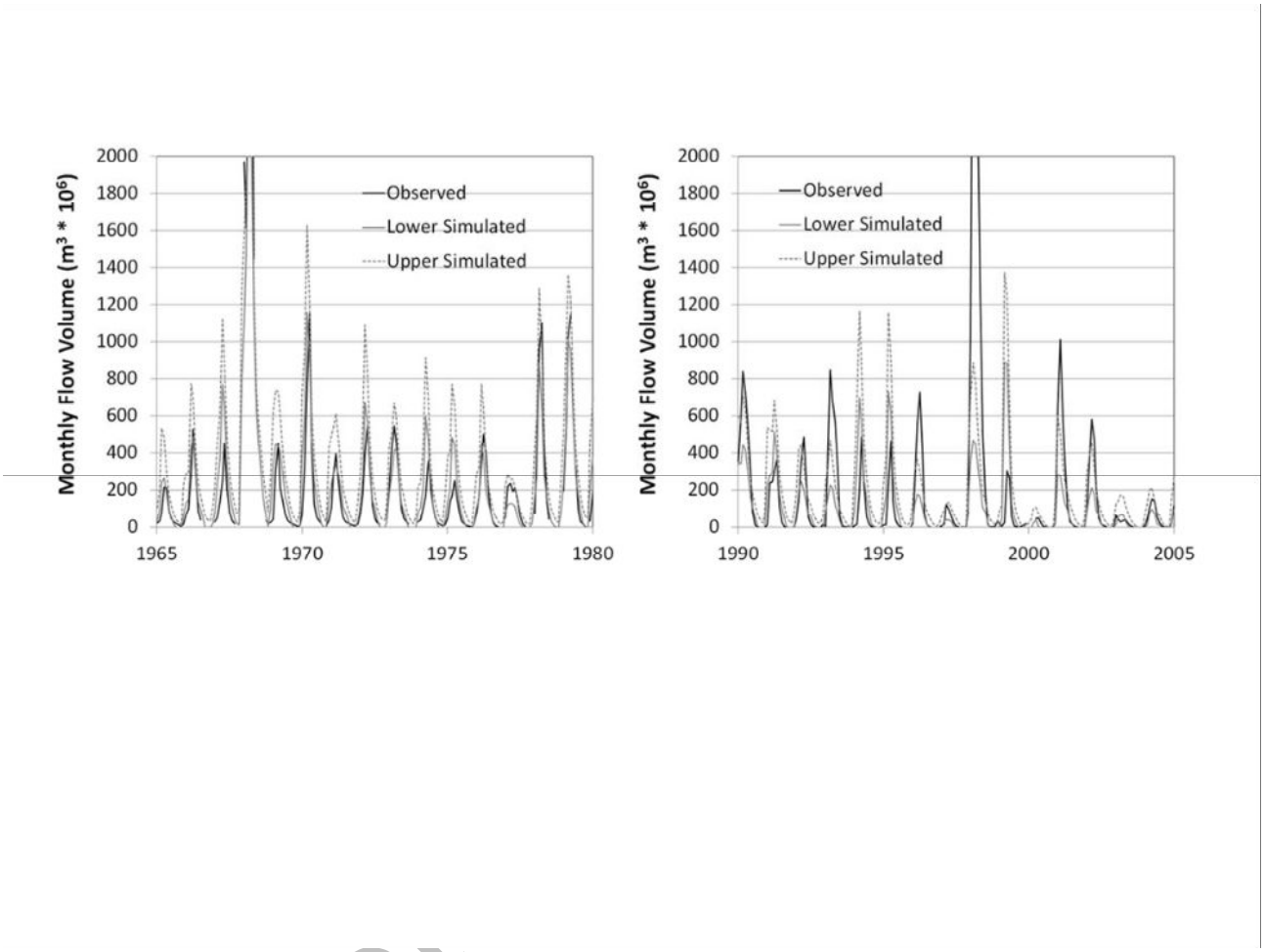
Figure 7 Flow duration curves of simulated bounds and observed data for 1ka59 before and after the wetland functions were applied to upstream sub-basins 1ka27a and 1ka71.



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Figure 8 Sample time series (1965 to 1980 and 1990 to 2005) of the simulated uncertainty bounds and observed data for 1ka59 after the wetland functions were applied to upstream sub-basins 1ka27a and 1ka71.



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