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A Hydrological Model of the Mundaú River Basin

Recalibration of a MGB-IPH rainfall-runoff model using updated land-use data

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Division of Water Resources Engineering
Department of Building and Environmental Technology
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It has been said that behind every success there are many successful failures. In applying this thought, I consider myself successful. It has been the help and support of others that has encouraged towards my success.

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It has been these people and so many more that have helped me along my path to where I am today. And to all of you, *Thank You*.

Lund in October 2015
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Abstract

The relatively unregulated, union domain Mundaú river basin, upper reaches originating in the Brazilian state of Pernambuco and flowing southeast to the Mundaú Lagoon along the Alagoas state's Atlantic coast, suffers from both flooding and drought. Modeling the basin's hydrology can lead to a deeper understanding of these events, and how changes within the basin can affect its hydrology. This study aims to build a MGB-IPH hydrological model of the river basin to be used to evaluate whether or not current water extraction permits for the Mundaú basin exceed the regulated flow (Q_{95}) regulations – on a *monthly* basis – using a modeled monthly flow average. For this purpose, the MGB-IPH model has been calibrated to a best fit to observed data. The model's simulated flows indicate that the observed data does not follow a pattern for unregulated flows in the basin. It is believed that there are large water extractions that affect the downstream data, extractions that cannot be quantified at the moment.

Sammanfattning

Avrinningsområdet Mundaú har sitt ursprung i den Brasilianska delstaten Pernambuco och rinner i sydöstlig riktning mot Mundaúlagunen längs Atlantkusten tillhörande delstaten Alagoas. Området faller under nationell jurisdiktion, är relativt oreglerat och erfar både översvämningar och torrperioder. Modellering av avrinningsområdets hydrologi kan ge en fördjupad förståelse av dessa händelser och hur förändringar i området kan påverka dess hydrologi. Denna studie syftar till att bygga en MGB-IPH hydrologisk modell av avrinningsområdet som kan användas för att avgöra huruvida gällande tillstånd att använda vatten överstiger regleringar av tillåtna nivåer på månadsbasis baserat på ett genomsnittligt modellerat månatligt flöde. För detta syfte har MGB-IPH modellen kalibrerats för att närmast efterlikna uppmätta värden. Modellens simulerade flöden indikerar att de uppmätta värden som finns inte följer det förväntade mönstret för oreglerade flöden. Detta indikerar att det sker stora vattenuttag som påverkar uppmätta flöden nedströms. Dessa uttag kan ännu inte kvantifieras.

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1. Introduction

1.1. Background

Interdisciplinary cooperations aim to increase the knowledge of complex situations by using synergy through sharing of expertise between different disciplines. They are part of a foundation towards enlightenment. One such cooperation was founded between the Division of Water Resources Engineering at Lund University in Lund, Sweden, the Centre for Technology at the Federal University of Alagoas and the Technology Centre at the Federal University of Paraíba, both located in northeastern Brazil. This cooperation brings together scientists from hydrology, climatology, the natural sciences and engineering. The aim of this cooperation is *to use state-of-the-art long- and short-term forecasting techniques to produce probabilistic and deterministic forecast tools for reproducing flood events over northeast Brazil*. One such technique has been developed at the Division of Water Resources Engineering at Lund University; an atmospheric-hydrological coupled system, TVRL-AHCS (Pereira et al. 2014). It is a two-way coupled atmospheric and hydrological model using the B-RAMS and MGB-IPH (Collischonn 2007) models.

Hydrological modeling is widely used for stream-flow reproduction (for example: Li et al. 2009; Miller et al. 2002; Ghaffari et al. 2010; Choi & Deal 2007). Flood mitigation is one area of application for these models (for example: Schwanenberg et al. 2015; Fan et al. 2014; Brath, Montanari & Moretti 2006). During 1989, 2000 and 2010, northeastern Brazil had flooding events that have been quantified to approximately 50, 100 and 200 years reoccurrence time respectively (Fragoso Jr, Pedrosa & Souza 2010). These flooding events have taken place in virtually unregulated river basins (Mundaú and Paraíba) where the population typically lives close to and along the rivers' banks. The flood of 2010 had a flow height that, at one flow station in the Mundaú basin, was last recorded as being at 8.10 meters before the station was washed away. Reconstruction of the flood height estimated the actual wave closer to 11.50 meters (Ibid). Normal flow levels are under 2 meters.

By modeling the hydrology of the basin, simulated data from any point within the basin can be analyzed thus complementing the available observed data.

1.2. Purpose

This study *aims* to build a MGB-IPH hydrological model of the Mundaú river basin located in northeastern Brazil. The MGB-IPH model will then be used to evaluate whether or not current water extraction permits for the Mundaú basin exceed the regulated flow (Q_{95}) regulations - on a *monthly* basis – using a modeled monthly flow average. Building of the MGB-IPH model will allow for future coupling to the B-RAMS atmospheric model for further research in flood event analyses.

1.3. Delimitations

Due to the time restrictions that are necessarily placed on a study of this kind, rather than a complete model build, this research is primarily a recalibration of the Mundaú river basins' MGB-IPH model presented during 2015 at the Centre for Technology at the Federal University of Alagoas by Mahelvson Chaves in his Masters thesis. The MGB-IPH *cell* and *albiaf* input files have been updated and model recalibration has been performed. Hence, descriptions of other model building steps are not given in this thesis. The calibration has been performed using observed flow data downloaded from the Agéncia Nacional de Águas (National Water Agency, ANA) in 2009. All other input data files are collected from the model referred to above. The data covering the extent of the water usage has been collected from official government sources.

1.4. Disposition

Beginning with a theoretical background, the thesis will describe rainfall-runoff modeling and the introduction of water allocation permits in Brazil. Thereafter a general description of the study area and the MGB-IPH hydrological model will be introduced. Finally, the results of the model's calibration process will be presented with an in-depth discussion concluding with recommendations for further research. Full model calibration parameters can be found in Appendix 1 while calibration and validation results can be found in Appendix 2 and 3. The *Matlab* code used for data analysis has been added as Appendix 4.

2. Theoretical Background

2.1. Rainfall-Runoff Modeling

There are numerous ways to (1) demonstrate correlation between rainfall and runoff and (2) represent the reproduction of river flow. Keith Beven (2012) in his book *Rainfall-Runoff Modelling : the primer* describes the modeling process as including: building of the perceptual model, conceptual model and procedural model, model calibration and validation and then model result evaluation. At each step of the process the *approximation* of reality increases. The perceptual model is the individual's own understanding of the hydrological environment to be modeled. The conceptual and procedural models are respectively the mathematical descriptions thereof and computer code that executes these descriptions.

Further, Beven (2012) explains that different models can range from being statistically based to being physically-based/process-based. These models can then be either *lumped* or *distributed* in nature. Lumped models assume that the modeled catchment acts as a single unit, thus using state variables for the entire catchment. These variables can be seen as averages of each phenomenon that is included in the model (for example: soil water content, leaf area index and evapotranspiration rates). Distributed models assume that known data can be distributed through space by means of dividing the catchment into a grid, or squares, where each grid point will have state variables describing the different processes to be modeled. In a distributed model, the modeler decides how this known data will be distributed and discretized from the data source throughout the grid. The smaller the grid, the closer the distributed models come to be purely physically-based models.

Models can have any degree of discretization. Many models are commonly referred to as semi-distributed, where the river basin is divided into grids, yet each grid-point is not broken into smaller grids due to the inaccuracy of the conceptual model representing the catchment.

Where comprehensive, spatially distributed input data is available, a semi- to fully distributed model can be advantageous over statistically based or lumped models, depending on the available data's density. Brazil has invested in recent years in quantifying different environmental factors such as soil distribution (*Radambrasil*), fluvio- and pluviometric data, wind speed, atmospheric pressure, solar radiation, relative humidity and land-usages, also making these data available through different actors such as *INMET*, the web-based *hidroweb* from ANA and state and local government authorities.

2.2. Water Permit Legality

The granting of permits for the use of water resources is a recent development within Brazil. Several laws, both Federal and State, have been implemented since 1997 in order to regulate these permits. Different states have quantified the regulated flow in different ways. Following is a short description of the applicable laws and regulations for the Mundaú River basin.

2.2.1. Federal

Federal Law 9.433 from 8 January 1997 (Lei N° 9.433) establishes the National Water Resources Policy and creates the National System of Water Resources Management. This law allows for the granting of permits for the use of the nation's water resources.

Further, the Agéncia Nacional de Águas (National Water Agency, ANA) issued Resolution Number 425 on 4 August 2004 (Resolução N° 425) establishing the criteria for water extraction from Union Domain water bodies. A Union Domain body of water is any body of water that 1) is contained in more than one state in the Union *or* 2) crosses the border between a state and another country. Extraction permits must be attained if flows exceeding the limits in Article 3 are to be extracted. Article 3 states that the resolution refers to collection points where extracted instantaneous flows are above the following:

- Industry: 36 m^3/h or 10 l/s
- Irrigation: 360 m^3/h or 100 l/s
- Sanitation: 72 m^3/h or 20 l/s.

In addition, Article 8 of this resolution states that the resolution *also* applies to the water users in the resolution's Appendix II. Appendix II lists the Piranhas-Açu River as the only river within the Eastern Northeast Atlantic Hydrography Region that the resolution directly applies to.

Resolution Number 1041 from 19 August 2013 (Resolução N° 1041) defines the relevant reference flows for water extractions in Union Domain water bodies. For stretches of a river that are not influenced by flow regulating reservoirs, Q_{95}, the flow that is exceeded 95% of the time, is the extraction reference flow.

Where water-granting rights do not fall under national jurisdiction, state laws are applicable. As the Mundaú basin is of union domain, the states of Alagoas and Pernambuco do not have jurisdiction regarding user permits.

However, background in how the state utilizes its water domain is still of relevance when analyzing water usage prior to implementation of a national water policy. Following is a brief description of the state regulations pertaining to water user permits.

2.2.2. State

The State of Alagoas implemented Decree Number 6 on 23 January 2001 (Decreto N° 6) regulating permits for use of the state's water resources. This decree was implemented under State Law number 5.965 from 10 November 1997 (Lei N° 5.965) that established the state's policy on water resources, and, among other things, the states integrated water resource management system. This decree states that water resources can be allocated to a volume of 90% of the basin's *annual* regulated flow ($0.90 \cdot Q_{90}$), at a statistical 90% confidence.

The State of Pernambuco issued Decree Number 20.269 (Decreto N° 20.269) on 24 December 1997 defining the state's criteria of maximum flow allocation for water usage permits. This decree states that the regulated flow is to be based on studies of the available water resources for where the specific permit is to be approved. According to Sefione, Moura & Girondoli (n.d.), Q_{90} is used as the reference flow by the ANA technicians. Decree 20.269 regulates State Laws 11.426 and 11.427 which (respectively Lei N° 11.426 and Lei N° 11.427) establish the foundation of the State's water resource management policy. State Law 11.426 has subsequently been replaced by Law 12.984 on 30 December 2005 (Lei N° 12.984). The defined regulated flow was not changed from its previous definition in 1997. Law 11.426 (currently Law 12.984) and 11.427 apply respectively to surface and subsurface water

3. Materials and Method

3.1. Study Area

3.1.1. General

The Mundaú river basin stretches across the states of Alagoas and Pernambuco in northeastern Brazil located between 8°30’00” and 10°0’00” south latitude and 35°30’00” and 37°0’00” west longitude, Figure 1, in the Eastern Northeast Atlantic Hydrographic Region (ANA 2003). Of the river’s 4 105 km^2 drainage area, 2 154 km^2 (Apac 2013) and 1 951 km^2 (PERH 2010) of the basin are located in the states of Pernambuco and Alagoas respectively. The headwaters are in Pernambuco state close to the city of Garanhuns where the river flows towards the southeast and empties into the Mundaú Lagoon, just west of the city of Maceió, Alagoas.

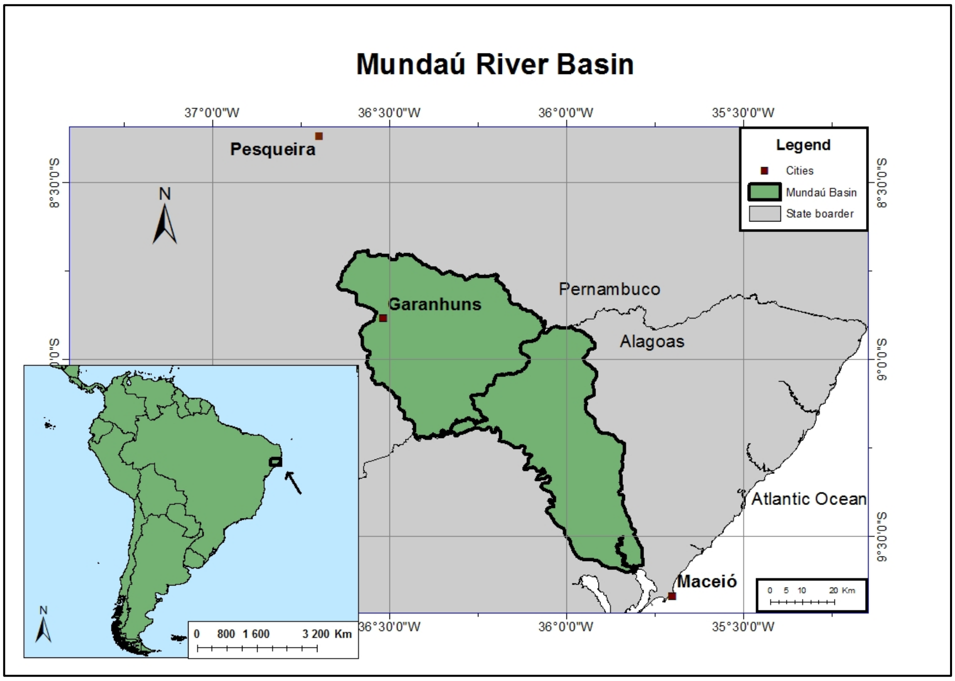

Figure 1 Location of the Mundaú River Basin in northeastern Brazil.

3.1.2. Bedrock, Topography and Soils

The underlying rock formations of the basin are predominantly crystalline in nature, with sedimentary formations closer to the outlet at Mundaú Lagoon (Apac 2013; PERH 2010). There are four main soils represented in the basin. Beginning from the northwest corner of the basin looking towards the outlet, regosol followed by planosol dominate in Pernambuco State while podzolic and latosol are more common in Alagoas State (PDRH 1999). Elevations within the basin range from 1010 meters a.m.s.l. (above mean sea level) in the northwestern section of the basin to 7 meters a.m.s.l. at the Mundaú Lagoon, see Figure 8 located on page 19.

3.1.3. Climate

The climate varies greatly from the outlet near Maceió towards the headwaters near Garanhuns. For illustration purposes, three cities have been used: Maceió, Garanhuns and Pesqueira. Maceió and Garanhuns lay inside the basin while Pesqueira is to the northwest of Garanhuns, Figure 1. According to the Thornthwaite climate classification as presented in PERH (2010), Maceió is classified as having a humid climate, while Garanhuns and Pesqueira (APAC 2013) have a sub-humid (with dry summers) and semi-arid climate respectively.

Using the period from 1961 – 1990 as a reference, the Brazilian National Meteorological Institute, INMET (2009), has calculated the monthly average-temperature (°C) and precipitation/evaporation (mm) for different meteorological stations across Brazil. The temperature in Maceió varies from 20.2 – 30.4°, for the austral winter and summer respectively. In Garanhuns, the fluctuation is between 15.6-28.7° and in Pesqueira it is between 16.5-31.6°. Regarding precipitation and evaporation, Maceió, with a humid climate, demonstrates a clear wet period from March through August, with a dry period from October through January. Garanhuns, exhibiting a more transition climate, has a wet period from April through July and a clear dry period from September through February. Pesqueira, in a semi-arid climate, has a wet month during April and a clear dry period from August through February. These averages for Maceió, Garanhuns and Pesqueira are illustrated in Figure 2 - Figure 5.

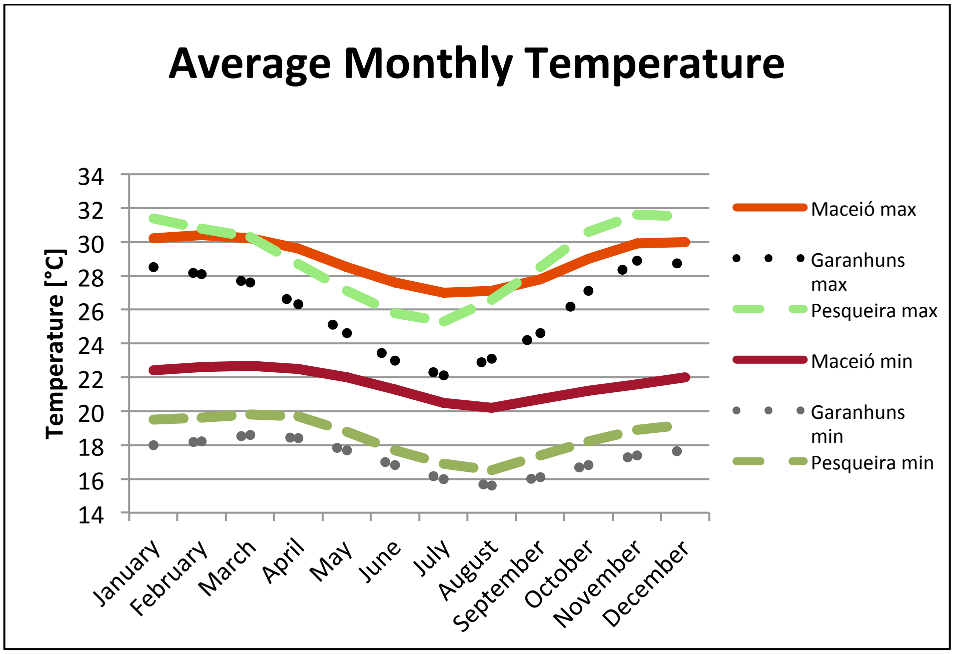

Figure 2 Average monthly maximum and minimum temperatures in °C for Maceió, Garanhuns and Pesqueira Brazil using a reference period of 1961-1990 (INMET 2009).

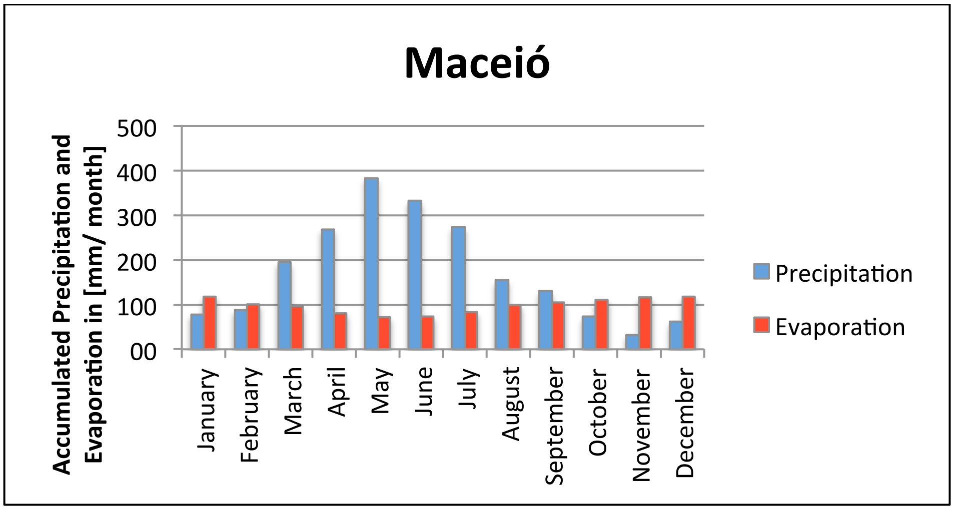

Figure 3 Average monthly Precipitation and Evaporation in mm per month for Maceió, Brazil using a reference period of 1961-1990 (INMET 2009).

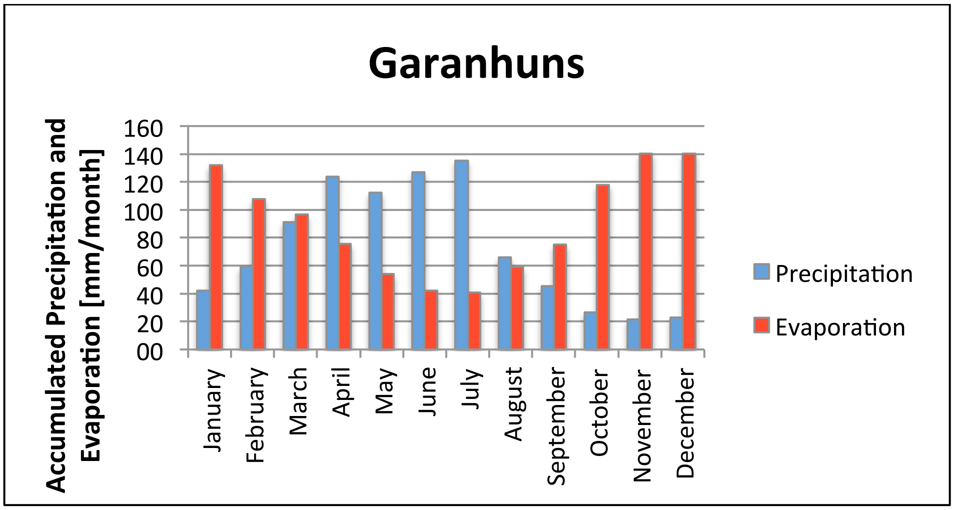

Figure 4 Average monthly Precipitation and Evaporation in mm per month for Garanhuns, Brazil using a reference period of 1961-1990 (INMET 2009).

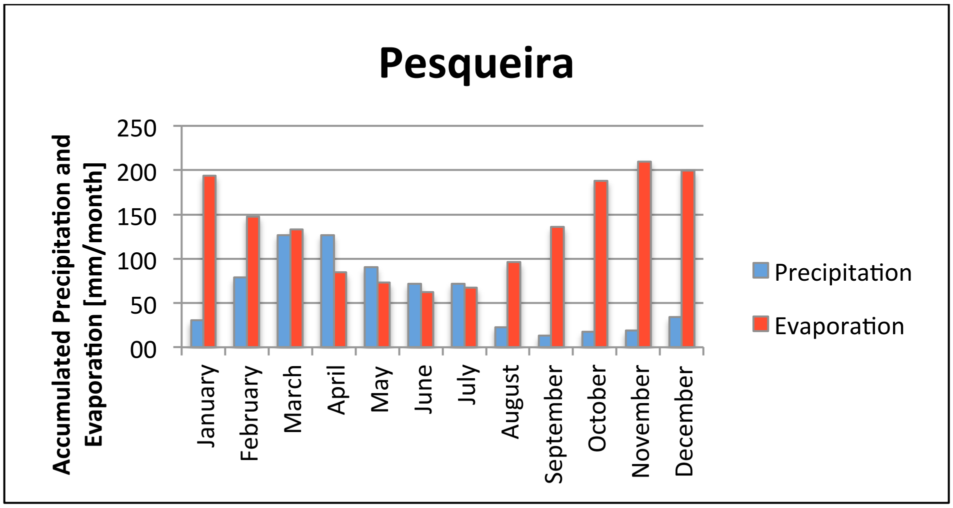

Figure 5 Average monthly Precipitation and Evaporation in mm per month for Pesqueira, Brazil using a reference period of 1961-1990 (INMET 2009).

3.1.4. Infrastructure

The Mundaú river basin is fairly unregulated having a larger concentration of weirs in the drier northeastern section of the basin (Fragoso Jr, Pedrosa & Souza 2010). There are no water transfer schemes within the basin.

3.1.5. Land-use

According to PDRH (1999), the Mundaú basin's land-use consists of approximately 52% anthropic areas, 22% sugar cane, 23% forest and an assortment of other usages, Table 1. Substance farming and ranching is included within the anthropic classification. The land-use from PDRH (1999) was compiled from multiple sources, for example Food and Agriculture Organization of the United Nations vegetation maps and LANDSAT-TM images from 1990. The total area of 412 637 ha is slightly different than the combined Apec (2013) and PERH (2010) basin area of 4 105 km^2. The reason for this discrepancy is unknown.

Table 1 Land-use for the Mundaú river basin in northeastern Brazil, adapted from PDRH (1999).

Class	Area (ha)	Area (%)
Forest	12 475	3.02%
Forest vegetation I	72 380	17.54%
Forest vegetation II	579	0.14%
Forest vegetation III	8 520	2.06%
Anthropic areas	215 873	52.32%
Freshly planted sugar cane	29 675	7.19%
Young sugar cane	40 521	9.82%
Adult sugar cane	19 614	4.75%
Exposed soil	3 631	0.88%
Urban areas	2 935	0.71%
Water	214	0.05%
Unidentified areas	6 220	1.51%
Total	412 637	100.00%

3.1.6. Water Demands

Water is gathered directly from precipitation, wells and/or the rivers and streams in the basin.

According to census data from 2007 presented in PERH (2010) and data from 2010 presented in APAC (2013), the population of the basin is approximately 465 000 people, excluding the downstream urban area of Maceió of 940 971 people. Considering rural areas as being purely rural up to and including settlements of less than 2500 people, 30% of the basin's population lives in rural areas. Urban areas account for less than 1% of the total land-use of the basin (PDRH 1999).

Social economic factors have led PLIRHINE, Plano de Aproveitamento Integrado dos Recursos Hídricos do Nordeste, to establish an average usage of 70 liters water per person and day for the basin's rural areas (APAC 2013). Furthermore, for the urban environment, there is a five-category graduated scale, dependent on the size of the settlement, from 120 – 240 liters per person and day (Ibid). The combined effect exceeds 30 000 000 m^3 water per year (APAC 2013; APG n.d.).

Using a per capita bovine water equivalent for livestock (Beda, see Equation 1), the Mundaú basin has a demand of approximately 5 335 000 m^3 of water (APAC 2013; PERH 2010) per year for ranching purposes and 71 739 000 m^3 of water (APG n.d.) for irrigation purposes where approximately 90% of the irrigation demand originates from Alagoas. The Mundaú basin has more agriculture in the lower portion of the basin, where approximately 86% of the area for crop production is allocated to sugar cane (PERH 2010).

Equation 1

$$Beda = \left(Cattle + buffaloes + \frac{horses + mules + donkeys}{1.25} + \frac{sheep + goats}{6.25} + \frac{swine}{5} + \frac{poultry}{250}\right) \cdot 50\ l\ water\ per\ animal\ per\ day$$

3.1.7. Time of Concentration (TOC)

An estimation of the basin's TOC has been calculated using the Kirpich equation as described by Lopes da Silveira (2005), Equation 2. The reason for choosing the Kirpich TOC formula is due to the MGB-IPH model, in conjunction with its Cs and Ci parameters, uses a variation of the Kirpich equation.

Equation 2

$$Tc = 0.0063 \cdot L^{0.77} \cdot S^{-0.385}$$

Tc is the time of concentration in hours, L is the length of the river [km] and S is the river slope [m^1m^{-1}].

The initial TOC has been calculated to approximately 25 hours for the modeled area of the Mundaú basin. TOC for each sub-basin has also been calculated as seen in Table 2.

Table 2 Initial calculation of the time of concentration (TOC) in hours for the Mundaú river basin and sub-basins to be modeled in the MGB-IPH model. TOC has been calculated using the Kirpich equation as decribed in Lopes da Silveira (2005).

Sub-basin	Time of Concentration [h]
1	6.5
2	23.8
3	4.5
4	4.5
5	2.3
Mundaú total	*25*

3.2. Distributed Hydrological Model

The MGB-IPH model for large-scale river basins described in Collischonn's (2001) doctoral thesis is designed specifically for Brazilian conditions. An in-depth description can be found in for example Collischonn (2001) and Collischonn et al. (2007). It is based on the LARSIM (Krysanova et al. 1998) and VIC-2l (Liang et al. 1994; Nijssen et al. 1997) models where the basin is divided into cells that simulate both flow propagation within each cell and river routing between the cells. These cells are then sub-divided into *Hydrological Response Units*, HRUs, (Beven 2012, chapter 6), each HRU combining one specific soil type and land-use/-cover. Each HRU is defined using model parameters such as: maximum water storage in the soil layer, drainage rates of water from the upper soil layer at saturation, albedo, leaf-area index and vegetation height. Each specific HRU has the same hydrological characteristics regardless of its location within the modeled basin. The number of HRUs is defined by the modeler.

MGB-IPH can be used in two different modes: using basin-wide parameters for each HRU, e.g. Collischonn et al. (2007), or by calibrating each HRU at the sub-basin scale, e.g. Da Silva (2005), Getirana et al. (2009) and Paiva et al. (2011). This study calibrates each HRU at a sub-basin scale.

At the cell level, the model uses a vertical water balance for each HRU, Figure 6. This vertical water balance is calculated regardless of the HRU's area within each cell. The next step in the model's process is to take into account each HRU's area, in percent, in each cell before summing the runoff into the three linear reservoirs: surface runoff, subsurface runoff and groundwater (D_{sup}, D_{int} and D_{bas} respectively). These reservoirs are then routed to a downstream cell as defined during model preprocessing procedures.

An overview of the each cell's computations can be found in Appendix 5.

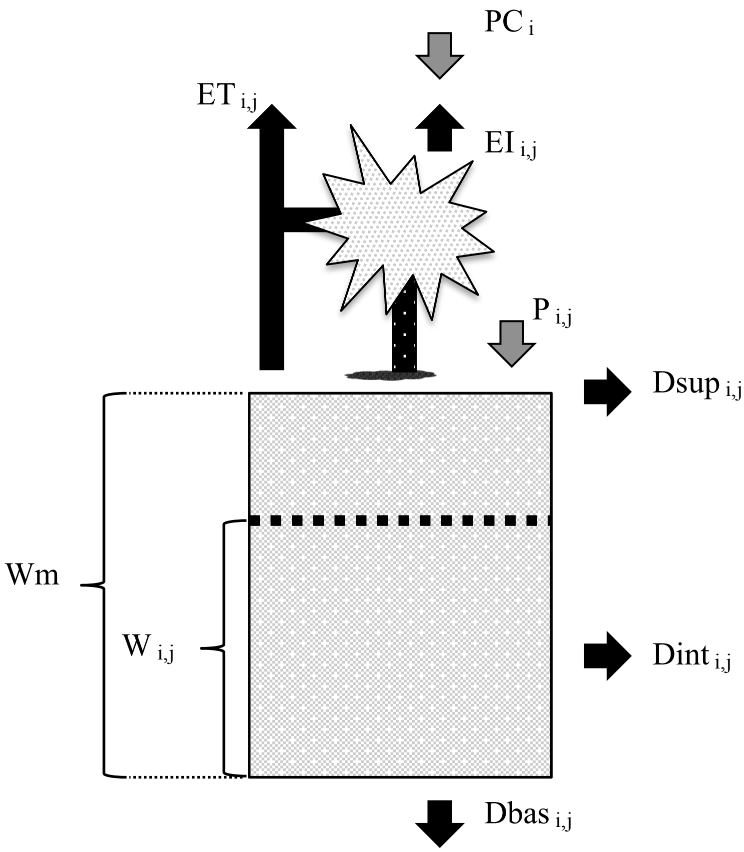

Figure 6 Graphical representation of the MGB-IPH water balance for each HRU as illustrated in Collischonn et al. (2007).

Calibration of the different HRU parameters is needed for optimal hydrological simulation of the basin. Understanding of how each parameter is used in the model is thus prudent. A general description of each parameter can be found in Table 3. Even though these are model parameters, each parameter can be, in some way, associated with a natural process.

Wm can be related to soil depth, typically 50-350 mm for shallow soils. The soil depth is usually associated with a wilting point, in this case Wc. Contrary to a typical wilting point where, when the soil layer water is less than the Wc the vegetation begins to die, MGB-IPH uses Wc as the depth of the water bound to the soil layer that does not drain into the layer below. CAP allows for losses from the soil layer to the atmosphere. XL can be seen in two different ways. It can literally be seen as a soil grain parameter, for instance 0,165 for clay through 0,694 for sand. It is also a parameter for the relationship between drainage, sub-surface flow and soil moisture. b is somehow related to the basin’s characteristics – the soil types and the soil’s spatial variability. This is a parameter that can be estimated from the data and should be between 0.12-1.6. Kbas and Kint are drainage rates of the upper soil layer in saturated soil conditions. They can be calculated based on soil types. Typically, clay should be in the range below 1.00 while sand can be closer to 300.00. CS, CI and CB are all coefficients for flow calculations. A description according to MGB-IPH recommendations can be seen in Table 3.

Table 3 List and description of the calibration parameters for the Paruso file for the MGB-IPH model. These values are from the MGB-IPH Windows based interface.

Paruso file	MGB code	Typical values	Description
Wm	Wm1	50-1000	Soil depth [mm]
Wc	WC	0.1	Residual storage parameter limiting the flow to the subsurface storages [mm]
CAP	CAP	0.00	Capillary water height, typically discarded in the model [mm]
XL	PLAM	0.67	Soil grain parameter; controls the shape of the reduction curve of the intermediate drainage or sub-surface soil.
b	B	0.12-1.6	Basin characteristics parameter, the lower the "b" the less reactive the basin is to rainfall [n/a]
Kbas*	KBAS	0.05- 5	Flux between Dint and Dbas [$mm^1 \Delta t^{-1}$]
Kint*	KINT	4.00-40.00	Flux between Dsus and Dint [$mm^1 \Delta t^{-1}$]
Kflux	KFLUX	n/a	Radiation flux for coupled mode [n/a]
RW	RW	1-2	Relationship between the capacity of Soil Layer 2 and 1 [n/a]
CS	CS	1-20	Coefficient to multiply for superficial flow time of concentration [dimensionless]
CI	CI	50-200	Coefficient to multiply for subsurface flow time of concentration [dimensionless]
CB	CB	1200-8000	Delay time in hours for underground reservoirs [h]
QB	QESP	0.01	Initial Groundwater Flow in [$m^3 s^{-1} km^{-2}$]

3.3. Data Sets

3.3.1. MGB-IPH

The MGB-IPH model requires many different types of data sets. Vegetation parameters (albedo, leaf-area index, vegetation height, surface resistance), soil, rainfall, climate (temperature, relative humidity, insolation, wind speed, barometric pressure, global solar radiation) and observed flow data are preprocessed in order to produce the different model files.

3.3.1.1. HRU

In this model, each HRU is composed of two parts, soil and vegetation. Soil maps (1:5 000 000) were gathered from the *Radambrasil* project published by EMBRAPA. These soil maps have been reclassified using the Satori et al. (2005) reclassification system, Table 4 and Figure 7. Vegetation maps have been gathered through personal contacts with local authorities in both Alagoas and Pernambuco states. The data from Alagoas originates from 2009 while the data from Pernambuco originates from 2002. These maps were complemented with data from Landsat 2010 day 144 (inland) and 2011 day 076 (towards the coastline) data files to extend the vegetation information to the areas surrounding the Mundaú basin.

Table 4 Soil reclassification table adapted from Sartori et al. (2005).

Group	Soil Depth	Permeability	Soil types
A	Very deep (>2m) Deep (1-2m)	High/High Moderate to High	LR, LE, LV, LVr, LVT, LH, LEa and LVa
B	Deep (1-2m)	High/High High/Moderate Moderate/Moderate	LJ, LVP, PV, PVL, Pln, TE, PVls, R, RPV, RLV, Lea and LVA
C	Deep (1-2m) to Moderately deep (0.5-1.0m)	Low/High Low/Moderate High/Moderate	Pml, PVp, PVls, PC and M
D	Moderately deep (0.5-1.0m) to shallow (0.25-0.50m)	High, Moderate and Low/Low	Li-b, Li-ag, gr, Li-fi, Li-ac and PVP (shallow)

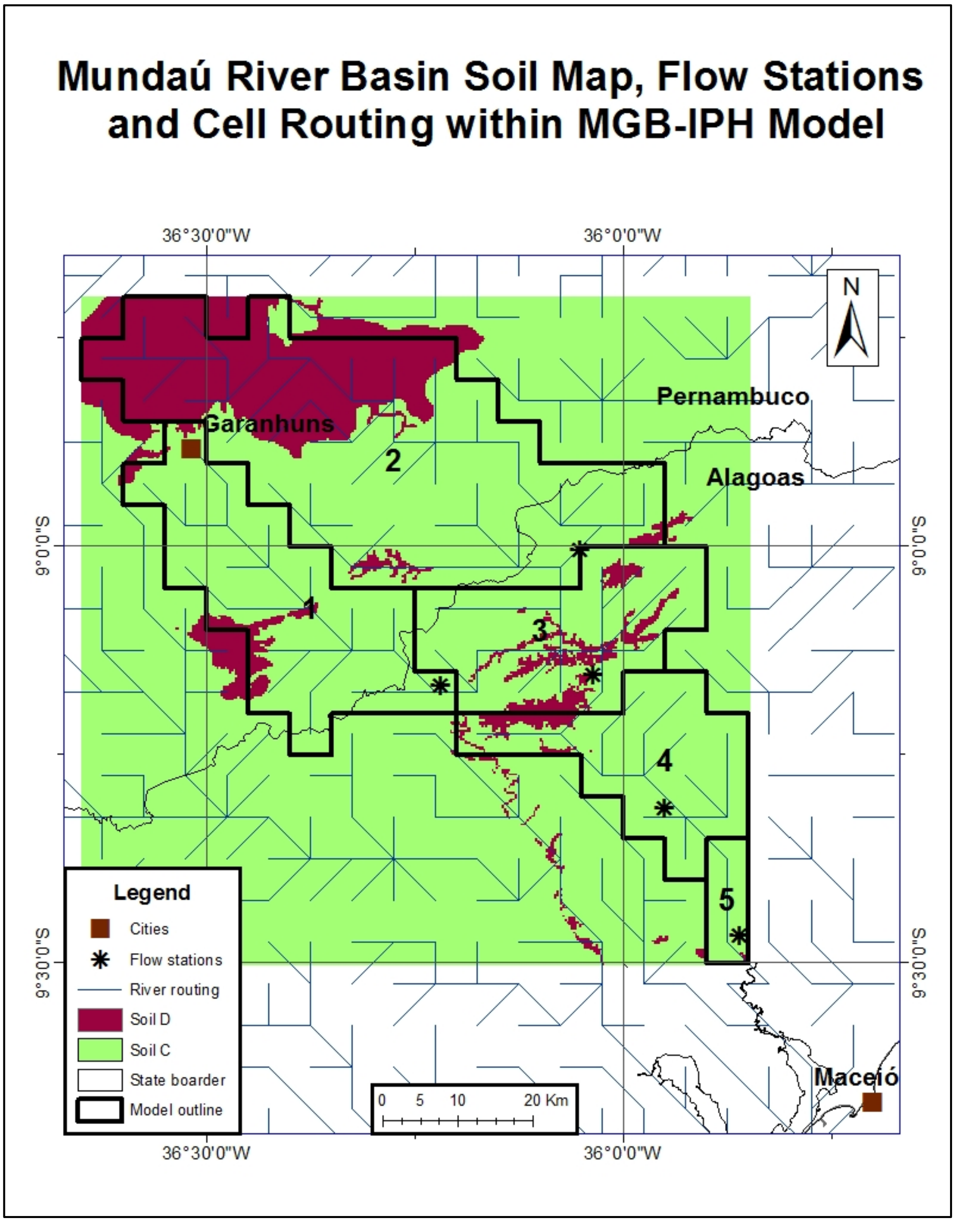

Figure 7 Soil map and MGB-IPH water routing information for the Mundaú river basin.

3.3.1.2. Topography

Topographic information has been gathered from the Shuttle Radar Topography Mission. These maps (90x90 meters) were downloaded from CGIAR-CSI, the CGIAR Consortium for Spatial Information (2008). The model input data is represented in Figure 8.

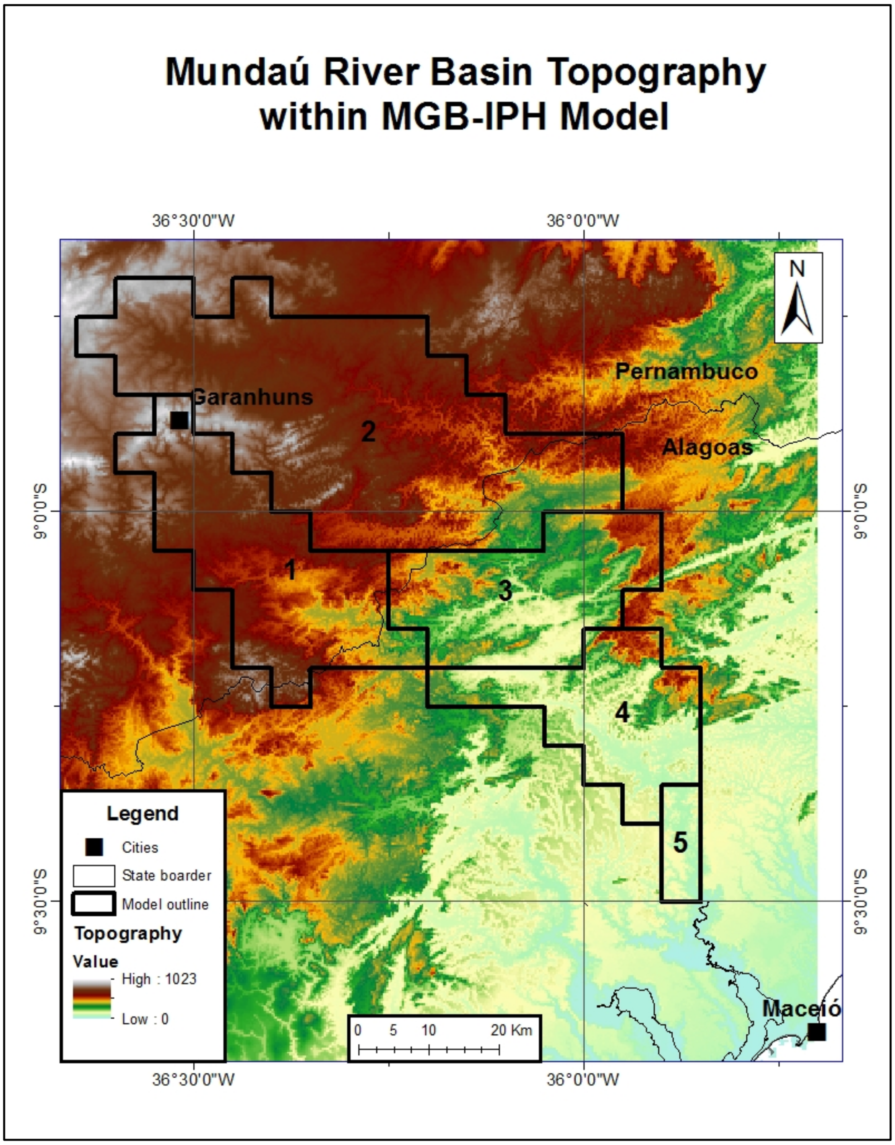

Figure 8 Topographic data of the Mundaú river basin, from the CGIAR-CSI project. The highest topographical value inside the modeled area is 1010 meters a.m.s.l..

Data from 100 ANA and ITEP rain gauging stations amount for the pluviometric data, Figure 9. Five fluviometric stations have been used, data being acquired from ANA, Table 5. The basin's final flow station is located in the city of Rio Largo, just north of Maceió. Meteorological data was collected at two points in the basin, Garanhuns and Maceió from INMET, Table 5. The data is monthly averages of temperature (°C), relative humidity (%), solar radiation ($h^1 day^{-1}$), wind speed ($m^1 s^{-1}$), atmospheric pressure (kPa) and global solar radiation ($MJ^1 m^{-2} day^{-1}$).

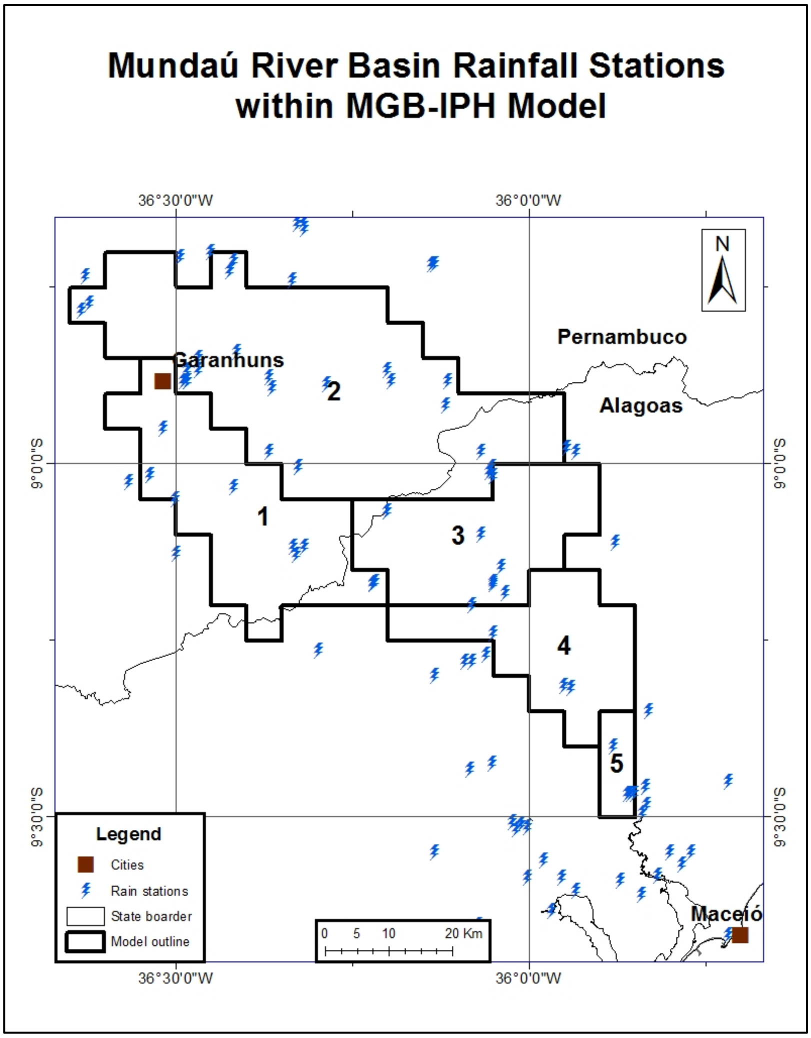

Figure 9 Rainfall stations for the MGB-IPH model of the Mundaú river basin.

Table 5 Fluviometric and Meteorological stations from ANA and INMET respectively, including the actual (ANA) and modeled (MGB-IPH) upstream drainage areas.

Sub	Name	River	Code	Lat.	Long.	Upstream Area (ANA) [km^2]	Upstream Area (MGB) [km^2]
	Fluviometric stations						
1	Santana do Mundaú	Rio Mundaú	39700000	-9.168	-36.218	767	795.5
2	São José da Laje	Rio Caruru	39720000	-9.004	-36.051	1170	1653.1
3	União dos PalMares	Rio Mundaú	39740000	-9.154	-36.036	2900	3060.5
4	Murici-Ponte	Rio Mundaú	39760000	-9.314	-35.950	3290	3580.4
5	Fazenda Boa Fortuna	Rio Mundaú	39770000	-9.467	-35.860	3560	3672.1
	Meteorological stations						
	Garanhuns		00082893	-8.883	-36.517		
	Maceió		00082994	-9.667	-35.700		

3.3.2. Data Preprocessing

The MGB-GIS (2008) and MGB-Auxi (2008) user manuals have been used in the making of the *cell* file. ArcGIS and Idrisi have been the main programs used during this process. For the water allocation permits, ArcGIS has been used.

3.3.2.1. Cell File: Scenario Building

A complete description of the *cell* file process can be found in the above mentioned user manuals. Briefly outlined, the size and number of cells to be modeled are chosen. This gives the area (km^2) and location of each cell (degree decimal). The topographical data is used for cell water routing, upstream drainage area (km^2) river length (km) and river slope (m^1km^{-1}). Soil data is combined with land-use data in a single file, the HRU. These different data are then combined in a preprocessing routine PREPARA. The result is the *cell.hig* file used in the MGB-IPH program.

When making the HRU data file, several *model-sensitive* steps had to be taken. First, the land-uses provided from the authorities were merged with each other to reduce the number of HRUs to be modeled. For example, all different forest areas were combined as a single land-use – *forest*, all ages of sugar cane were combined as a single land-use – *cane*, exposed soil and urban areas were combined as *exposed soils* and anthropic areas were redefined as *pasture*.

Second, the data from the local authorities in Pernambuco extended only to the actual size of the basin, while data from Alagoas encompassed the whole state. The model uses a grid system that can extend past the actual basin outline. Both the basin outline and the modeled outline can be seen in Figure 10. To solve the issue of missing data, two Landsat images were added as complementary information to the data maps. This process was done using ArcGIS. The Landsat reclassification process involved using the known data provided from the authorities' files as a basis for the Landsat files' reclassifications. The reclassification was calibrated to the Mundaú basin and surrounding areas. When the reclassified Landsat files resembled the known data, they were merged with the authorities' land-use files creating one single map.

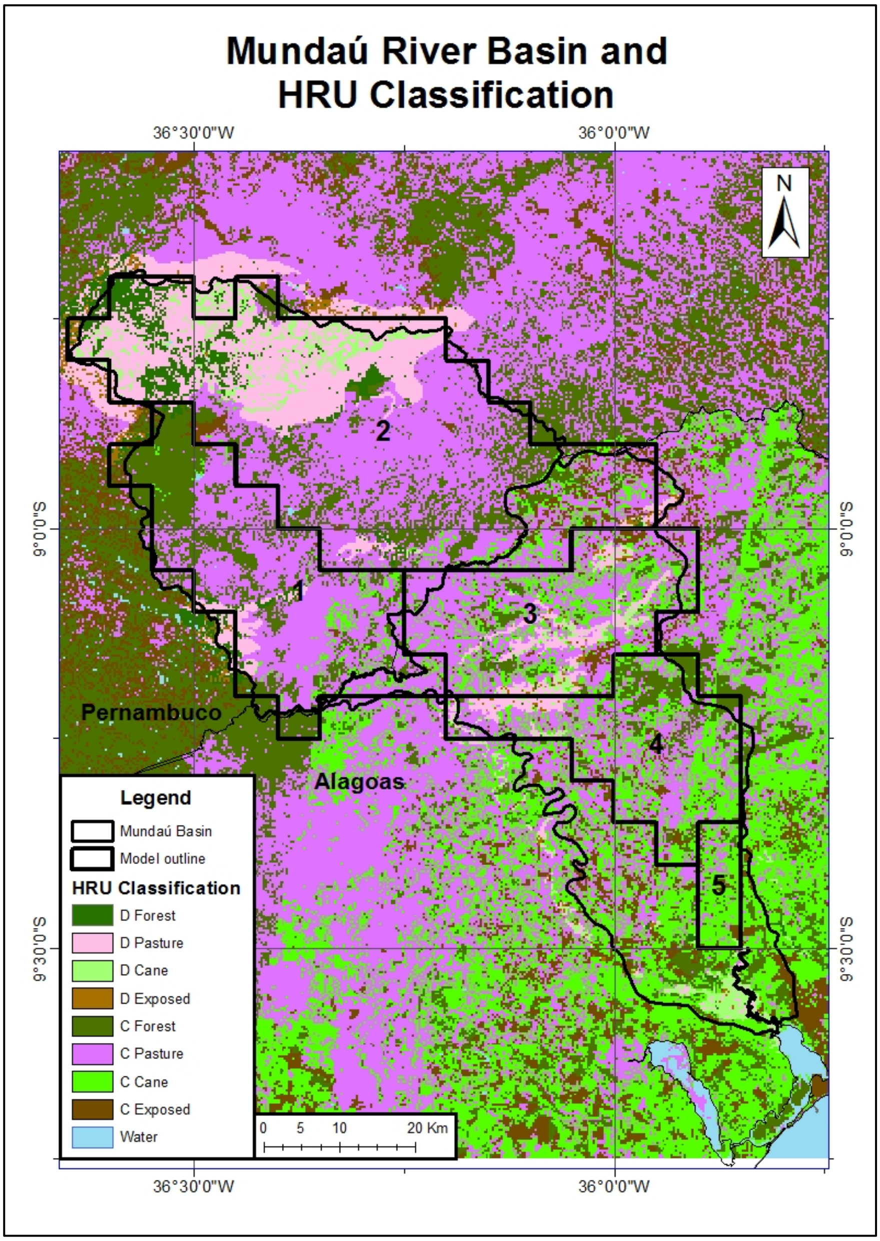

Figure 10 Mundaú river basin HRU Classification data. Land-use data for Alagoas state and inside the Mundaú basin in Pernambuco state was provided by local authorities while the remaining land-use data is from reclassification of Landsat 2010 day 144 and 2011 day 076 data. A portion of the downstream area of the basin was not included in the model due to a possibility of backwater effects on possible flow data at the river's outlet at Mundaú lagoon.

3.3.2.2. Water Allocation Permits

ANA (2015) publishes a list of all the permits issued since 2001. This Excel document is issued in compliance with ANA Resolution Number 147 from 4 May 2012. The document lists, among other things, the name of the permit holder, where the permit is valid, when the permit is valid, what the permit is valid for and withdrawal limits. The Excel file is for all of Brazil.

To extract the information necessary for the Mundaú basin, the file was uploaded as a text file into ArcMap, and converted into points in the GIS software. A shape file of the modeled basin was then overlaid over these points and the relevant permits were then extracted into a separate file, Figure 11. Of the 82 permits granted by ANA since 2001, 13 have since expired. An overview of the allowed flows can be seen in Table 6 and permit uses can be seen in Table 7. Sixty-six of 69 permits have been issued within the state of Alagoas. Industry, irrigation and mining account for over 80% of the total issued permits.

Table 6 Mundaú basin water permit extraction in monthly flows by volume m^3s^{-1}. Permits allowing for the possibility of water return have been omitted. This allows for calculation of a maximum water withdrawal. The data is for MGB-IPH model-areas in the basin. April – August are typical wet-season months.

Month	Monthly flow Volume	m^3s^{-1}
Jan	6 807 780	2.54
Feb	6 420 740	2.65
Mar	6 122 580	2.29
Apr	2 975 420	1.15
May	2 067 620	0.77
Jun	2 067 620	0.80
Jul	2 067 620	0.77
Aug	2 077 620	0.78
Sep	5 569 580	2.15
Oct	6 751 580	2.52
Nov	6 649 360	2.57
Dec	6 815 700	2.54
	yearly average	*1.79*

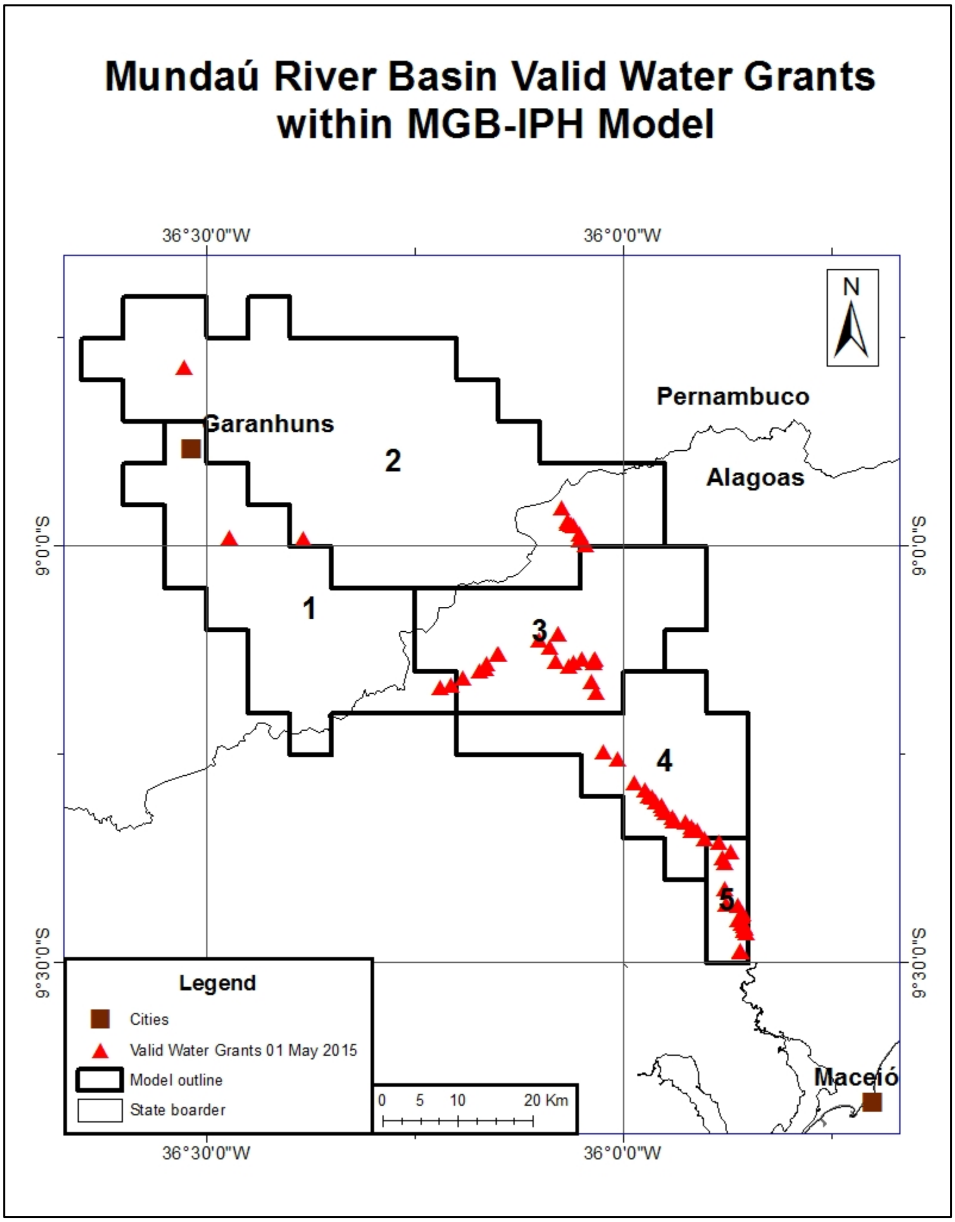

Figure 11 Map of the valid water permits within the MGB-IPH model area as of May 2015.

Table 7 List of Water permit users by sub-basin and total.

Sub-basin	Number of users	Type of user	State	total (%)
1	1	Public water	Pernambuco	
	1	Sanitation	Alagoas	4.3%
	1	Mining	Alagoas	
2	2	Public water	Pernambuco	
	7	Industry	Alagoas	14.5%
	1	Mining	Alagoas	
3	3	Public water	Alagoas (3)	
	1	Livestock	Alagoas	
	1	Sanitation	Alagoas	27.5%
	6	Industry	Alagoas	
	8	Mining	Alagoas	
4	2	Public water	Alagoas	
	15	Irrigation	Alagoas	29.0%
	3	Mining	Alagoas	
5	13	Irrigation	Alagoas	
	1	Industry	Alagoas	24.6%
	2	Mining	Alagoas	
	1	Other	Alagoas	

Total:	8	Public water		11.6%
	2	Sanitation		2.9%
	1	Livestock		1.4%
	14	Industry		20.3%
	28	Irrigation		40.6%
	15	Mining		21.7%
	1	Other		1.4%
		TOTAL		99.9%

4. Results

The extent of the modeled dataset, calibration parameters, including a sensitivity analysis, will be followed by model calibration and validation results. Water permit analysis will be addressed in the discussion. Under each section of the model fit results, the calibration results are presented followed directly by the validation results - before continuing to the next model fit section. This allows for continuity in visual comparison of the figures. For simplification purposes, sub-basins 1-5 will be denoted as S1-5 throughout the results and discussion sections.

There are ***no*** observed flow data points of 0.00 (zero) m^3s^{-1} in the available data. There are however missing data points, represented as -1.00 m^3s^{-1}. Where this occurs, both the observed and simulated data for the same date have been excluded from the analysis.

Each modeled cell has an area of 30.6 km^2.

4.1. Data Points

Model spin-up begins 1 January 1990, followed by calibration beginning 1 September 1992 and validation beginning 1 January 2002. The validation series runs through 30 November 2008. The model is run for the entire period, January 1990 through November 2008, with calibration and validation period data being separated before data analysis is conducted. Excluding the spin-up period, calibration stretches for 3 409 time-steps, continuing through a validation period of 2 526 time-steps. For further information see Table 8.

During 1994 and 2000, S1 has extended periods of missing data, totaling approximately 10 months worth. S2 has extended periods during 1994, 1995, 1996 and 2000. This accounts for approximately one year of data. Missing data points occur only sporadically in the remaining three sub-basins.

Table 8 Size of observed flow data set for model calibration and validation, in total time-steps and total time-steps used in the analysis in both number and percent. During the validation period for Sub-basin 3, observed data from November 2008 is missing, compared to the other four sub-basins. The dates are in day/month/year format.

	Dates	Total Time-steps	Time-steps used per sub-basin				
			1	2	3	4	5
Spin-up	01/01/90 – 31/08/92	974	---	---	---	---	---
Cal	01/09/92 – 31/12/01	3 409	3 119 (91%)	3 053 (89%)	3 409 (100%)	3 390 (99%)	3 409 (100%)
Val	01/01/02 – 30/11/08	2 526	2 524 (99%)	2 526 (100%)	2 440* (96%)	2 524 (99%)	2 523 (99%)

4.2. Model Calibration Parameters

Complete calibration parameters can be found in Appendix 1.

4.2.1. Sensitivity Analysis

A sensitivity analysis shows that there is an interconnection between the different parameters. Initially, the values were set at the values used in Mahelvson's work, subsequently showing very little sensitivity within each sub-basin. Kint, Kbas, Kflux, RW, CI, CB and QB show virtually no change to the flow, temporal or size. Wm, b, Wc, XL, CAP and CS all affected the flow in different ways as seen in Table 9. After partial calibration, basin sensitivity to change increased and CI, CB became relevant.

Table 9 Basin Sensitivity analysis of Peaks and Base-flow. CAP began at zero (0.00) thus only could be increased. With increased CAP the base-flow goes towards zero (0.00). H and L stand for higher and lower respectively while J and R are for jagged and more rounded. CI and CB results are after partial calibration. CI and CB have a similar reaction as CS.

Parameter	Change (%)		Change (%)	
	- 50	+ 100	- 50	+ 100
Wm	H	L	H	L
b	L	H	H	L
XL	H	L	L	H
CAP	-	L	-	L
Wc	L	H	H	L
CS	J (H)	R (L)	L	H
*CI**	*J (H)*	*R (L)*	*L*	*H*
*CB**	*J (H)*	*R (L)*	*L*	*H*
	Peaks		**Base-flow**	

4.2.2. Calibration Parameters

Generally, S1 and S2 have similar values while S3-5 in turn have similar values. S1 and S2 have relatively small Wm values compared to S3-5. XL and b values are within "normal" values for the Mundaú basin soil types and common basin reactivity levels. Zero (0.00) CAP and low Wc are below what is expected of the region. RW, CS, CI and CB values are within reasonable limits.

When comparing S3-5 with S1 and S2, the former have a Wm value in the range of 5-10 times higher than the latter. Additionally, b values are set at the model's lower limitations (0.02 and lower). CAP of 9.00 and 8.00 are introduced in S3 for soil types C and D respectively, subsequently lowered to 0.50 and 0.00 in S4 and S5 respectively. Wc is drastically increased for S4 and essentially set at model lower-limits in S5. CS, CI and CB are substantially higher in S3-5 than in S1-2.

4.3. Model Fit

For illustrative purposes, only figures for S1 and S3 have been imbedded in the following text. Full calibration results for all five sub-basins can be found in Appendix 2 while full validation results can be found in Appendix 3.

For each sub-basin, efficiency criteria, hyeto- and hydrograph analysis, flow duration curves and QQ-plots (simulated flow plotted against observed flow) have been used in determining the best fit for the model calibration, subsequently evaluated during the validation process. Flow that is exceeded 95% of the time, Q_{95}, has been calculated for both the observed flow and the simulated flow. The results of the Q_{95} calculations have been added to the efficiency criteria results.

4.3.1. Efficiency Criteria

Each sub-basin has been calibrated according to three different efficiency criteria, *Relative Volume Error* (RVE), *Nash-Sutcliffe coefficient* (NS) and *Root-Mean-Square Error* (RMSE), Equation 3 - Equation 5. The results, including the validation period, can be seen in Table 10. The data is from results from the cell where each flow station is located.

Equation 3

$$RVE\ (\%) = \frac{\sum Q_{sim} - Q_{obs}}{\sum Q_{obs}} \times 100$$

Equation 4

$$NS = 1 - \frac{\sum(Q_{obs} - Q_{sim})^2}{\sum(Q_{obs} - \overline{Q_{obs}})^2}$$

Equation 5

$$RMSE\ (m^3 s^{-1}) = \sqrt{\frac{\sum(Q_{obs} - Q_{sim})^2}{n}}$$

Table 10 *Nash-Sutcliffe coefficient*, *Relative Volume Error* and *Root mean square error* efficiency criteria for the calibration and validation of the Mundaú river basin, including calculated 95% exceedance (Q_{95}) for observed and simulated flows. The basin has been divided into five sub-basins. Calibration is from 1 Sep 1992 through 31 Dec. 2001 with validation from 1 Jan. 2002 through 30 Nov. 2008.

Criteria	Sub 1		Sub 2		Sub 3		Sub 4		Sub 5	
	Cal	Val	Cal	Val	Cal	Val	Cal	Val	Cal	Val
NS	0.48	0.62	0.53	0.43	0.66	0.57	0.78	0.65	0.80	0.69
RVE	-8.06	-1.48	-21.70	-29.73	26.10	34.30	13.50	19.60	2.14	14.09
RMSE	6.88	6.49	5.72	5.35	19.29	20.74	21.07	30.00	20.45	27.35
$Q_{95,\ obs}$	0.33	1.18	0.62	1.32	1.72	4.12	0.36	4.96	3.28	5.68
$Q_{95,\ sim}$	0.19	1.30	0.47	1.14	0.07	9.92	0.00	8.84	1.27	10.29

4.3.2. Hyeto- and Hydrographs

Hyeto- and hydrographs have been plotted for both sub-basin averaged rainfall and outlet observed and simulated flows, as illustrated in Figure 12 through Figure 15. Missing flow data is represented as a discharge of -1.00 m^3s^{-1} in the figures. Model sensitivity to rainfall correlates well with the observed flow, both peak and low flows, in all five sub-basins. The recession curves generally have a good fit to observed data.

During calibration, S1 and S2 generally underestimate the observed flows both during the wet, including peak flows, and dry seasons. S3-5 generally underestimate the wet season peak flows while dry season flows, including peak flows, tend to be overestimated.

During validation, S1 wet season peak flows are underestimated while dry season flows are overestimated. S2 flow is generally underestimated. Most S3-5 flows tend to be overestimated.

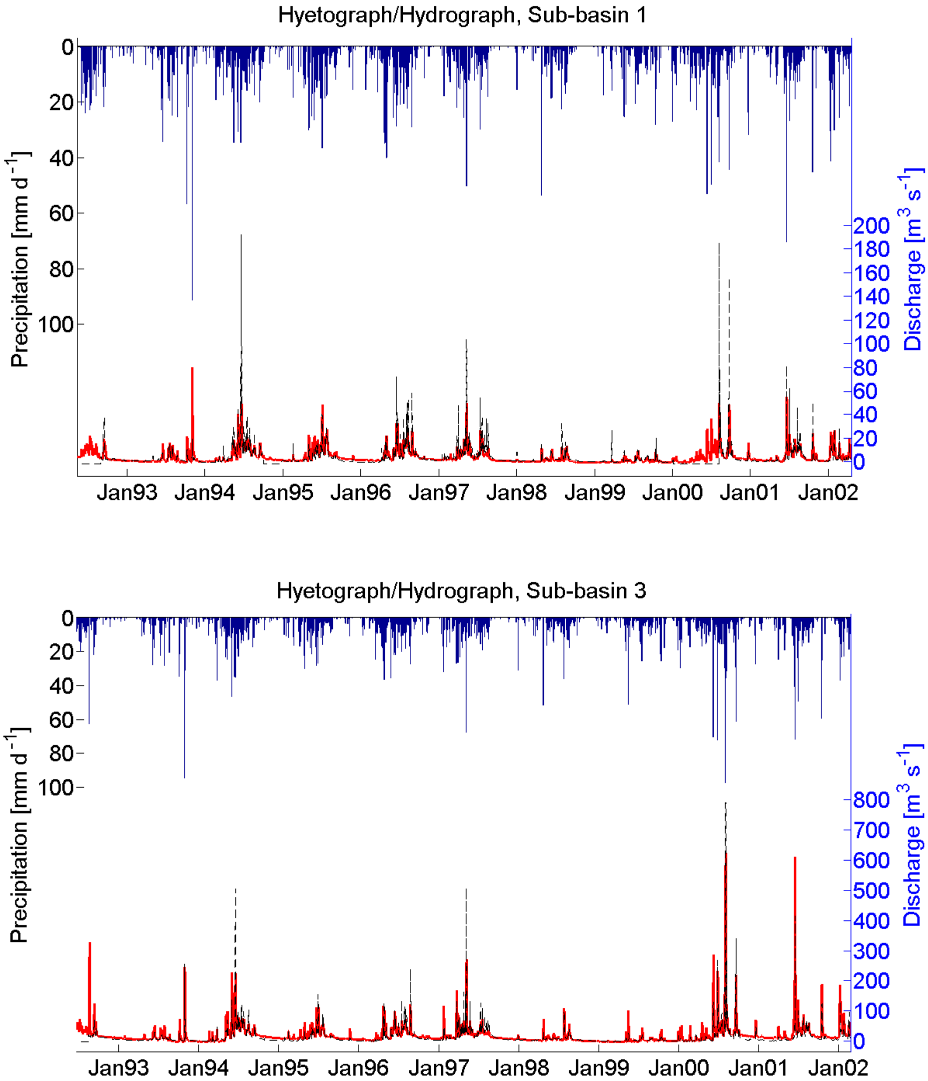

Figure 12 Calibration Hyetograph/Hydrograph of sub-basins 1 and 3 from 1 Sept. 1992 through 31 Dec. 2001. The dashed black line indicates observed flow while the solid red line indicates simulated flow, both in m^3s^{-1}. The blue bars at the top are sub-basin average rainfall in mm per day.

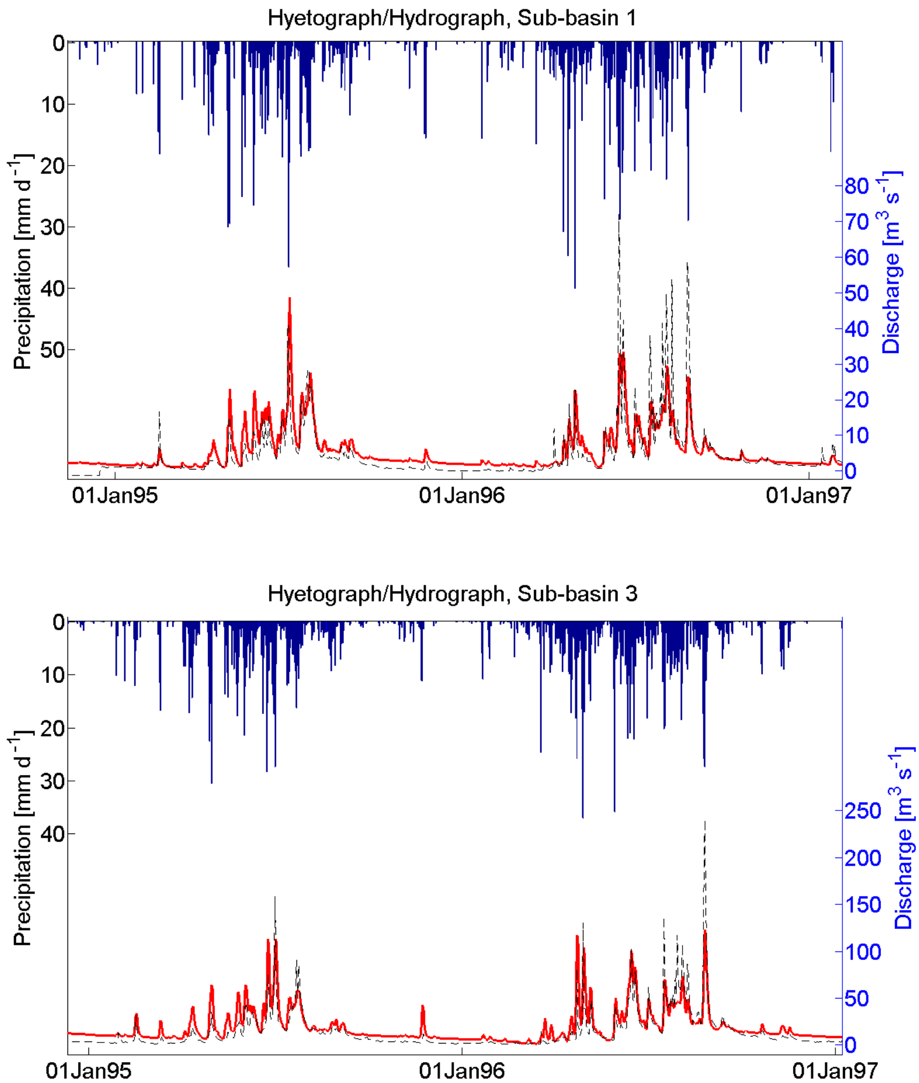

Figure 13 Calibration Hyetograph/Hydrograph of sub-basins 1 and 3 from 1 Jan. 1995 until 1 Jan. 1997. The dashed black line indicates observed flow while the solid red line indicates simulated flow, both in $m^3 s^{-1}$. The blue bars at the top are sub-basin average rainfall in mm per day.

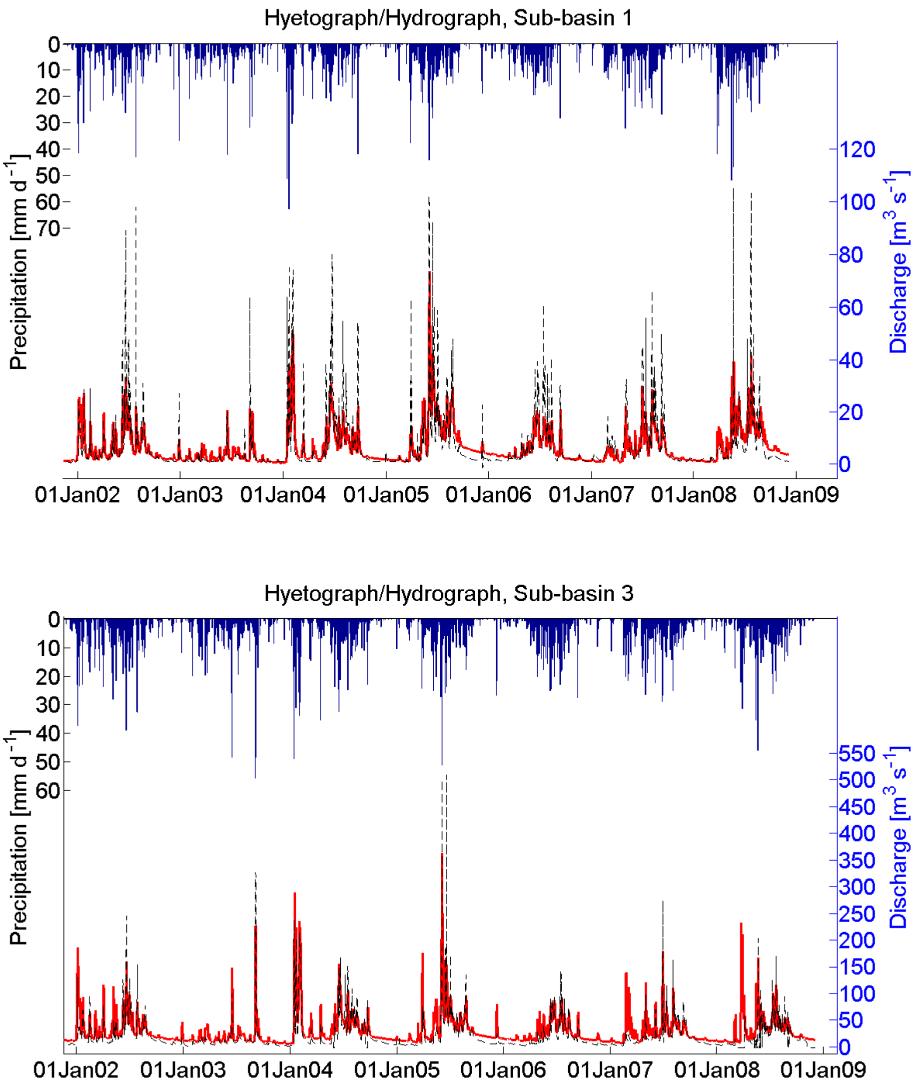

Figure 14 Validation Hyetograph/Hydrograph of sub-basins 1 and 3 from 1 Jan. 2002 through 30 Nov. 2008. The dashed black line indicates observed flow while the solid red line indicates simulated flow, both in m^3s^{-1}. The blue bars at the top are sub-basin average rainfall in mm per day.

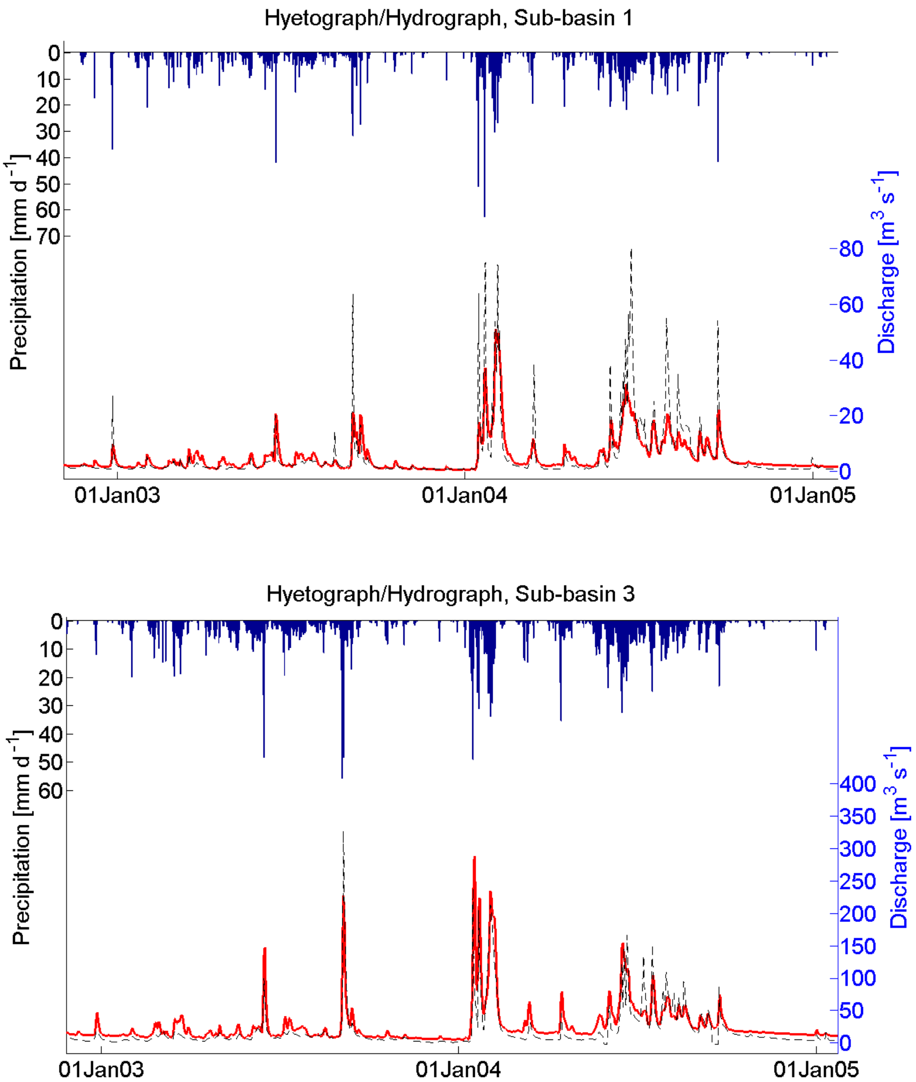

Figure 15 Validation Hyetograph/Hydrograph of sub-basins 1 and 3 from 1 Jan. 2003 until 1 Jan. 2005. The dashed black line indicates observed flow while the solid red line indicates simulated flow, both in m^3s^{-1}. The blue bars at the top are sub-basin average rainfall in mm per day.

4.3.3. Flow Duration Curves

Flow Duration Curves (FDCurves) have been plotted for both observed and simulated flows, as illustrated in Figure 16 and Figure 17. As with the efficiency criteria, where observed flow data was missing, the data point was discarded both in the observed and simulated datasets. Both $Q_{95,obs}$ and $Q_{95,sim}$ where then calculated. During the calibration process, the general shape of the FDCurves and the Q_{95} were taken into account.

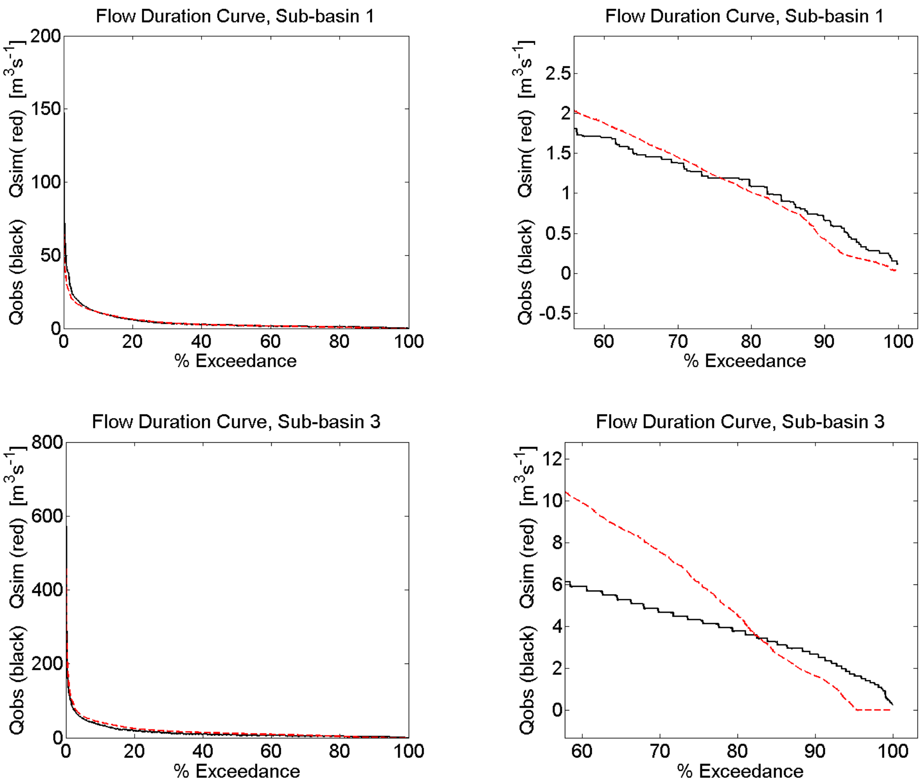

Figure 16 Calibration Flow Duration Curves for sub-basins 1 and 3. The observed flow is represented with a solid black line while the simulated flow is represented with a dashed red line. Relatively good fit for sub-basin 1 while it can be seen that in sub-basin 3 the simulated flow is overestimated until approximately 83% exceedance where there flow continues to drop towards a value of 0.00 m^3s^{-1} at 95.5% exceedance.

The form of the simulated curves in general follow the form of the observed data, as illustrated to the left in Figure 16 and Figure 17. With closer evaluation of the data, for example to the right in said figures, there can be great differences in the relative results. Values of observed and simulated data at a given % exceedance can differ more than 100%. Within the first few % exceedance, the flow generally drops rapidly and, excluding S4 calibration, becomes relatively horizontal by 10% exceedance. In S4 (calibration), this happens around 20% exceedance.

After calibration, S1-2 generally have a good fit. Simulation of S3-5 tend to result in higher flows throughout the different exceedances. For the validation period, most simulated flows are higher for most exceedances.

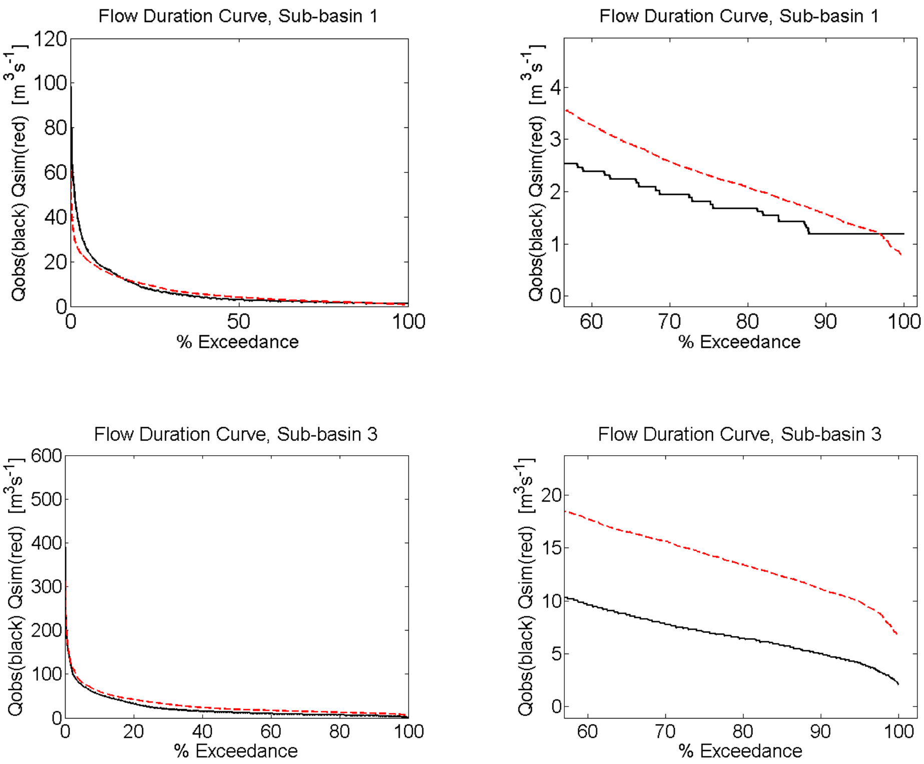

Figure 17 Validation Flow Duration Curves for sub-basins 1 and 3. The observed flow is represented with a solid black line while the simulated flow is represented with a dashed red line. Sub-basin 1 overestimates the observed flow – a flow that unnaturally becomes constant at approximately 88% exceedance. Simulated flow in sub-basin 3 greatly overestimates the observed flow.

4.3.4. QQ-Plots

Simulated flow is plotted against observed flow, y-axis and x-axis respectively, to visually represent the accuracy of the calibration. A perfect calibration would result in a 1:1 ratio, thus resulting in a straight line in the graph. Trend curves with one and three degrees of freedom have been plotted.

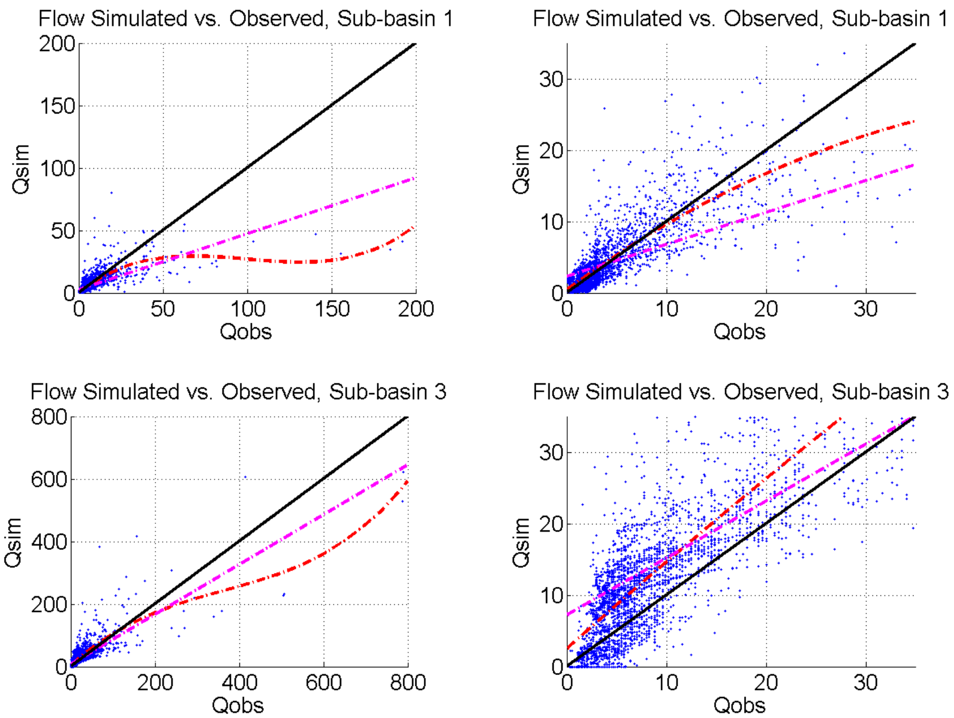

Figure 18 Calibration QQ-plots for the period from 1 Sept. 1992 through 31 Dec. 2001 of Simulated vs. Observed flow, where the top two graphs are of sub-basin 1 and the bottom two are of sub-basin 3. The black line represents a 1:1 ratio. The dashed magenta (straight) line indicates a data fit with one degree of freedom while the (curved) dashed red line indicates a data fit with three degrees of freedom. In the graphs to the left, all data points for each sub-basin are plotted while to the right only data points for 35 m^3s^{-1} and less are plotted. The higher simulated flows in sub-basin 1 generally underestimate the observed flow while the lower flows have a relatively good fit. For sub-basin 3 the high flows have a better general fit than in sub-basin 1 while the low flows are generally overestimated.

During calibration, peak flows tend to be underestimated. Low flows in S1-2 have a satisfactory fit but tend to be overestimated in S3-5. Below 35 m^3s^{-1}, S1, S2 and to some extent S4 show a classic cone like pattern where S3 and S5 have more of a smokestack formation, see Figure 18.

During the validation period, S1 has a good fit at lower flows and simulations of S2 underestimate the observed flows. S3-5 low flows tend to be greatly overestimated. Peak flows for all sub-basins tend to be underestimated, see Figure 19.

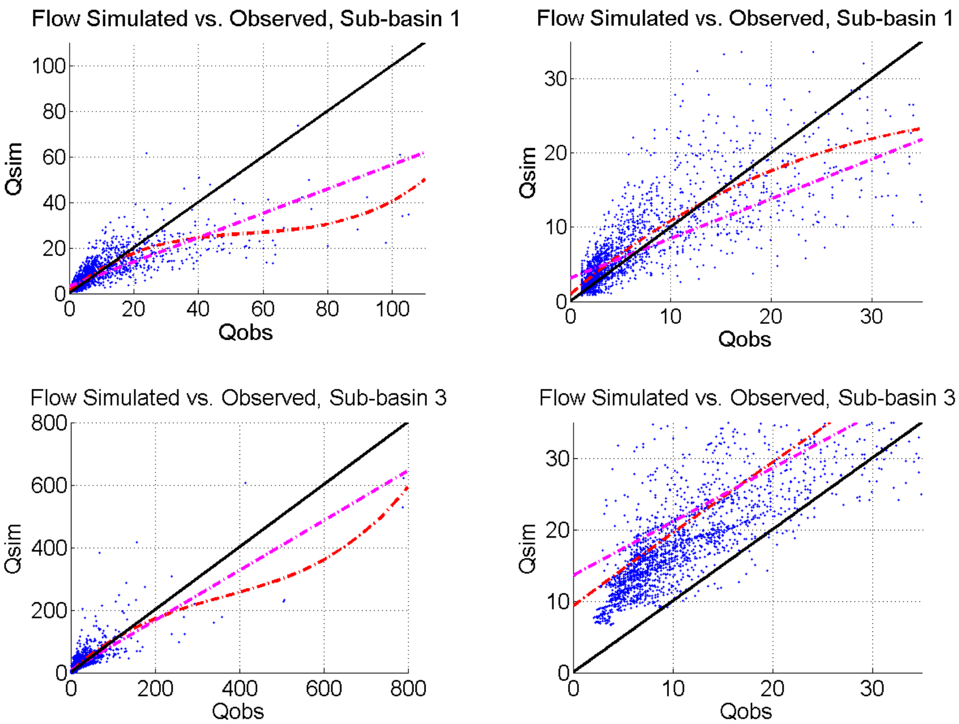

Figure 19 Validation QQ-plots for the period from 1 Jan. 2002 through 30 Nov. 2008 of Simulated vs. Observed flow, where the top two graphs are of sub-basin 1 and the bottom two are of sub-basin 3. The black line represents a 1:1 ratio. The dashed magenta (straight) line indicates a data fit with one degree of freedom while the (curved) dashed red line indicates a data fit with three degrees of freedom. In the graphs to the left, all data points for each sub-basin are plotted while to the right only data points for 35 m^3s^{-1} and less are plotted. The higher simulated flows in sub-basin 1 generally underestimate the observed flow while the lower flows are slightly overestimated and tend to be underestimated the higher the flows. For sub-basin 3 the high flows have a better general fit than in sub-basin 1 while the low flows are overestimated.

5. Discussion

Readdressing the *Purpose* of this study, *to build a MGB-IPH hydrological model of the Mundaú river basin which then will be used to evaluate whether or not current water extraction permits for the Mundaú basin exceed the regulated flow (Q_{95}) regulations - on a monthly basis – using a modeled monthly flow average*, after model calibration, the *purpose* was deemed unattainable. Simply put, the model was deemed to not reliably represent the hydrology of the Mundaú basin, thus not allowing for reliable simulated flow data extraction. Accordingly, the following discussion highlights how this determination has been realized.

Before exclusion of missing observed data points, the model has been calibrated using over 3 400 time-steps with a validation of over 2 500 time-steps. Each time-step has the length, in the observed data, of one (1) day. A dataset of this size enables a solid base for analyses.

5.1. Model Limitations

Developed for large-scale basins, 10 000 km^2 and larger, cells of 1 km^2 or less within MGB-IPH can be seen as points within each basin. The Mundaú basin is modeled using individual cells calibrated for five sub-basins ranging in size from approximately 92 km^2 to 1 653 km^2, totaling 3 672 km^2, Table 11. Individual cell characteristics thus play a predominant roll in the basin's hydrological responses.

Table 11 Sub-basin number of cells and drainage area in the MGB-IPH model.

Sub-basin	Number of cells	Drainage Area [km^2]
1	26	795
2	54	1 653
3	20	612
4	17	520
5	3	92
Total	120	3 672

The model uses one-day time-steps. With a time of concentration (TOC) of approximately one day for the entire Mundaú basin, changes in flow in the upper reaches of the basin would be better represented on an hourly scale. As the flow propagates downstream, the time-step scale should approach one day, thus also approach what is seen in the observed data.

Meteorological information is taken from two stations, Garanhuns and Maceió. At each station the data is considered reliable. Each modeled cell interpolates this data from nearby cells, resulting in the cells closest to each station most likely best representing the actual conditions, with an accuracy decrease in the transition area between Garanhuns and Maceió.

Rainfall data at each station is available at a daily time-step. MGB-IPH uses the inverse distance method for data interpolation to model the rainfall data throughout the cells that do not have data. Resulting catchment sensitivity to peak flows due to both localized and widespread convective events may be misrepresented due to both spatial and temporal data limitations.

The model uses only one land-use scenario for the entire modeled period. This scenario is from 2002-2009. Even though the map is 17-19 years after the model run-up period begins, the percent of each land-use closely resembles the studies from the mid 1990's, see Table 12 below. It can be expected that as the model approaches the mid to late 2000's, that the hydrological response units within the basin will more closely resemble what actually is there.

Table 12 Comparison between governmental land-use data and modeled land-use data. Anthropic areas are listed as pasture in the MGB file. The "exposed soil" land-use includes urban areas.

Land-use Type	PDRH 1999 (1990 data)	MGB-IPH cell file
Forest	22.76	21.62
Anthropic areas (Pasture)	52.32	57.96
Cane	21.76	15.22
Exposed soil	1.59	4.29
Water	0.05	0.09
Other	1.51	---
Total:	99.99%	99.79%

Furthermore, a single land-use scenario in the model should create discrepancies in the flow when comparing natural and simulated flows for the period of the year that is not represented by the land-use scenario. For instance, large areas of pasture in the state of Pernambuco tend to be bare soil during dry seasons.

5.2. Calibration Parameters

As seen in Appendix 1 under the parameters for sub-basin 3, a substantial change in the calibration parameters can be seen in comparison to the two upstream sub-basins. The differences in soil depth between S1-2 and S3 indicate that the soils of S3 should be able to hold more water than those in S1 and S2 before surface flow occurs. A b-parameter of 0.01 indicates the lowest possible basin reaction to rainfall. High CS, CI and CB parameters slow the surface and subsurface flow propagation. The Wm, b, CS, CI and CB parameters all are calibrated to hold water in the sub-basin considerably longer than in the upstream sub-basins. Additionally, CAP parameters of 8.00 and 9.00 essentially allow for losses from each cell to the atmosphere. As CAP increases, flows drop towards zero (0.00) m^3s^{-1}.

Continuing downstream from S3, S4-5 also incorporate the larger Wm values, in comparison to S1-2. The b-parameters are 0.02 and 0.01 respectively and the Wc values fluctuate from 4.55 and 6.77 in S4 to 0.01 in S5. CAP parameters are reduced from 8.00 and 9.00 in S3 to 0.50 and 0.00 in S4 and S5 respectively. CS, CI and CB are drastically reduced from their S3 levels in S4 to be raised again in S5.

Clearly a change has occurred from the upper reaches of the catchment compared to the downstream areas. Essentially, S1-2 attempt to have a quick reacting hydrology: thin soil layers, middle to high b-values, and generally reactive CS, CI and CB values, while S3 attempts to allow for rainfall to influence the flow as little as possible. S4-5 begin a rainfall reintroduction process as can be seen with a lowering towards negligible CAP values and the substantial lowering of CS, CI and CB. Still, b-values in S4-5 are not really able to leave the model lower limit of 0.01.

5.3. Calibration and Validation Fit Results

Calibration of S1 and S2 give satisfactory results. Even though both sub-basins' flows are under-simulated, the upper reaches of the Mundaú basin are within a dry, transition climate between a semi-arid (to the northwest) and humid (downstream) climate to the southeast. Not having upstream inflows to help supplement the flow, both the QQ-plots and FDCurves show satisfactory results. As seen in Table 10 in the results and Table 13 below, NS of approximately 0.50, low RVE in sub-basin 1 (-8) and low RMSE results (6.9 and 5.5 for sub-basin 1 and 2 respectively) support this conclusion.

As for the high RVE in sub-basin 2, this can partly be explained by looking at the observed data quality as described below in the *Data Quality* section. Long durations of steady flows in the observed data are not represented in the simulated flow data set.

Looking at the RVE difference between S1-2 and S3, both S1 and S2 have negative error (-8 and -22) while S3 has a large positive error (+26).

Table 13 Efficiency Criteria including calculated 95% exceedance for both observed and simulated flow.

Criteria	Sub 1		Sub 2		Sub 3	
	Cal	Val	Cal	Val	Cal	Val
NS	0.48	0.62	0.53	0.43	0.66	0.57
RVE	-8.06	-1.48	-21.70	-29.73	26.10	34.30
RMSE	6.88	6.49	5.72	5.35	19.29	20.74
$Q_{95, obs}$	0.33	1.18	0.62	1.32	1.72	4.12
$Q_{95, sim}$	0.19	1.30	0.47	1.14	0.07	9.92

With both underestimated flows as inputs into S3, and a large positive error at the outflow point, this leads to a conclusion that a change has occurred in S3.

Flow duration curves (FDCurves) represent how often a flow occurs in the basin while a QQ-plot represents the accuracy of each individual data point, simulated vs. observed. Each plot represents a different side of the same story. With FDCurves, the flow data is not temporally coupled to the basin. These curves give an idea of the magnitude of general over- or underestimation of the flow. This is easy to see in the validation graphs of S1 and S2 compared to S3-5, where most flows are largely overestimated.

Furthermore, generally speaking, with a large amount of data, smooth rounded shaped graphs give an indication that the data represents naturally occurring flows. An example of this can be seen in the validation graph of S1 at 90-100% exceedance. The straight line indicates that further investigation of the flow data should be done. The jaggedness of S2 combined with a sudden drop-off of flow right at 98% exceedance also indicates that there can be data issues. FDCurves for S1 and S2 are in contrast to those of S3-5 that are smooth and flowing in nature.

QQ-plots represent model accuracy in the temporal scale. From these plots conclusions can be drawn on the accuracy of not only the flows as a whole, but also which sections of flows that are over or underestimated. A classic cone shape distribution allows for a conclusion that the more densely distributed low flows are more accurately modeled than the dispersed high-flow (or peak flows). A more smokestack formation gives rise that the model has issues simulating low flows. The flows would at first be greatly under-simulated (most data points are below the 1:1 line), and then as the model begins to more accurately simulate the low to moderated flows, over simulation would begin to occur (most data points are above the 1:1 line). A classic example of this is in the calibration plots of S3 and S5.

A clear change in the look of the QQ-plots from S1-2 to S3-5 indicates that something has occurred. There is a clear over-estimation of the low flows in S3-5, compared to S1-2. This pattern can be seen for both the calibration and validation periods. Evidently, the model has difficulty with excess water during low flow periods.

5.4. Data Quality

Data anomalies in S2, both during the calibration and validation periods may have the effect of artificially high (observed data) flow values. This will result in an artificially low *NS* and *RVE*. Two examples can be seen during the calibration period. Thirty-five days straight from February through March 1997 of 4.23 m^3s^{-1} is an example of flow that is unlikely to occur naturally. This flow occurs in the calibration FDCurve at 19-23% exceedance. Another instance occurs at 4.5-7.5% exceedance, a flow of 9.18 m^3s^{-1}. Furthermore, when examining lower flows, there are numerous occurrences of steady flows during the dry seasons of, for example 1.21 followed by 0.992 m^3s^{-1}. The simulated flows do not follow a similar pattern.

During June 2010, the river basin had a large flood that washed away all of the river's flow stations. These manual stations have since been replaced with automatic stations. The river's morphology has also changed due to the erosion caused by the high flows. One result of this new morphology has been the need of calculating new Stage-Discharge curves (rating curves) for the river at each station. This curve was to be applied to the data points after the flood, but it was applied to the full data series. The accuracy of the currently available data from ANA previous to the June 2010 flood event is now in question. The presented model has been calibrated and validated using a flow time series from 1965 – 2008 that was acquired before this flooding event, a series not affected by the new rating curves. This should allow for a more accurate representation of the basin's hydrological responses before 2010.

5.5. Water Users

Not directly seen in the results of this study are the influences of the water users on the basin's surface flow. These users have not been required to apply for user permits prior to the implementation of the 1997 Federal Law 9.433 establishing the National Water Resources Policy that creates the National System of Water Resources Management. Recent data from 2010/13 from the states of Pernambuco and Alagoas estimated the combined water demands for irrigation, ranching and human consumption at over 100 000 000 m^3y^{-1}. This is equivalent to an average of over 3.17 m^3s^{-1} (per year) for the basin as a whole. This average can be compared to the current permit data that shows a basin-wide maximum average water usage of 1.79 m^3s^{-1}. The remaining 1.38 m^3s^{-1} is not quantifiable in the temporal/spatial scale. Additionally, pre-1997 data for the spatial water usage, for example: surface flows, subsurface flows, rainwater collection facilities and where these usages occur, and the temporal scale of the water usage is not directly available at this time.

The limits of the law (from Resolution N. 425, 2004) state that if the water user requires an instantaneous flow below

- Industry: 36 m^3/h or 10 l/s
- Irrigation: 360 m^3/h or 100 l/s
- Sanitation: 72 m^3/h or 20 l/s,

the user is not required to apply for a permit. Small-scale irrigation regimes and livestock needs can easily fall beneath the permit flow requirements. Many inhabitants within the basin are subsidence farmers – including small livestock ranches. While each user individually may not significantly affect the basin's hydrology and river flows, as a whole, their cumulative usage volume should not be underrated.

The MGB-IPH model only considers the input values of the observed data series. With water usage not accounted for in the data, lower than naturally occurring flows are likely to be seen in the data. Yet quantification of these inaccuracies is not easily accounted for. Consequently, if the model over-estimates for example the dry seasonal flow, the quantification of the actual model error is difficult to estimate.

A comparison of the precipitation patterns in Figure 3 and Figure 4 to the water usage in the grants in Table 6 does allow for withdrawal quantification, *to some extent*. It can be seen that the grants allow for larger extractions during the dry periods of the year, approximately 2.50 m^3s^{-1} from September through March. During the remaining months the grants allow for relatively small extractions. This is most likely due to the grant owner's request for less extraction during wet periods of the year.

To apply these grant flows to the observed data, assumptions would have to be made. For example, these grants are all upper limits to what is allowed to legally be withdrawn; they are not actual withdrawal values. Assuming a so called *worst-case scenario* where the users apply their grants to their fullest extent would allow for a maximum instantaneous flow that could directly be added to the observed flow. Notably though, the first available grant information is from 2001, which does not directly allow for reconstruction of pre-2001 flow series.

5.6. Final Thoughts

The MGB-IPH model has been calibrated for a best fit, primarily for low flows, but also considering general efficiency criteria. The change from underestimation of flows in S1-2 towards clear overestimation of the flows in S3-5 has been a monumental task to overcome. The flow issue begins in S3 followed by an attempt to bring the model parameters back towards a more hydrologically representative parameter regime in S4-5. Most current water grants are allocated within S3-5, for further information see Table 7. These documented water users only account for a portion of the actual users in the basin.

Flow reconstruction for the five flow stations used in this model's calibration is one way of attempting overcome the limitations of the available flow data sets. However, data is not readily available and any discrepancies within the data will need to be investigated.

A second approach to quantifying the water usage in the basin would be calibrating the model to *physically-based parameters* instead of a best-fit to observed data. This would allow for a basin-wide estimated usage volume. A preliminary model calibration of this type, examining the flow duration curves for S3-5 – with an exceedance of 50-80%, reveals a model overestimation of the low flows in the magnitude of 6-10 m^3s^{-1} in these sub-basins.

6. Conclusion

Rainfall-runoff models have been used extensively to better understand basin hydrology. This study has encompassed MGB-IPH model calibration to a best fit to observed flows of the union domain Mundaú river basin in northeastern Brazil in order to examine water grants' compliance with regulations within the basin.

Model calibration has produced mixed results. Upstream sub-basins 1-2 have a good fit using parameters that can be seen as resembling nature while the downstream sub-basins 3-5 have a poor fit, even with calibration parameters far outside hydrologically representative values. The downstream areas simulate substantially higher river flows than can be seen in the observed data.

Examination of the water usages in the basin accounts for a portion of the difference in simulated vs. observed flows. Water permits valid in 2015 would, if applied to their fullest extent, account for a usage of 1-3 m^3s^{-1} averaged per month. Additionally, complementary data describes a total basin usage of approximately 3 m^3s^{-1} averaged over a year. However, this complementary data lacks both the temporal and spatial resolution needed to supplement observed flow data.

Calibration to observed flow data has produced a model that cannot be seen as representing the basin's hydrology, thus examination of the government granted water permits' compliance has not been conducted.

There are predominantly two ways of moving the research forward. A study that quantifies both spatially and temporally the extent of water usage would help in a "natural" flow reconstruction. Then a model recalibration can be done. The second way forward would be model recalibration to hydrologically representative parameters, thus resulting in an approximation of the actual basin-wide water usage – without a long quantifying study. A preliminary recalibration to hydrologically representative parameters shows a water usage in the range of 6-10 m^3s^{-1} at a 50-80% exceedance. I believe that the second method would enable future research in the basin's hydrology and serve as a tool for governmental water resource management.

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8. Appendix 1, Calibration Parameters

Sub-basin	1							
HRU	**Wm**	**b**	**Kbas**	**Kint**	**Kflux**	**XL**	**CAP**	**Wc**
D+Forest	280.0	0.19	2.00	2.00	793.00	0.25	0.00	0.24
D+Pasture	220.0	0.19	2.00	2.00	793.00	0.25	0.00	0.24
D+Cane	250.0	0.19	2.00	2.00	793.00	0.25	0.00	0.24
D+Exp	150.0	0.19	2.00	2.00	793.00	0.25	0.00	0.24
C+Forest	360.0	0.28	90.00	90.00	793.00	0.46	0.00	0.26
C+Pasture	280.0	0.28	90.00	90.00	793.00	0.46	0.00	0.26
C+Cane	320.0	0.28	90.00	90.00	793.00	0.46	0.00	0.26
C+Exp	160.0	0.28	90.00	90.00	793.00	0.46	0.00	0.26
Water	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RW	1.30							
CS	78.00							
CI	98.00							
CB	4500.00							
QB	0.010							

Sub-basin	2							
HRU	**Wm**	**b**	**Kbas**	**Kint**	**Kflux**	**XL**	**CAP**	**Wc**
D+Forest	120.0	0.39	2.00	2.00	793.00	0.25	0.00	0.07
D+Pasture	60.0	0.39	2.00	2.00	793.00	0.25	0.00	0.07
D+Cane	100.0	0.39	2.00	2.00	793.00	0.25	0.00	0.07
D+Exp	50.0	0.39	2.00	2.00	793.00	0.25	0.00	0.07
C+Forest	150.0	0.48	90.00	90.00	793.00	0.46	0.00	0.09
C+Pasture	100.0	0.48	90.00	90.00	793.00	0.46	0.00	0.09
C+Cane	120.0	0.48	90.00	90.00	793.00	0.46	0.00	0.09
C+Exp	70.0	0.48	90.00	90.00	793.00	0.46	0.00	0.09

Water	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RW	1.30							
CS	38.00							
CI	58.00							
CB	4800.00							
QB	0.010							

Sub-basin	**3**							
HRU	**Wm**	**b**	**Kbas**	**Kint**	**Kflux**	**XL**	**CAP**	**Wc**
D+Forest	1300.0	0.01	2.00	2.00	793.00	0.15	08.00	0.31
D+Pasture	1050.0	0.01	2.00	2.00	793.00	0.15	08.00	0.31
D+Cane	1200.0	0.01	2.00	2.00	793.00	0.15	08.00	0.31
D+Exp	200.0	0.01	2.00	2.00	793.00	0.15	08.00	0.31
C+Forest	1700.0	0.01	90.00	90.00	793.00	0.20	09.00	0.38
C+Pasture	1300.0	0.01	90.00	90.00	793.00	0.20	09.00	0.38
C+Cane	1500.0	0.01	90.00	90.00	793.00	0.20	09.00	0.38
C+Exp	400.0	0.01	90.00	90.00	793.00	0.20	09.00	0.38
Water	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RW	1.50							
CS	4578.00							
CI	7598.00							
CB	45500.00							
QB	0.010							

Sub-basin	**4**							
HRU	**Wm**	**b**	**Kbas**	**Kint**	**Kflux**	**XL**	**CAP**	**Wc**
D+Forest	1600.0	0.02	2.00	2.00	793.00	0.45	00.50	4.55
D+Pasture	1450.0	0.02	2.00	2.00	793.00	0.45	00.50	4.55
D+Cane	1500.0	0.02	2.00	2.00	793.00	0.45	00.50	4.55

D+Exp	200.0	0.02	2.00	2.00	793.00	0.45	00.50	4.55
C+Forest	2300.0	0.02	90.00	90.00	793.00	0.66	00.50	6.77
C+Pasture	1700.0	0.02	90.00	90.00	793.00	0.66	00.50	6.77
C+Cane	1900.0	0.02	90.00	90.00	793.00	0.66	00.50	6.77
C+Exp	400.0	0.02	90.00	90.00	793.00	0.66	00.50	6.77
Water	0.0	0.00	0.00	0.00	0.00	0.00	00.00	00.0
RW	1.50							
CS	178.00							
CI	198.00							
CB	7500.00							
QB	0.010							

Sub-basin	**5**							
HRU	**Wm**	**b**	**Kbas**	**Kint**	**Kflux**	**XL**	**CAP**	**Wc**
D+Forest	1300.0	0.01	2.00	2.00	793.00	0.50	00.00	0.01
D+Pasture	1200.0	0.01	2.00	2.00	793.00	0.50	00.00	0.01
D+Cane	1250.0	0.01	2.00	2.00	793.00	0.50	00.00	0.01
D+Exp	100.0	0.01	2.00	2.00	793.00	0.50	00.00	0.01
C+Forest	1400.0	0.01	90.00	90.00	793.00	0.65	00.00	0.01
C+Pasture	1220.0	0.01	90.00	90.00	793.00	0.65	00.00	0.01
C+Cane	1270.0	0.01	90.00	90.00	793.00	0.65	00.00	0.01
C+Exp	1130.0	0.01	90.00	90.00	793.00	0.65	00.00	0.01
Water	0.0	0.00	0.00	0.00	0.00	0.00	00.00	0.00
RW	1.50							
CS	278.00							
CI	398.00							
CB	18500.00							
QB	0.010							

albedo												
HRU	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
D+Forest	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.22
D+Pasture	0.22	0.21	0.20	0.19	0.17	0.16	0.16	0.19	0.20	0.21	0.22	0.22
D+Cane	0.19	0.19	0.18	0.16	0.16	0.15	0.15	0.15	0.16	0.20	0.19	0.19
D+Exp	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
C+Forest	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
C+Pasture	0.22	0.21	0.20	0.19	0.17	0.16	0.16	0.19	0.20	0.21	0.22	0.22
C+Cane	0.19	0.19	0.18	0.16	0.16	0.15	0.15	0.15	0.16	0.20	0.19	0.19
C+Exp	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Water	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08

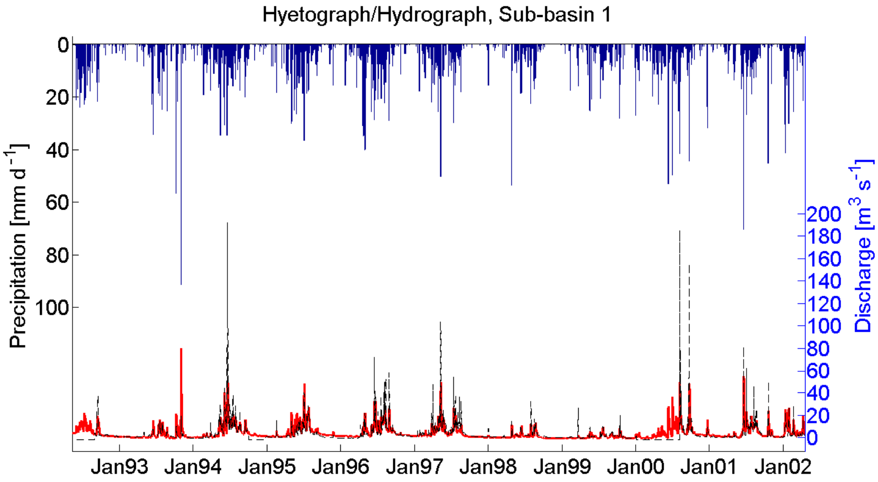
LAI	Leaf Area Index											
HRU	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
D+Forest	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
D+Pasture	0.40	1.00	2.00	3.00	3.50	4.00	4.00	3.00	2.00	1.00	0.40	0.40
D+Cane	2.50	2.50	3.00	4.00	4.50	5.00	5.00	5.00	4.00	2.00	2.50	2.50
D+Exp	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
C+Forest	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
C+Pasture	0.40	1.00	2.00	3.00	3.50	4.00	4.00	3.00	2.00	1.00	0.40	0.40
C+Cane	2.50	2.50	3.00	4.00	4.50	5.00	5.00	5.00	4.00	2.00	2.50	2.50
C+Exp	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Water	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Z	Vegetation Height											
HRU	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
D+Forest	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
D+Pasture	0.12	0.15	0.18	0.21	0.22	0.24	0.24	0.21	0.18	0.15	0.12	0.12
D+Cane	1.50	1.80	2.00	2.30	2.50	3.00	3.00	3.00	2.50	1.50	1.50	1.50
D+Exp	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
C+Forest	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
C+Pasture	0.12	0.15	0.18	0.21	0.22	0.24	0.24	0.21	0.18	0.15	0.12	0.12
C+Cane	1.50	1.80	2.00	2.30	2.50	3.00	3.00	3.00	2.50	1.50	1.50	1.50
C+Exp	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Water	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05

RS	Surface Resistance											
HRU	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
D+Forest	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
D+Pasture	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0
D+Cane	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0
D+Exp	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
C+Forest	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
C+Pasture	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0
C+Cane	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0
C+Exp	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
Water	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

9. Appendix 2, Mundaú Calibration Results

9.1. Hyeto- Hydrographs



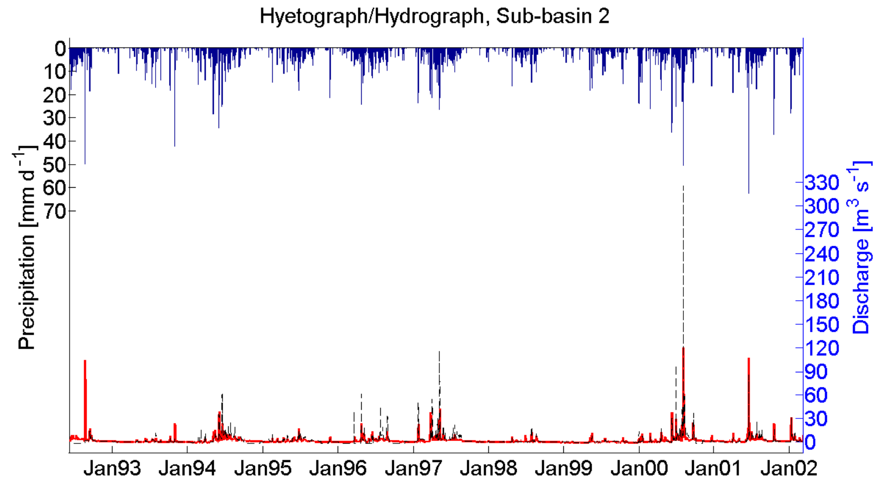
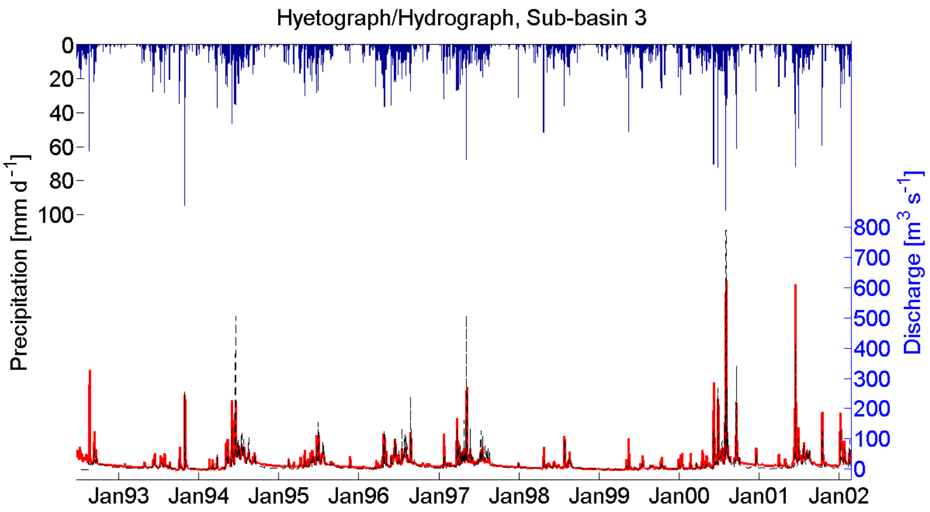


Figure 20 Calibration Hyetograph/Hydrograph of sub-basins 1 and 2 from 1 Sept. 1992 through 31 Dec. 2001. The dashed black line indicates observed flow while the solid red line indicates simulated flow, both in m^3s^{-1}. The blue bars at the top are sub-basin average rainfall in mm per day.



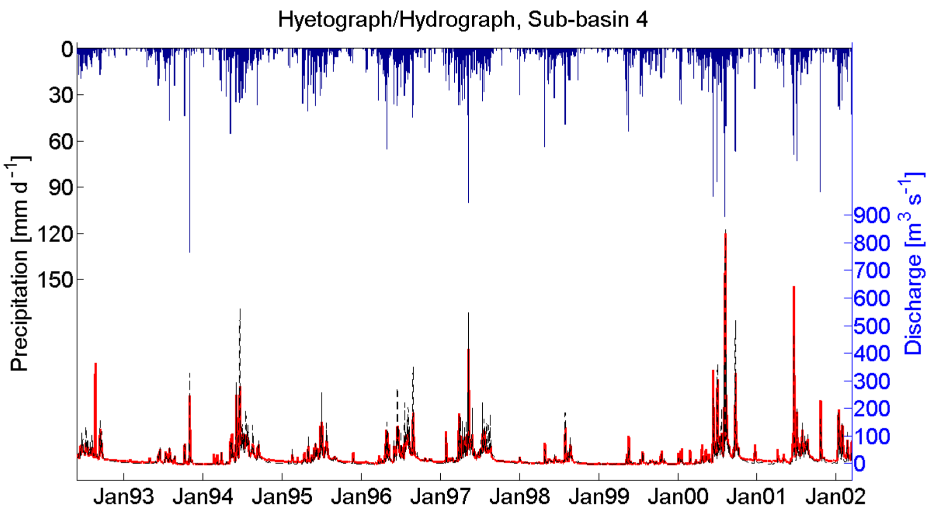


Figure 21 Calibration Hyetograph/Hydrograph of sub-basins 3 and 4 from 1 Sept. 1992 through 31 Dec. 2001. The dashed black line indicates observed flow while the solid red line indicates simulated flow, both in m^3s^{-1}. The blue bars at the top are sub-basin average rainfall in mm per day.

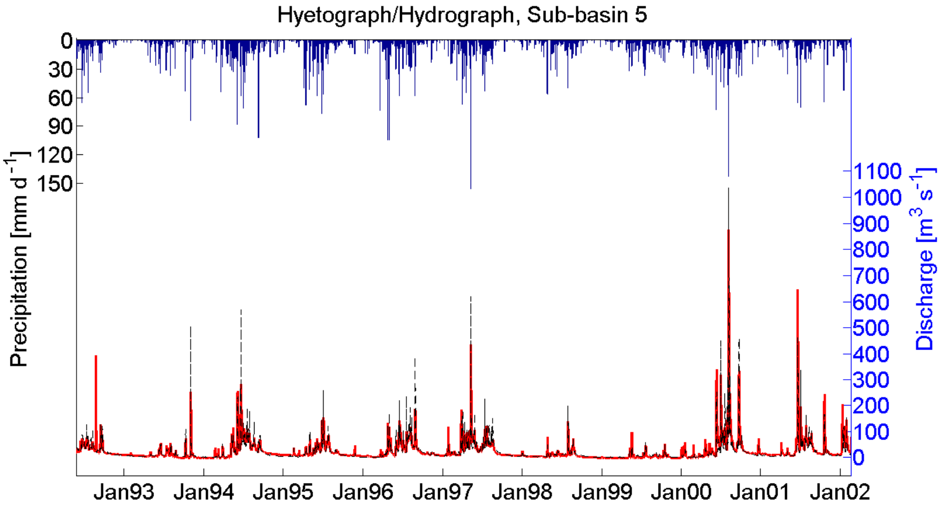


Figure 22 Calibration Hyetograph/Hydrograph of sub-basin 5 from 1 Sept. 1992 through 31 Dec. 2001. The dashed black line indicates observed flow while the solid red line indicates simulated flow, both in m^3s^{-1}. The blue bars at the top are sub-basin average rainfall in mm per day.

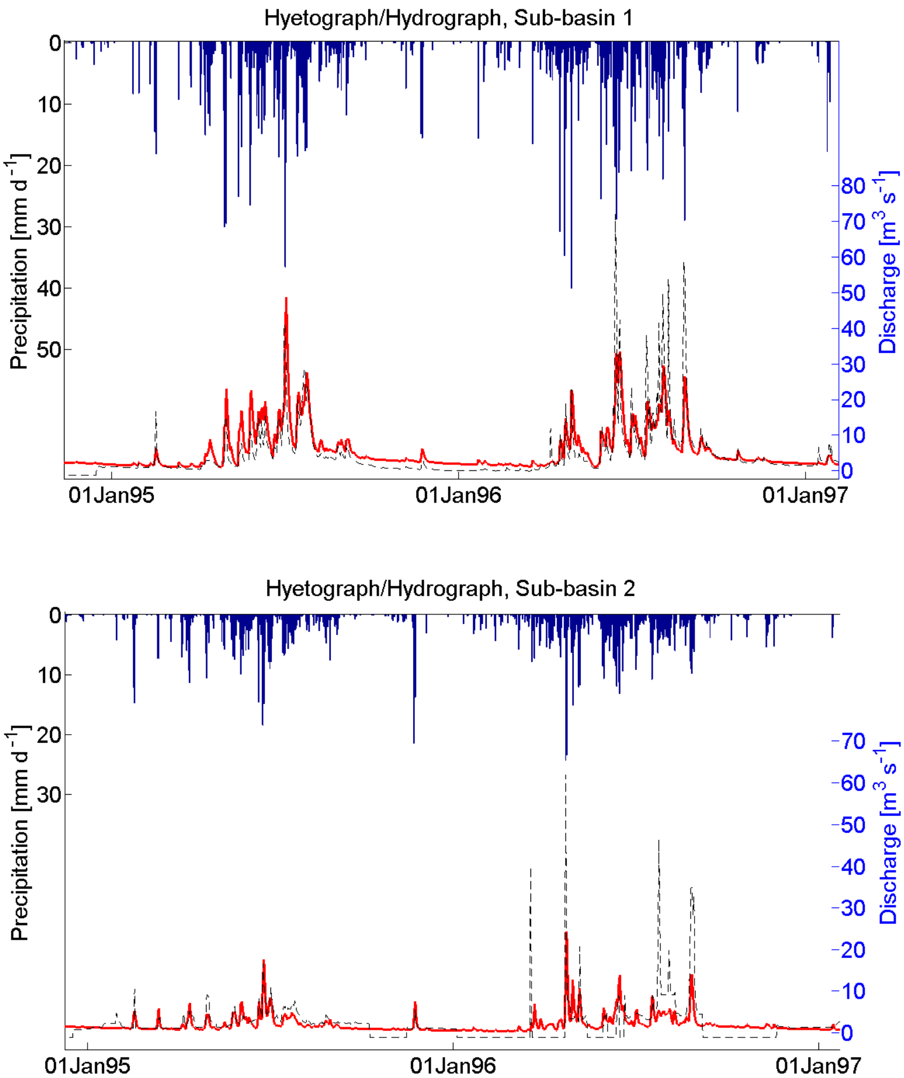


Figure 23 Calibration Hyetograph/Hydrograph of sub-basins 1 and 2 from 1 Jan. 1995 until 1 Jan. 1997. The dashed black line indicates observed flow while the solid red line indicates simulated flow, both in m^3s^{-1}. The blue bars at the top are sub-basin average rainfall in mm per day. Missing data is indicated as a discharge of -1.00 m^3s^{-1}.

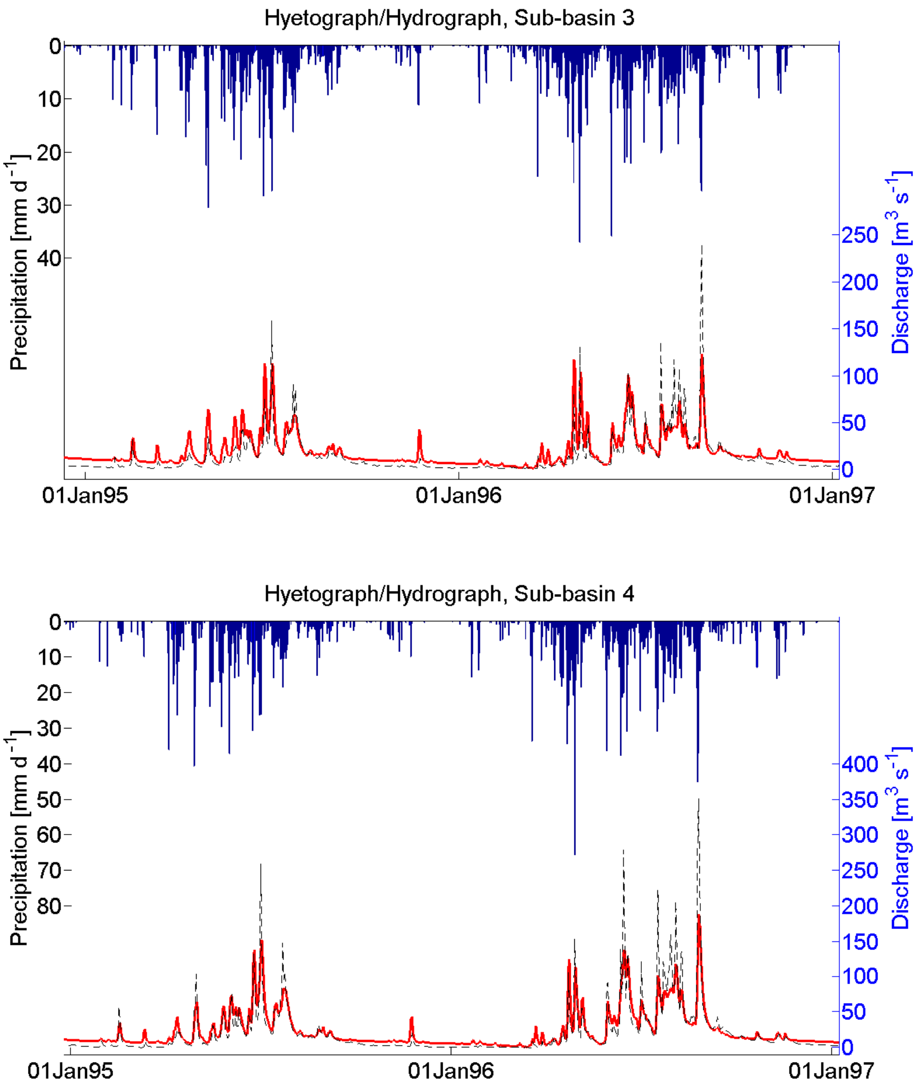


Figure 24 Calibration Hyetograph/Hydrograph of sub-basins 3 and 4 from 1 Jan. 1995 until 1 Jan. 1997. The dashed black line indicates observed flow while the solid red line indicates simulated flow, both in m^3s^{-1}. The blue bars at the top are sub-basin average rainfall in mm per day.

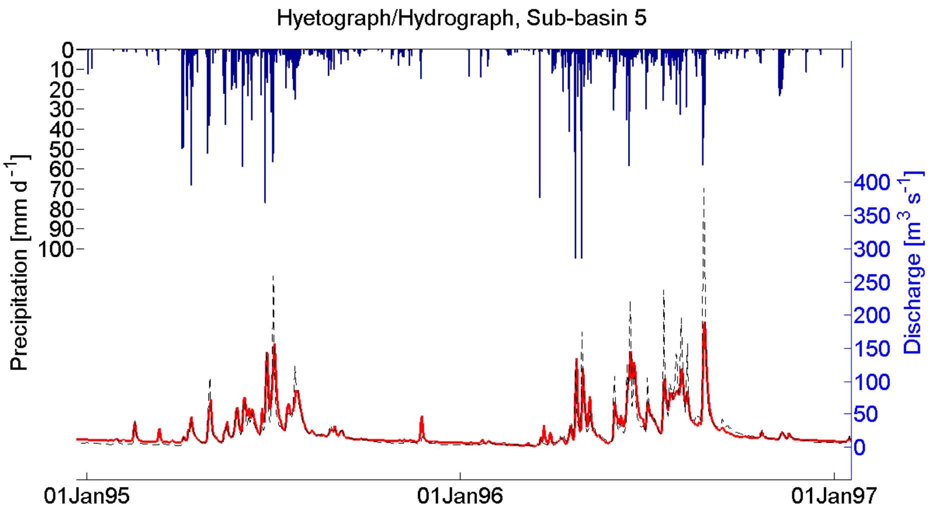


Figure 25 Calibration Hyetograph/Hydrograph of sub-basin 5 from 1 Jan. 1995 until 1 Jan. 1997. The dashed black line indicates observed flow while the solid red line indicates simulated flow, both in m^3s^{-1}. The blue bars at the top are sub-basin average rainfall in mm per day.

9.2. QQ-Plots

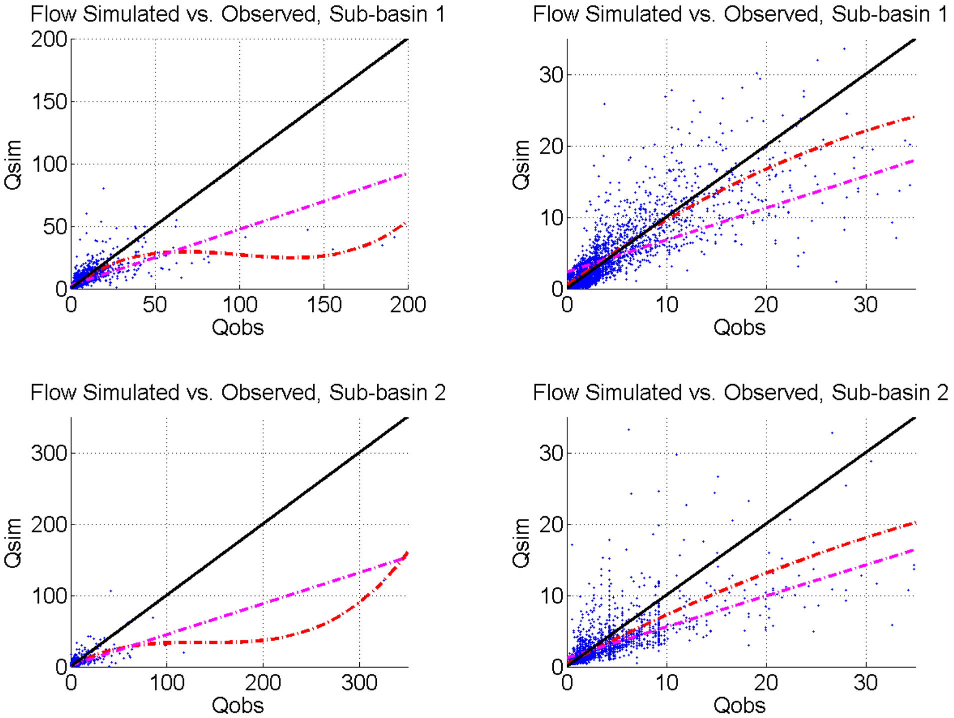


Figure 26 Calibration QQ-plots for the period from 1 Sept. 1992 through 31 Dec. 2001 of Simulated vs. Observed flow, where the top two graphs are of sub-basin 1 and the bottom two are of sub-basin 2. The black line represents a 1:1 ratio. The dashed magenta (straight) line indicates a data fit with one degree of freedom while the (curved) dashed red line indicates a data fit with three degrees of freedom. In the graphs to the left, all data points for each sub-basin are plotted while to the right only data points for 35 m^3s^{-1} and less are plotted.

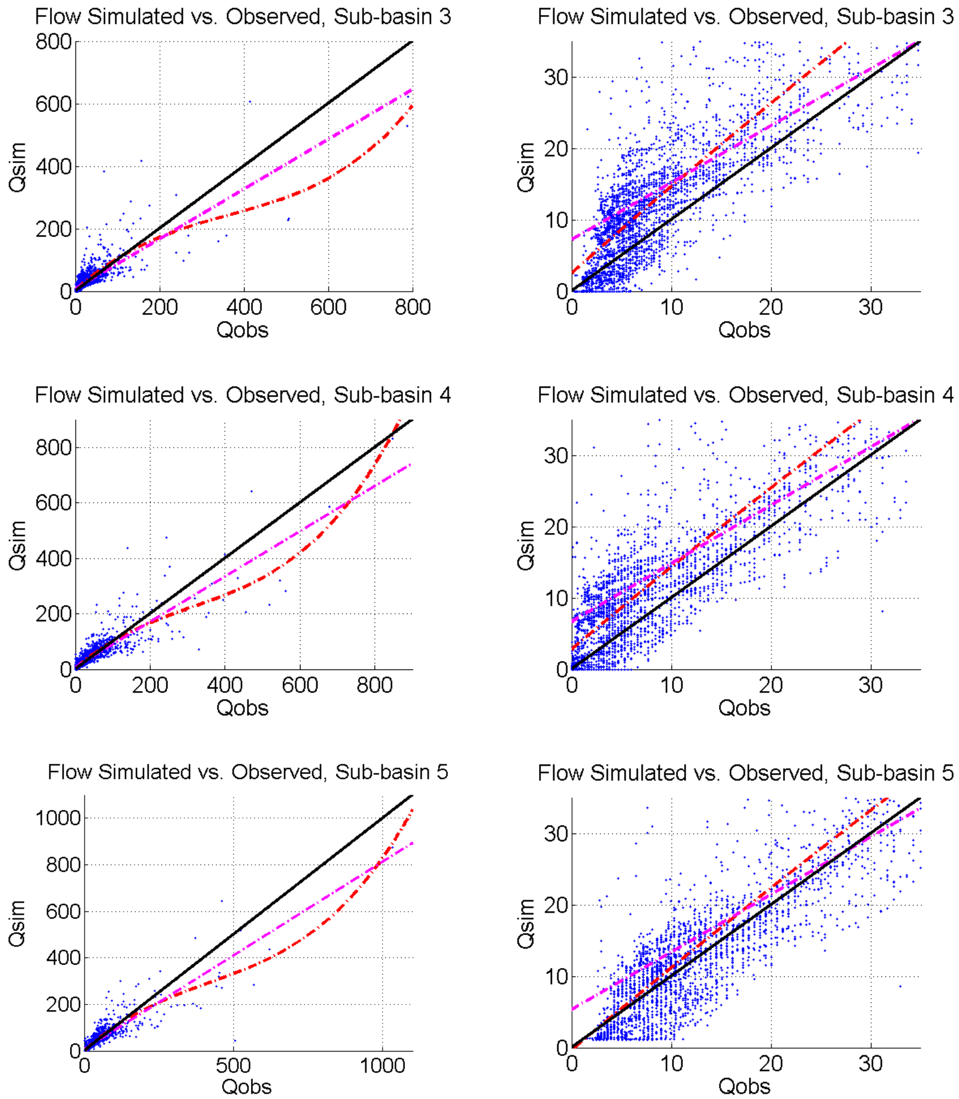


Figure 27 Calibration QQ-plots for the period from 1 Sept. 1992 through 31 Dec. 2001 of Simulated vs. Observed flow for sub-basins 3-5. The black line represents a 1:1 ratio. The dashed magenta (straight) line indicates a data fit with one degree of freedom while the (curved) dashed red line indicates a data fit with three degrees of freedom. In the graphs to the left, all data points for each sub-basin are plotted while to the right only data points for 35 m^3s^{-1} and less are plotted.

9.3. Flow Duration Curves

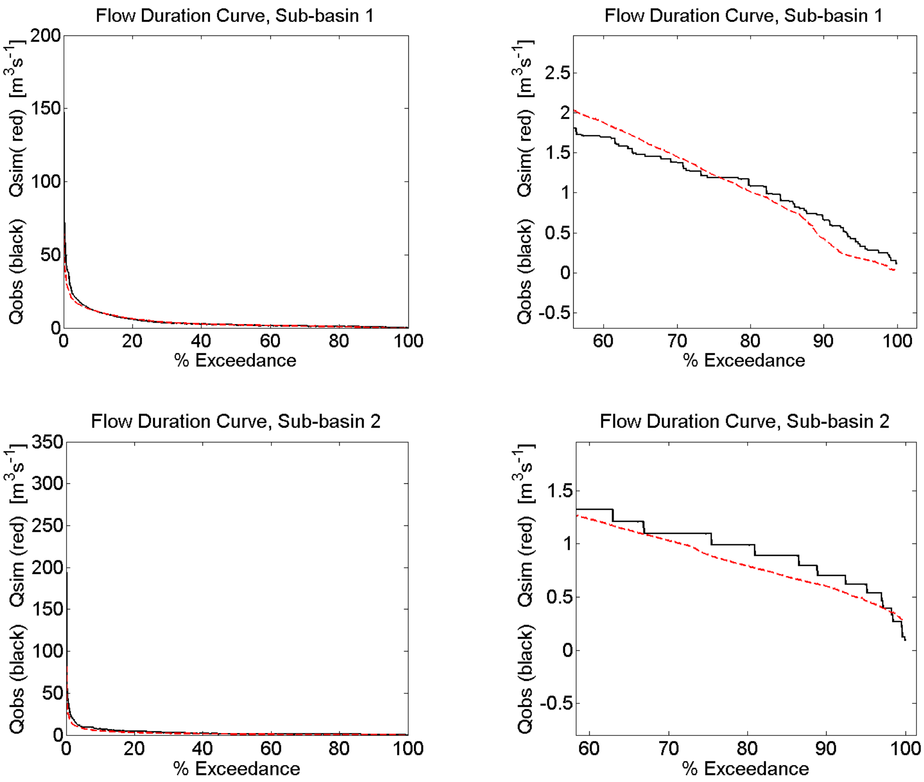


Figure 28 Calibration Flow Duration Curves for sub-basins 1 and 2. The observed flow is represented with a solid black line while the simulated flow is represented with a dashed red line.

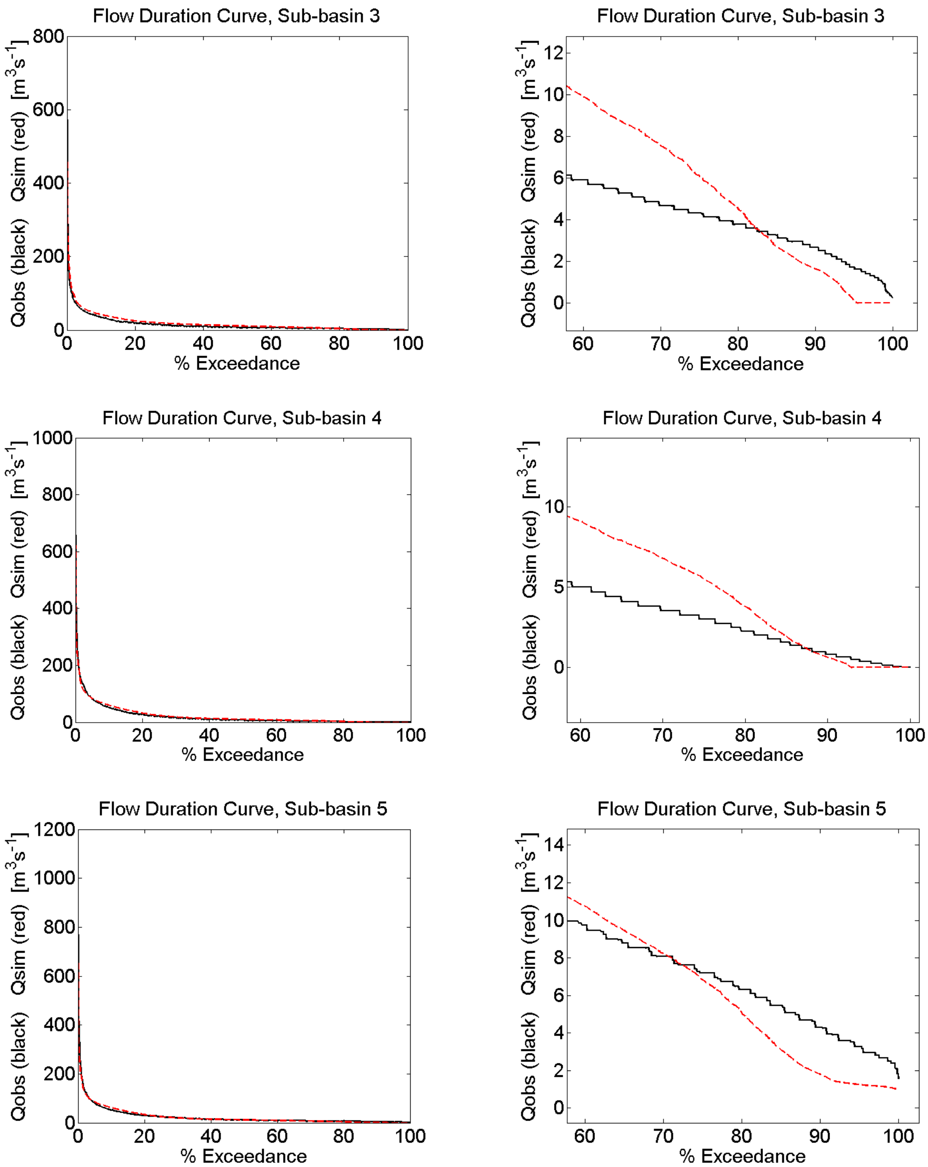
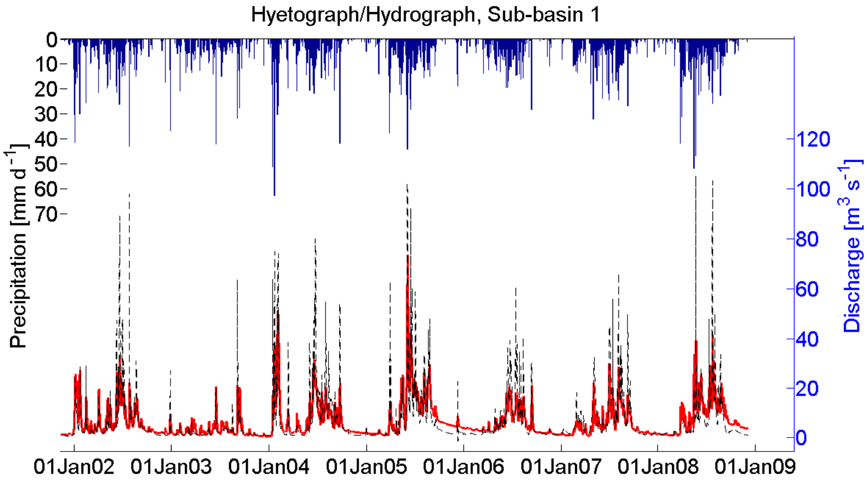


Figure 29 Calibration Flow Duration Curves for sub-basins 3-5. The observed flow is represented with a solid black line while the simulated flow is represented with a dashed red line.

10. Appendix 3, Mundaú Validation Results

10.1. Hyeto- Hydrographs



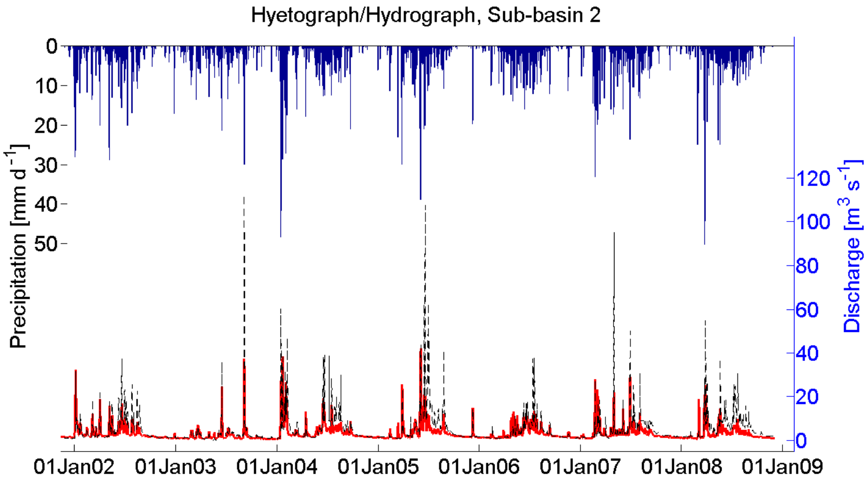


Figure 30 Validation Hyetograph/Hydrograph of sub-basins 1 and 2 from 1 Jan. 2002 through 30 Nov. 2008. The dashed black line indicates observed flow while the solid red line indicates simulated flow, both in m^3s^{-1}. The blue bars at the top are sub-basin average rainfall in mm per day.

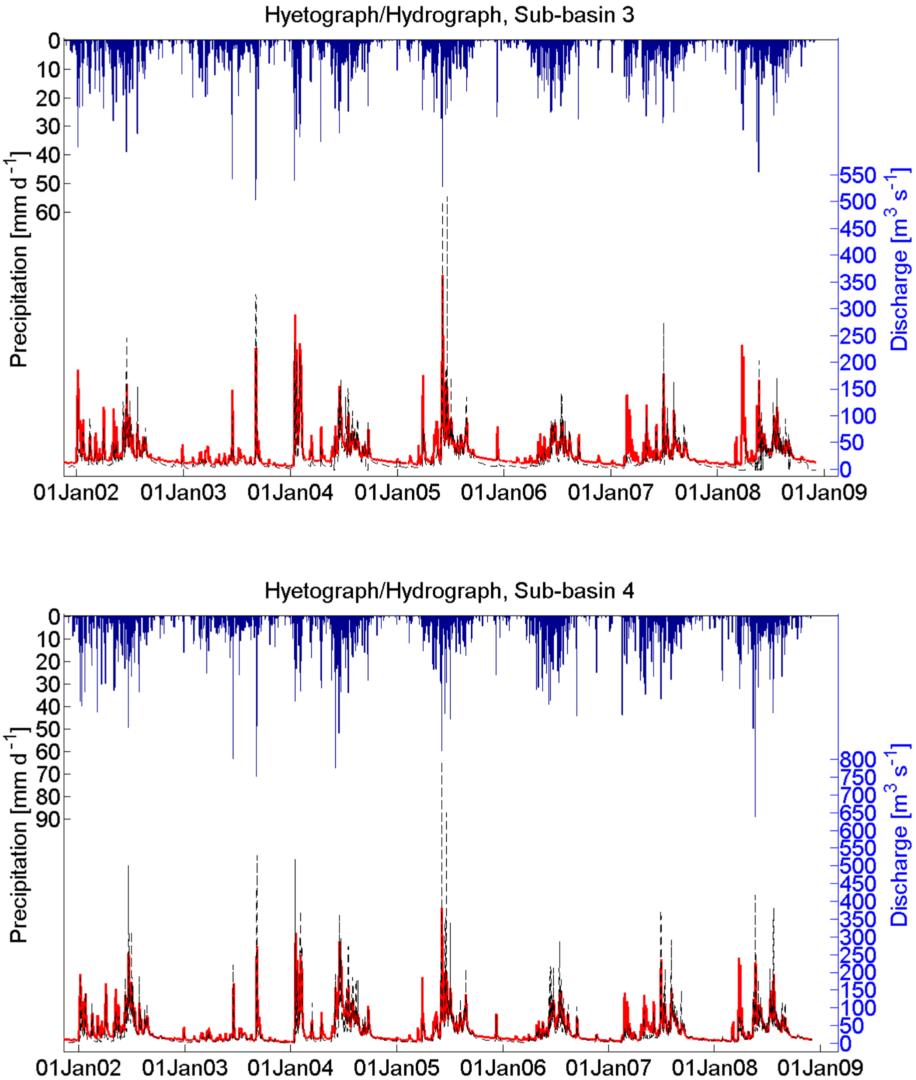


Figure 31 Validation Hyetograph/Hydrograph of sub-basins 3 and 4 from 1 Jan. 2002 through 30 Nov. 2008. The dashed black line indicates observed flow while the solid red line indicates simulated flow, both in m^3s^{-1}. The blue bars at the top are sub-basin average rainfall in mm per day.

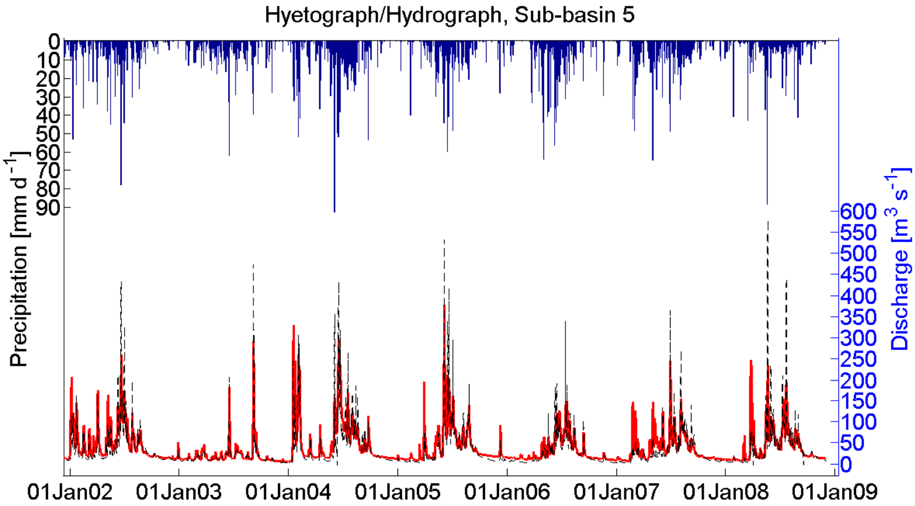
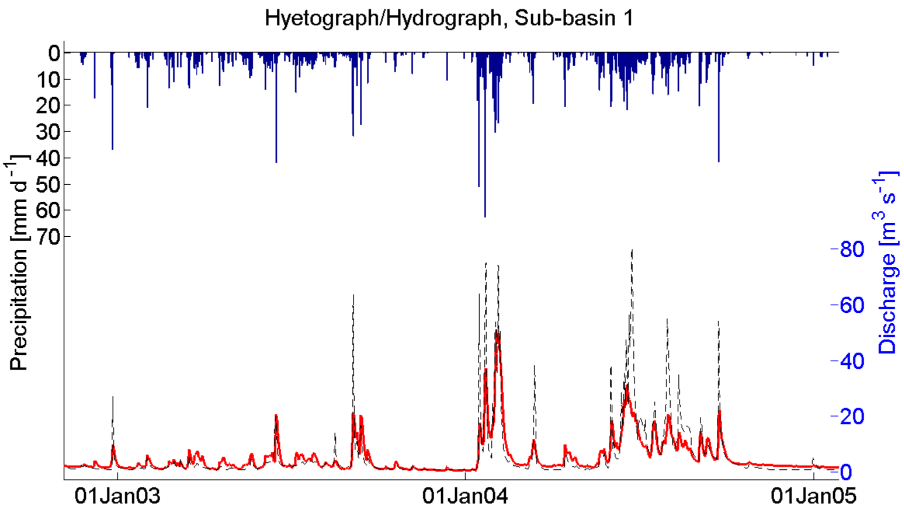


Figure 32 Validation Hyetograph/Hydrograph of sub-basin 5 from 1 Jan. 2002 through 30 Nov. 2008. The dashed black line indicates observed flow while the solid red line indicates simulated flow, both in m^3s^{-1}. The blue bars at the top are sub-basin average rainfall in mm per day.



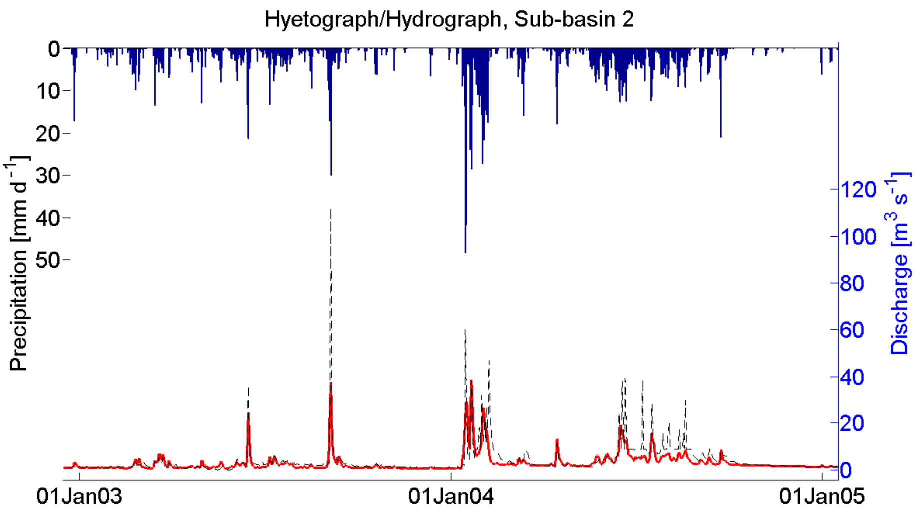


Figure 33 Validation Hyetograph/Hydrograph of sub-basins 1 and 2 from 1 Jan. 2003 until 1 Jan. 2005. The dashed black line indicates observed flow while the solid red line indicates simulated flow, both in m^3s^{-1}. The blue bars at the top are sub-basin average rainfall in mm per day.

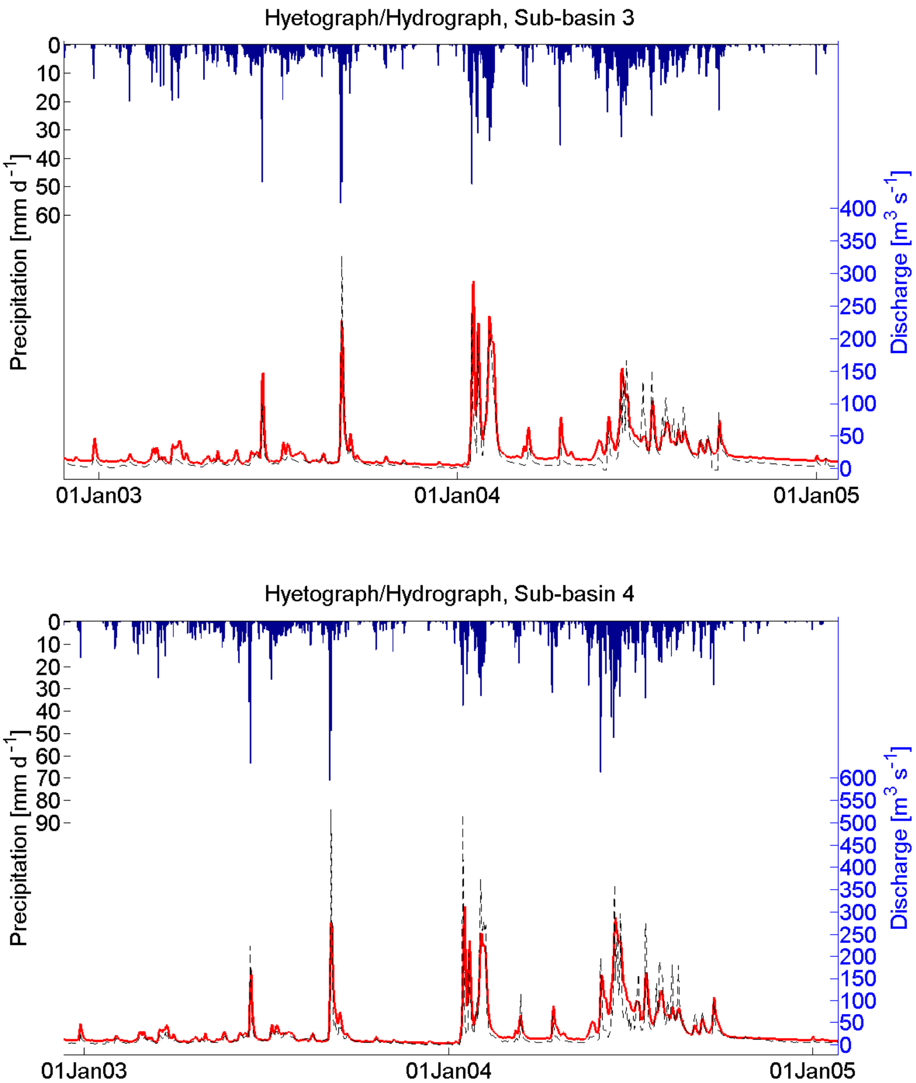


Figure 34 Validation Hyetograph/Hydrograph of sub-basins 3 and 4 from 1 Jan. 2003 until 1 Jan. 2005. The dashed black line indicates observed flow while the solid red line indicates simulated flow, both in m^3s^{-1}. The blue bars at the top are sub-basin average rainfall in mm per day.

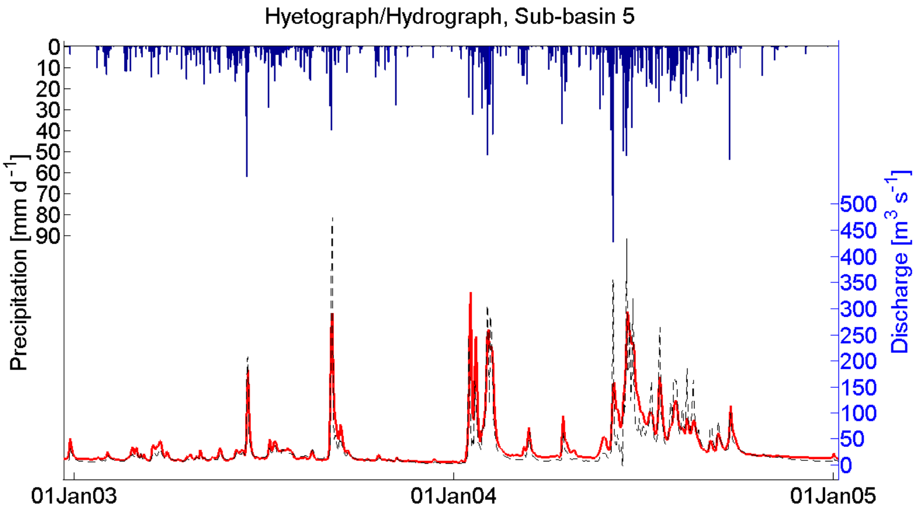


Figure 35 Validation Hyetograph/Hydrograph of sub-basin 5 from 1 Jan. 2003 until 1 Jan. 2005. The dashed black line indicates observed flow while the solid red line indicates simulated flow, both in m^3s^{-1}. The blue bars at the top are sub-basin average rainfall in mm per day.

10.2. QQ-Plots

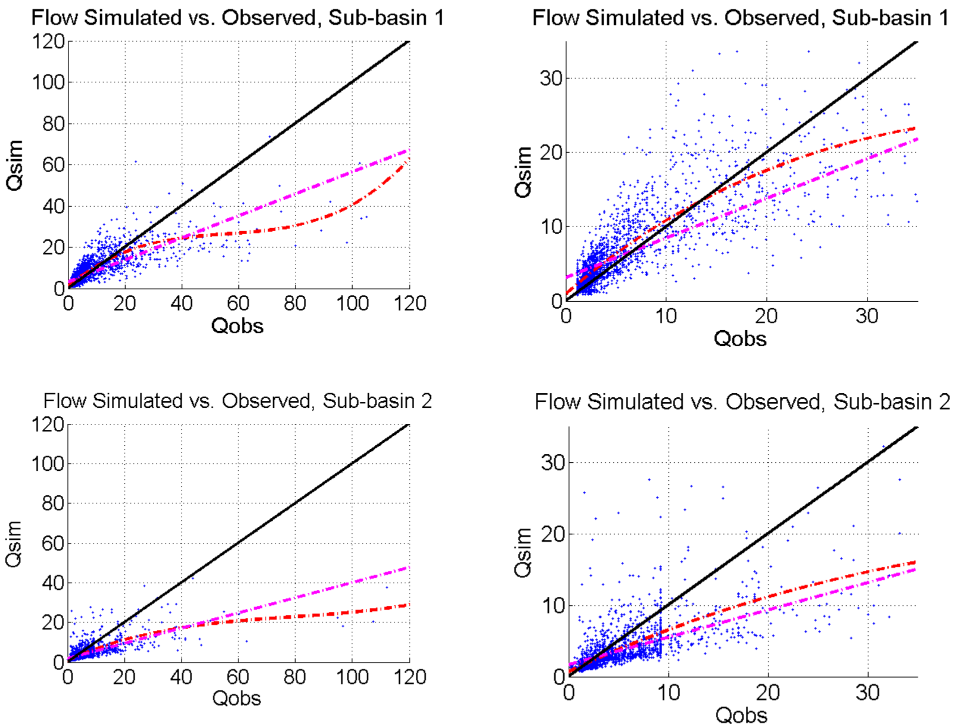


Figure 36 Validation QQ-plots for the period from 1 Jan. 2002 through 30 Nov. 2008 of Simulated vs. Observed flow for sub-basins 1-2. The black line represents a 1:1 ratio. The dashed magenta (straight) line indicates a data fit with one degree of freedom while the (curved) dashed red line indicates a data fit with three degrees of freedom. In the graphs to the left, all data points for each sub-basin are plotted while to the right only data points for 35 m^3s^{-1} and less are plotted.

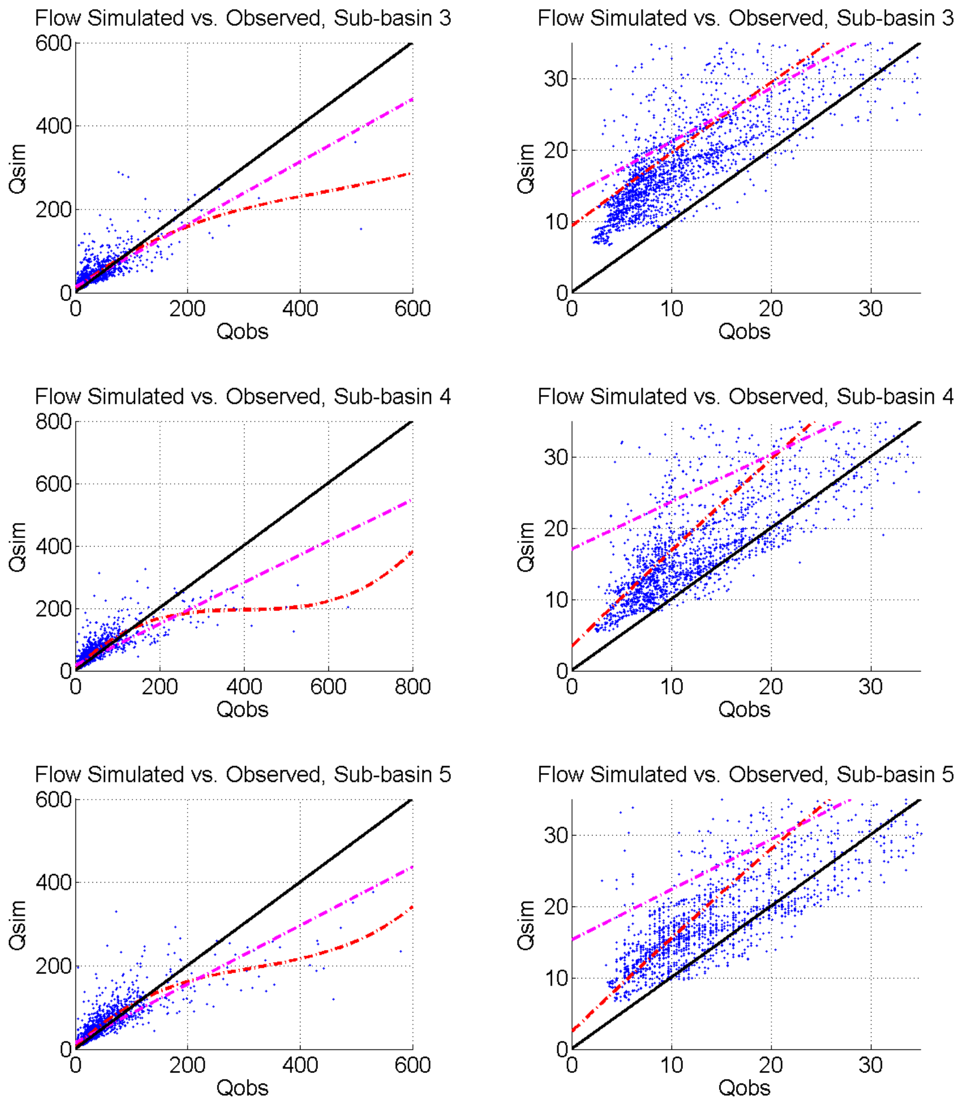


Figure 37 Validation QQ-plots for the period from 1 Jan. 2002 through 30 Nov. 2008 of Simulated vs. Observed flow for sub-basins 3-5. The black line represents a 1:1 ratio. The dashed magenta (straight) line indicates a data fit with one degree of freedom while the (curved) dashed red line indicates a data fit with three degrees of freedom. In the graphs to the left, all data points for each sub-basin are plotted while to the right only data points for 35 m^3s^{-1} and less are plotted.

10.3. Flow Duration Curves

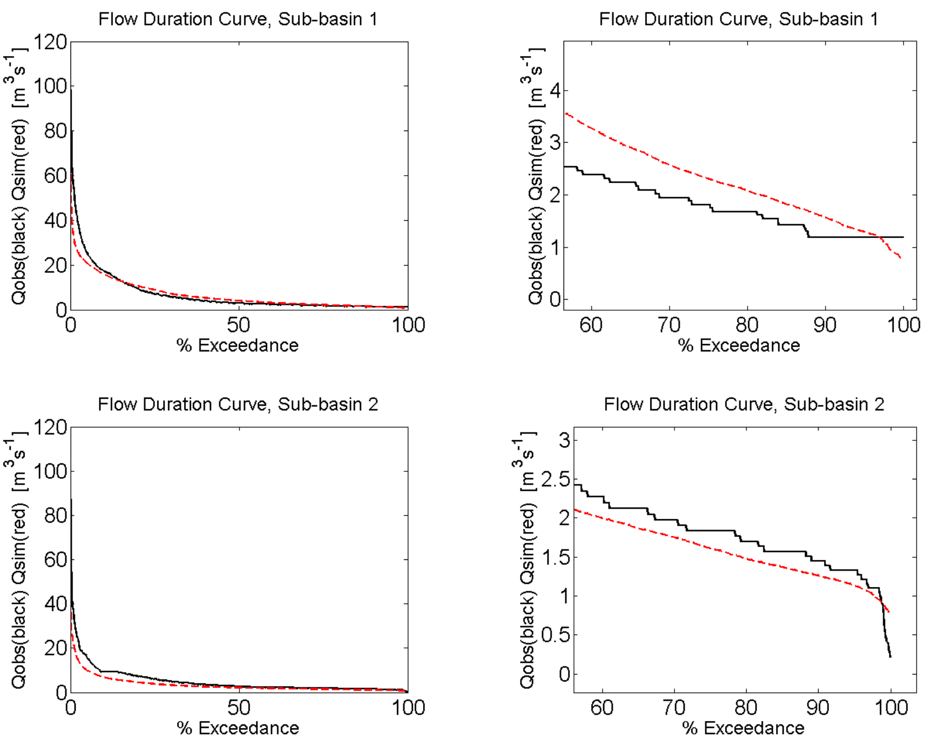


Figure 38 Validation Flow Duration Curves for sub-basins 1 and 2. The observed flow is represented with a solid black line while the simulated flow is represented with a dashed red line.

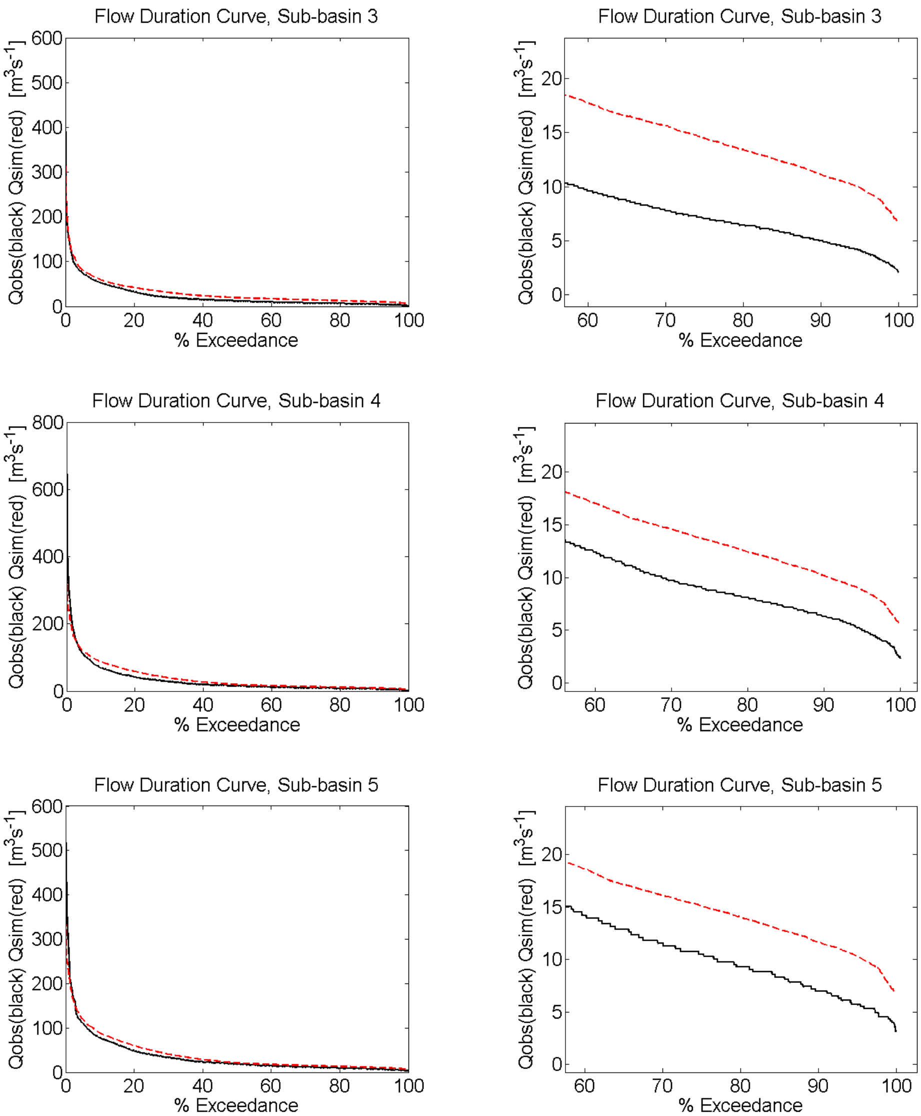


Figure 39 Validation Flow Duration Curves for sub-basins 3-5. The observed flow is represented with a solid black line while the simulated flow is represented with a dashed red line.

11. Appendix 4, Matlab Code

Matlab code example, calibration of sub-basin 4

```
clear all
format compact

%%
infosimf = load('input_files\VAZAO.TXT');
inforain = load('input_files\rainfall_1990_2010.txt');
infoobsf = load('input_files\QOBS.TXT');

columnsim  = 5;    %columns: timestep, sub1 sub2 sub3 sub4 sub5
columnrain = 5;    %columns: date sub1 sub2 sub3 sub4 sub5
columnobs  = 7;    %columns: day month year sub1 sub2 sub3 sub4 sub5

timestepstart = 975;
timestepstop  = 4383;

%% sorting out missing data, creating a data matrix where simulated data
% points correspond only with known obs data.
Qsim = infosimf(timestepstart:timestepstop,columnsim);
Qobs = infoobsf(timestepstart:timestepstop,columnobs);
Q = [Qobs Qsim];
L = length(Q(:,1));
k=0;
for g = 1:L
   if Q(g,1) >= 0
      k = k+1;
      FRED(k,1) = Q(g,1);
      FRED(k,2) = Q(g,2);
   end
end
L = length(FRED(:,1));
M = length(FRED(:,2));
qobs = FRED(:,1);          %obs data excluding missing data points
qsim = FRED(:,2);          %sim data corresponding to measured obs data

%% plots
%scatter plot Qsim vs Qobs
figure(1)
astart=0;
cend=35;
bpointsbetween=(cend-astart)/(length(FRED)-1);
```

```
scatter(qobs,qsim,4,'filled')
axis([astart cend astart cend])
grid ON
hold on
fit=polyfit(qobs,qsim,3);        %fitting a line with 3 degrees of freedom
tplot = astart:bpointsbetween:cend;
mplot = polyval(fit,tplot);
plot(tplot,mplot,'-.r', 'LineWidth', 3)
hold on
fit=polyfit(qobs,qsim,1);         %fitting a line with 1 degree of freedom
tplot = astart:bpointsbetween:cend;
mplot = polyval(fit,tplot);
plot(tplot,mplot,'-.m', 'LineWidth', 3)
set(gca,'FontSize', 20)
hold on
x=astart:bpointsbetween:cend;
y=astart:bpointsbetween:cend;
plot(x,y,'k', 'LineWidth', 3)
xlabel('Qobs')
ylabel('Qsim')
title('Flow Simulated vs. Observed, Sub-basin 4')
figure
aqobs = sort(qobs);
k = length(aqobs);
stat=[0];
for i=1:k;
   stat(i) =(1-( i/(k+1)))*100;
end
stat = stat';
aqsim = sort(qsim);
k = length(aqsim);
stats=[0];
for i=1:k;
   stats(i) =(1-( i/(k+1)))*100;
end
stats = stats';
plot(stat, aqobs, 'k', 'LineWidth', 2)
hold on
plot(stats, aqsim, '--r', 'LineWidth', 2)
set(gca,'FontSize', 22)
xlabel('% Exceedance')
ylabel('Qobs (black)   Qsim (red)  [m^3s^-^1]')
title('Flow Duration Curve, Sub-basin 4')

%% Efficiency Criteria, RVE is in percent, RMSE in m3/s
sstot = sum((qobs - mean(qobs)).^2);
```

```
ssres = sum((qobs - qsim).^2);
NS = 1 - (ssres / sstot);
RVE = (sum((qsim - qobs).^1)/sum(qobs))*100;
RMSE = sqrt(ssres/length(qobs));

NS
RVE
RMSE

%% p5 Q95obs
p=5;
[nr,nc] = size(qobs);
z = sort(qobs); % ascending, by columns
zmin = z(:,1);
zmax = z(:,nc);
index = 100*cumsum(ones(nr,1))/nr;
q95obs =  interp1(index,z,p)
% p   Q95sim
p=5;
[nr,nc] = size(qsim);
z = sort(qsim); % ascending, by columns
zmin = z(:,1);
zmax = z(:,nc);
index = 100*cumsum(ones(nr,1))/nr;
q95sim =  interp1(index,z,p)

%% plot of hydro/hyetographs

basinavg = inforain(:,columnrain);
outlet   = infosimf(:,columnsim);

xmin = 0;                % xaxis starts at point zero while yaxis starts at cell 1 in data vector
xmax = xmin+365*17;              % make sure this number is 1 less than total number of timesteps you want
ymin = xmin+1;
ymax = xmax+1;
datenumberstart = datenum(1989,12,31) + ymin; % the +ymin starts 19740101 plus the number of steps to the start data in the input vector
datenumberend   = datenum(1989,12,31) + ymax;
xaxis          = (datenumberstart:datenumberend);

figure
[AX,H1,H2] = plotyy(xaxis, basinavg(ymin:ymax), xaxis, outlet(ymin:ymax), 'bar', 'plot');
set(AX(1),'YDir','reverse')
set(get(AX(1),'Ylabel'),'String','Precipitation [mm d^-^1]','FontSize',22)
set(AX(1),'YLim',[0 270])
```

```
set(AX(1),'YTick',(0:30:150))
set(AX(1),'box','off')
%hold(AX(1), 'on')
set(H1, 'facecolor','b')
set(get(AX(2),'Ylabel'),'String','Discharge [m^3 s^-^1]','FontSize',22)
set(AX(2),'YLim',[0 1500])
set(AX(2),'YTick',(0:100:900))
hold(AX(2), 'on')
set(H2, 'color','r','linestyle','-', 'LineWidth', 2)                    % to set the color to black, change
the 'r' to 'k'
%hold on
axes(AX(2))
plot(xaxis,infoobsf(1:(1+ymax-1),columnobs), '--k', 'LineWidth',1)  %plot obs flow
title('Hyetograph/Hydrograph, Sub-basin 4', 'FontSize',22)
tick_locations = datenum(1990,1:12:((datenumberend-datenumberstart)),1);
set(AX,'XTick',tick_locations, 'FontSize',22)
datetick(AX(1),'x','mmmYY','keepticks',      'keeplimits')      %datetick('x','yy',      'keepticks',
'keeplimits')
datetick(AX(2),'x','mmmYY','keepticks',      'keeplimits')      %datetick('x','yy',      'keepticks',
'keeplimits')
```

12. Appendix 5 Model formulas

The following formulas are according to Collischonn et al. (2007).

Soil water balance for HRU of each cell

Equation 1:

$$W_{i,j}^{k} = W_{i,j}^{k-1} + \left(P_i - ET_{i,j} - Dsup_{i,j} - Dint_{i,j} - Dbas_{i,j}\right) \cdot \Delta t$$

Equation 2:

$$Dsup_{i,j} = \Delta t \cdot P_i - \left(Wm_j - W_{i,j}^{k-1}\right) \quad for\ A \leq 0$$

Equation 3:

$$Dsup_{i,j} = \Delta t \cdot P_i - \left(Wm_j - W_{i,j}^{k-1}\right) + Wm_j \cdot y^{b_j+1} \quad for\ y > 0$$

where $y = \left[\left(1 - \frac{W_{i,j}^{k-1}}{Wm_j}\right)^{\frac{1}{b_j+1}} - \frac{\Delta t \cdot P_i}{Wm_j \cdot (b_j+1)}\right]$

Equation 4:

$$Dint_{i,j} = Kint_j \cdot \left(\frac{W_{i,j} - Wz_j}{Wm_j - Wz_j}\right)^{3+\frac{2}{\lambda_j}}$$

Equation 5:

$$Dbas_{i,j} = Kbas_j \cdot \left(\frac{W_{i,j}^{k-1} - Wc_j}{Wm_j - Wc_j}\right)$$

k, i, j	Indexes related to time step, cell and GRU respectively
Δt	Time step
$W_{i,j}^{k}$	Water storage in the soil layer at the end of time step k [mm]
$W_{i,j}^{k-1}$	Water storage in the soil layer at the beginning of time step k [mm]
P_i	Rainfall that reaches the soil [mm Δt^{-1}]]
$ET_{i,j}$	Evapotranspiration form the soil [mm Δt^{-1}]]
$Dsup_{i,j}$	Surface runoff, or quick flow [mm Δt^{-1}]

$Dint_{i,j}$	Subsurface flow [mm Δt^{-1}]
$Dbas_{i,j}$	Flow to the groundwater reservoir [mm Δt^{-1}]
Wm_j	Maximum water storage in the upper soil layer [mm]
b_j	Parameter that represents the statistical distribution of water storage capacity of the soil [-]
$Kint_j$	Parameter which gives the subsurface drainage of the water from the soil layer [mm Δt^{-1}]
Wz_j	The lower limit below which there is no subsurface flow [mm]
λ_j	Soil porosity index [-]
$Kbas_j$	Parameter which gives the percolation rate to groundwater in the case of saturated soil [mm Δt^{-1}]
Wc_j	The lower limit below with there is no flow [mm]

Evapotranspiration from soil, vegetation and canopy to the atmosphere is estimated by the Penman-Monteith equation.

Equation 6:

$$e = \left(\frac{\Delta \cdot A + \rho_A \cdot c_p \cdot \frac{D}{r_a}}{\Delta + \gamma \left(1 + \frac{r_s}{r_a}\right)} \right) \frac{1}{\lambda \cdot \rho_w}$$

Evapotranspiration from vegetated soil is calculated by the Penman-Monteith equation weighted using a remaining evaporative demand, f_{DE} .

Equation 7:

$$ET_{i,j} = f_{DE} \left(\frac{\Delta \cdot A + \rho_A \cdot c_p \cdot \frac{D}{r_a}}{\Delta + \gamma \left(1 + \frac{r_s}{r_a}\right)} \right) \frac{M}{\lambda \cdot \rho_w}$$

e	Evaporation/Evapotranspiration [mm s^{-1}]
Δ	Gradient of the saturated vapor pressure-temperature function [kPa $°C^{-1}$]

A	Available energy [MJ m^{-2} s^{-1}]
ρ_A	Density of air [kg m^{-3}]
c_p	Specific heat of moist air [MJ kg^{-1} $°C^{-1}$]
D	Vapor pressure deficit [kPa]
r_a	Aerodynamic resistance [s m^{-1}]
γ	Psychrometric constant [kPa $°C^{-1}$]
r_s	Surface resistance of the land cover [s m^{-1}]
λ	Latent heat of vaporization [MJ kg^{-1}]
ρ_w	Specific mass of water [kg m^{-3}]
$ET_{i,j}$	Evapotranspiration weighted by the remaining evaporative demand [mm s^{-1}]
f_{DE}	Fraction of evaporative demand [-]
M	A constant for unit conversion between m s^{-1} and mm Δt^{-1}

f_{DE} is calculated as follows:

Equation 8:

$$S_{i,j}^{k+1/2} = S_{i,j}^{k} + PC_i \qquad \text{where } S_{i,j}^{k+1/2} \leq S\,max_j$$

Equation 9:

$$S\,max_j = 0.2\,LAI_{j,m}$$

Equation 10:

$$P_i = PC_i - S_{i,j}^{k+1/2} - S_{i,j}^{k}$$

Equation 11:

$$S_{i,j}^{k+1} = S_{i,j}^{k+1/2} - EI_{i,j} \qquad \text{where } EI_{i,j} = min\left(EIP_{i,j};\, S_{i,j}^{k+1/2}\right)$$

After interception evaporation at the rate of $EI_{i,j}$, the evaporation demand, f_{DE}, is calculated:

Equation 12:

$$f_{DE} = \frac{\left(\mathrm{EIP}_{i,j} - EI_{i,j}\right)}{\mathrm{EIP}_{i,j}}$$

$S_{i,j}^{k+1/2}$	Interception storage in the middle of the time step [mm]
$S_{i,j}^{k}$	Interception storage at the beginning of the time step [mm]
PC_i	Precipitation over the vegetation canopy [mm]
$S\,max_j$	Maximum interception storage capacity for GRU j [mm]
$LAI_{j,m}$	Leif area index
P_i	Throughfall, precipitation that reaches the soil surface [mm]
$EI_{i,j}$	Evaporation from the interception storage [mm]
$EIP_{i,j}$	Potential evaporation from the interception storage [mm]

It is assumed that soil conditions do not restrict evapotranspiration when

Equation 13:

$W_L = \frac{Wm}{2}$.

Between the wilting point and this threshold the surface resistance increases as below.

Equation 14:

$$r_s = r_{j,m} \cdot \frac{W_L - W_{PM}}{W_{i,j} - W_{PM}}$$

W_L	Water storage limit [mm]
W_m	Maximum water storage in the upper soil layer [mm]
W_{PM}	Wilting point [mm]
r_s	Surface resistance of the land cover [s m^{-1}]
$r_{j,m}$	Vegetation-dependent minimum surface resistance in conditions not affected by soil moisture [s m^{-1}]

Outflow from each reservoir is calculated as follows:

Equation 15:

$$Qsup_i = \frac{1}{TKS_i} \cdot Vsup_i^k$$

Equation 16:

$$Qint_i = \frac{1}{TKI_i} \cdot Vint_i^k$$

Equation 17:

$$Qbas_i = \frac{1}{TKB_i} \cdot Vbas_i^k$$

Equation 18:

$$Tind_i = 3600 \cdot \left(0.868 \cdot \frac{L_i^3}{\Delta H_i}\right)^{0.385}$$

Equation 19:

$$TKS_i = Cs \cdot Tind_i$$

Equation 20:

$$TKI_i = Ci \cdot Tind_i$$

$Qsup_i$	Outflow of the surface reservoir of cell i [$m^3\ s^{-1}$]
$Qint_i$	Outflow of the subsurface reservoir [$m^3\ s^{-1}$]
$Qbas_i$	Outflow of the groundwater reservoir [$m^3\ s^{-1}$]
TKS_i	Response time parameter
TKI_i	Response time parameter
TKB_i	Response time parameter
$Vsup_i^k$	Water volume in the surface reservoir [m^3]
$Vint_i^k$	Water volume in the subsurface reservoir [m^3]
$Vbas_i^k$	Water volume in the groundwater reservoir [m^3]
$Tind_i$	Time of concentration obtained by Kirpich formula
L_i	Length of the side of each cell [km]
ΔH_i	Difference in the maximum and minimum DEM altitudes in each cell [m]
Cs	Correction factor for retention time of surface flow [-]
Ci	Correction factor for retention time for subsurface flow [-]