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OBSERVING ZAMBEZI BASIN FROM SPACE

Satellite Rainfall Error Correction and Bias Propagation Analysis for Hydrological Modelling

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Outline

a. The Zambezi Basin

b. Performance evaluation of CMORPH satellite precipitation product in the Zambezi Basin

c. Bias correction schemes for CMORPH rainfall estimates in the basin

d. Hydrologic evaluation of bias corrected CMORPH rainfall estimates at the headwater catchment of the Zambezi River

e. Propagation of CMORPH rainfall errors to REW streamflow simulation mismatch in the Kabompo headwater catchment

f. Recommendations for future work

The Zambezi Basin

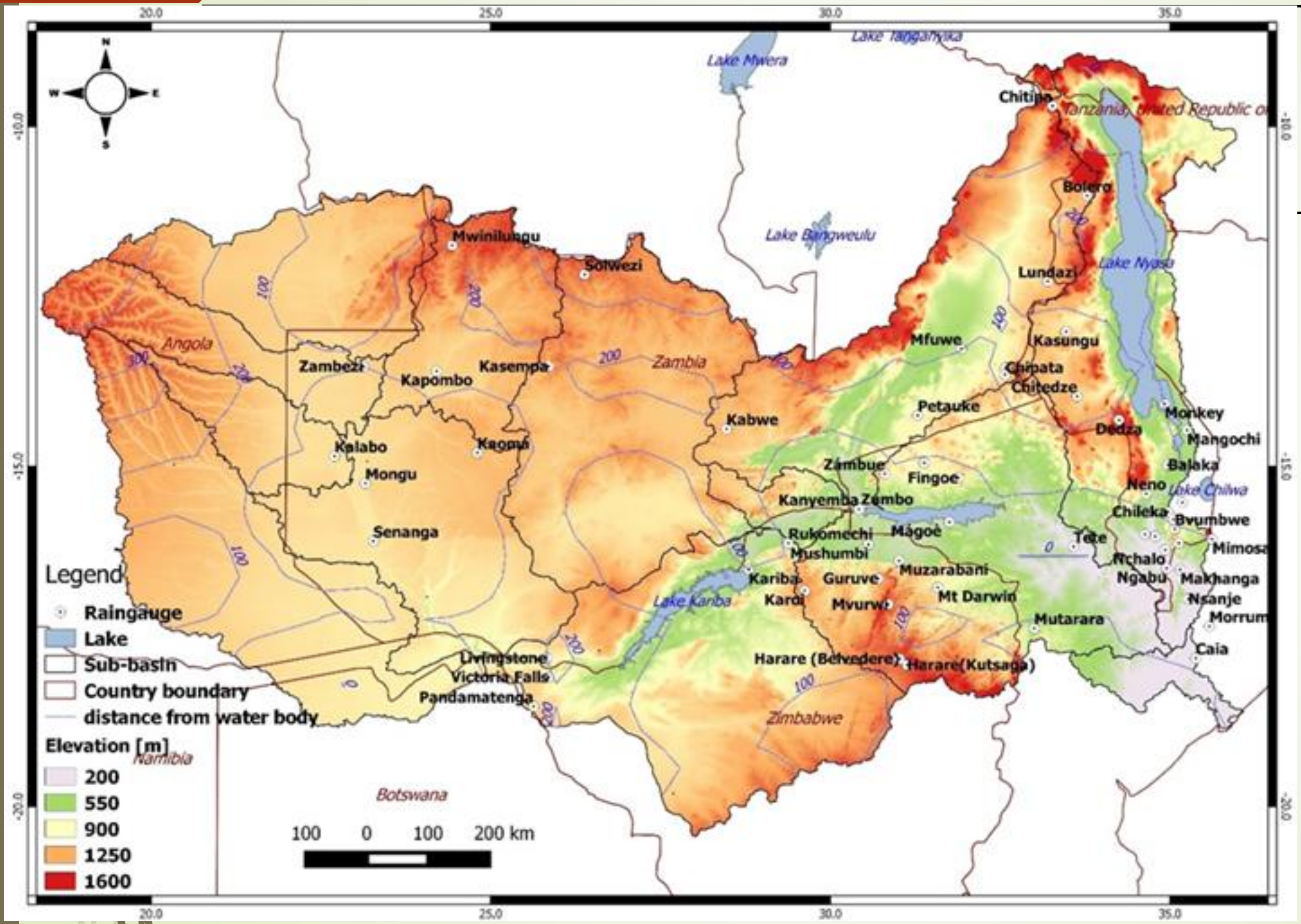
- For the Zambezi River Basin with over 50 million inhabitants:
  - ✓ No clear scientific understanding of all major variables affecting its hydrological cycle.
  - ✓ Hinders quantitative estimates of the water balance.

- Worsened by unavailability of both landsurface and met data

- Data only describes point scale characteristics.

- Remote sensing datasets
  - ✓ allows observation of time invariant catchment properties and
  - ✓ time variant hydrological cycle processes and properties in respective time and space domains
  - ✓ is the premise for application in such data poor catchments

Study area



- Daily rain gauge data from 60 stations.
- The average distance between the rain gauges is 565 km
- Distances to large scale water bodies 5-615 km.
- Daily streamflow data from Watopa gauging station

Objectives

a) To carry out performance evaluation of CMORPH satellite precipitation product in the Zambezi Basin.

b) To evaluate the performance of five bias correction schemes for CMORPH rainfall estimates in the Basin

c) To perform a hydrologic evaluation of bias corrected CMORPH rainfall estimates at the headwater catchment of the Zambezi River

d) To assess propagation of CMORPH rainfall errors to REW streamflow simulation mismatch in the Kabompo headwater catchment.

Satellite based estimates

- Time series (1998-2013) of CMORPH rainfall product (CMORPH version 0.x) at 8 km × 8 km, 30-minute resolution were selected.

- Successful applications of bias corrected CMORPH estimates in African basins
  - Hydrological modelling (Habib et al., 2014)
  - Flood predictions in West Africa (Thiemig *et al.*, 2013).

- CMORPH has been operational since 1998
- Data for the period 1998-2013 was downloaded via the GeoNETCAST's ISOD toolbox through the ILWIS GIS software
- The rainfall is aggregated to 1-day totals.

Performance evaluation of CMORPH satellite precipitation product in the Zambezi Basin

- To evaluate performance of CMORPH satellite precipitation product in the Zambezi Basin

$$\text{Probability of Detection (POD)} = \frac{hits}{hits+miss} \quad [1]$$

$$\text{False Alarm Ratio (FAR)} = \frac{false\ alarm}{hits+false\ alarm} \quad [2]$$

$$\text{Critical Success Index (CSI)} = \frac{hits}{hits+false\ alarm+miss} \quad [3]$$

$$\text{Frequency Bias (FB)} = \frac{hits+false\ alarm}{hits+miss} \quad [4]$$

Bias decomposition

Hit bias (HB),False bias (FB), Missed bias (MB) and Total bias (TB)

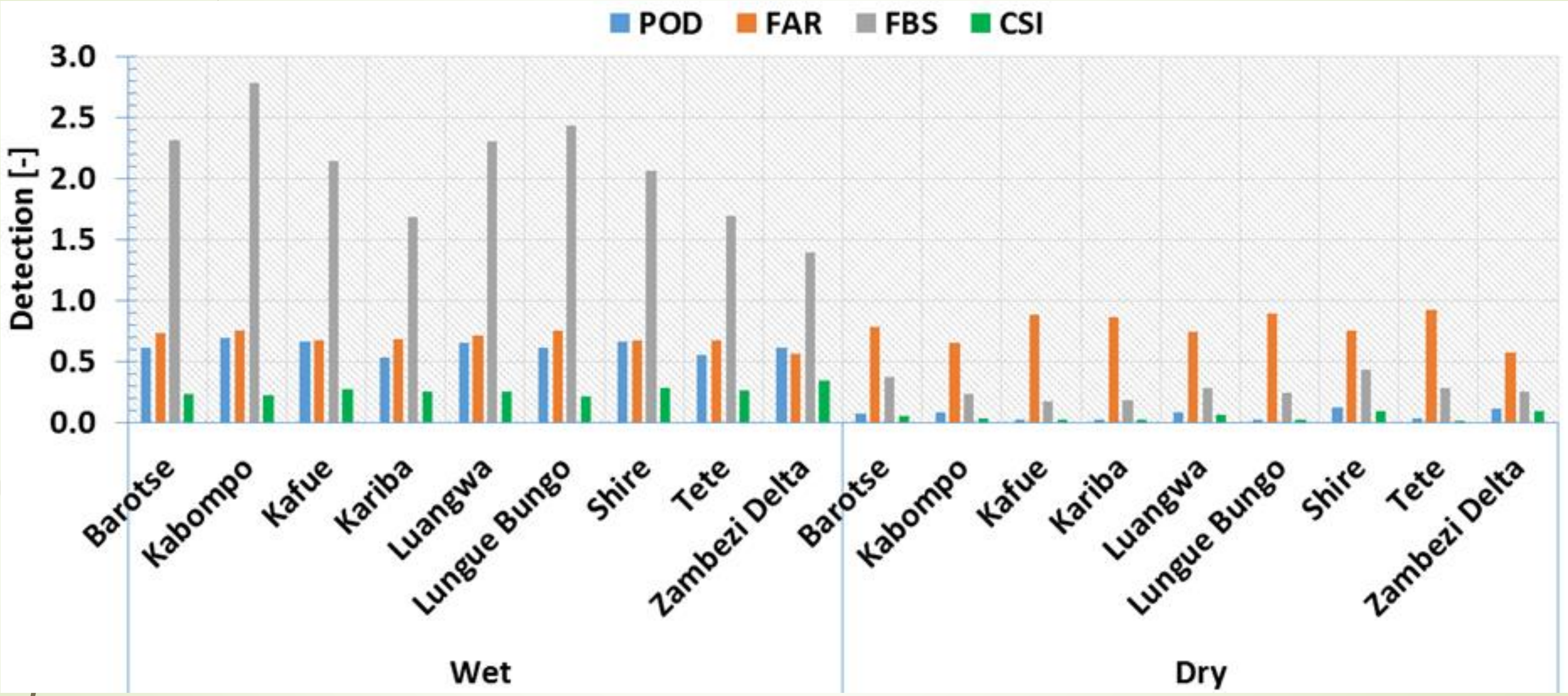
$$HB = \sum_{i=1}^{n} P_{satellite} - P_{rain\ gauge} (when\ P_{satellite} > 0\ and\ P_{rain\ gauge} > 0) \ / \sum_{i=1}^{n} P_{rain\ gauge} \ *100 \qquad [7]$$

$$MB = -\sum_{i=1}^{n} P_{rain\ gauge} (when\ P_{satellite} = 0\ and\ P_{rain\ gauge} > 0) \ / \sum_{i=1}^{n} P_{rain\ gauge} \ *100 \qquad [8]$$

$$FB = \sum_{i=1}^{n} P_{satellite} (when\ P_{rain\ gauge} = 0\ and\ P_{satellite} > 0) / \sum_{i=1}^{n} P_{rain\ gauge} *100 \qquad [9]$$

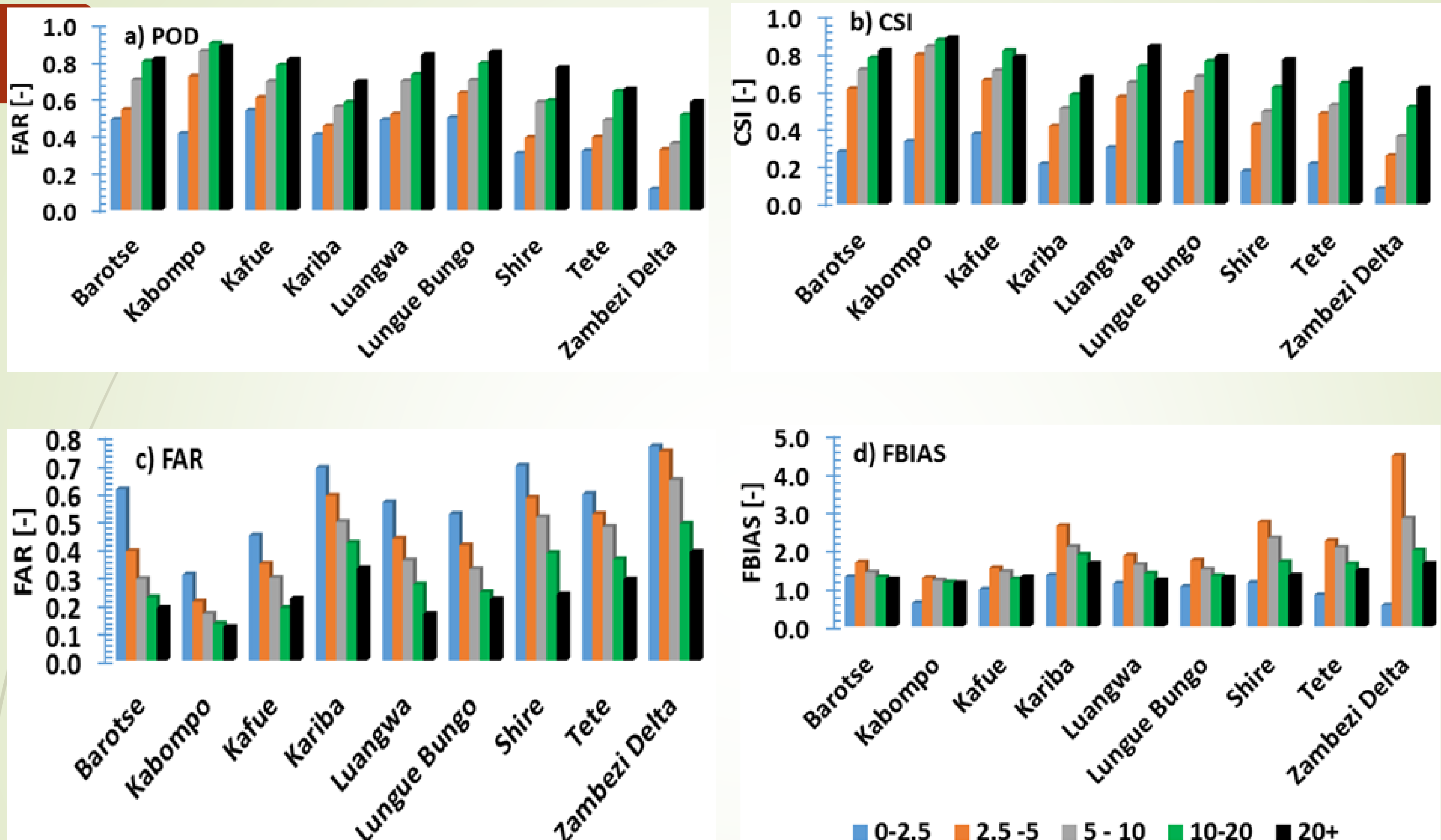
$$TB = Hit\ bias + Missed\ rainfall\ bias + False\ rainfal\ bias \qquad [10]$$

Seasonal influences for rain detection



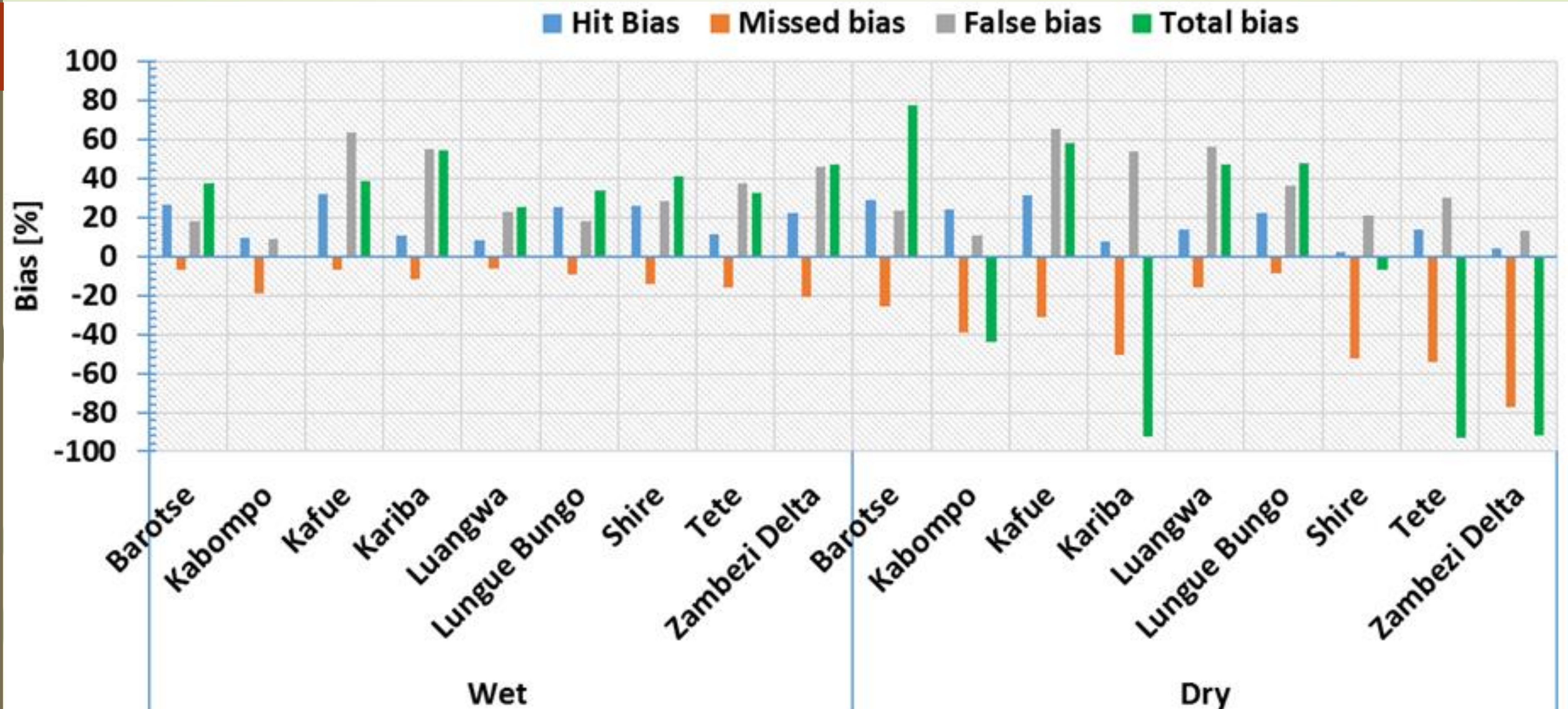
- CMORPH detects > 60 % of the rainfall occurrences in the wet season correctly
- but only detects 12 % of the occurrences for the dry season across the sub-basins.

Rainfall detection for Rainfall rates



- About 70 % of the rainfall rates higher than 20 mm/day detected by CMORPH in all the sub-basins except for the Zambezi Delta.
- < 37 % rainfall rate estimates are detected for 0-2.5 mm/day rate.
- There is improved FBS for very light rainfall (< 2.5 mm/day).

Seasonal influence for sources of SREs errors



- From wet season to dry season, hit bias decreases and the magnitude of False and Missed bias increases.
- There is significant underestimation for the dry season as shown by negative Total bias percentages for Kariba, Tete and Zambezi Delta which goes as low as -90 %.

Key points on satellite rainfall evaluation

- Probability of rainfall detection at daily/weekly time base satisfactory.
- The wrong detection of rainfall occurrences (> 50 %) is a concern to the direct application of CMORPH estimates.
- Accurate detection and estimation of precipitation during the dry season remains a challenge, a finding obtained in other studies in Africa.
- CMORPH requires further development to make CMORPH estimates more meaningful for operational use.
- Correction is also advocated for heavy rainfall events (> 20 mm /day) where CMORPH detection is found to be weak, which may cause deterioration of hydrological process simulation and flood forecasting.
- High False bias means the sensor type and technique of CMORPH retrieval algorithm may play a key role on the magnitude of False bias
- For rainfall rates or rainfall seasons, there is relative better performance for detection than for estimation

Bias correction schemes for CMORPH rainfall estimates in the basin

Bias correction of CMORPH rainfall

Specific objectives were to:

(1) evaluate the effectiveness of linear/non-linear and time-space variant/invariant bias correction schemes and

(2) assess the performance of bias correction schemes to represent different rainfall magnitudes for climate seasonality.

Bias correction methods

Spatio-temporal bias correction (STB)

$$S_{STB} = S \frac{\sum_{t=d}^{t=d-l} S(i,t)}{\sum_{t=d}^{t=d-l} G(i,t)}$$

Elevation Zone bias correction (EZ)

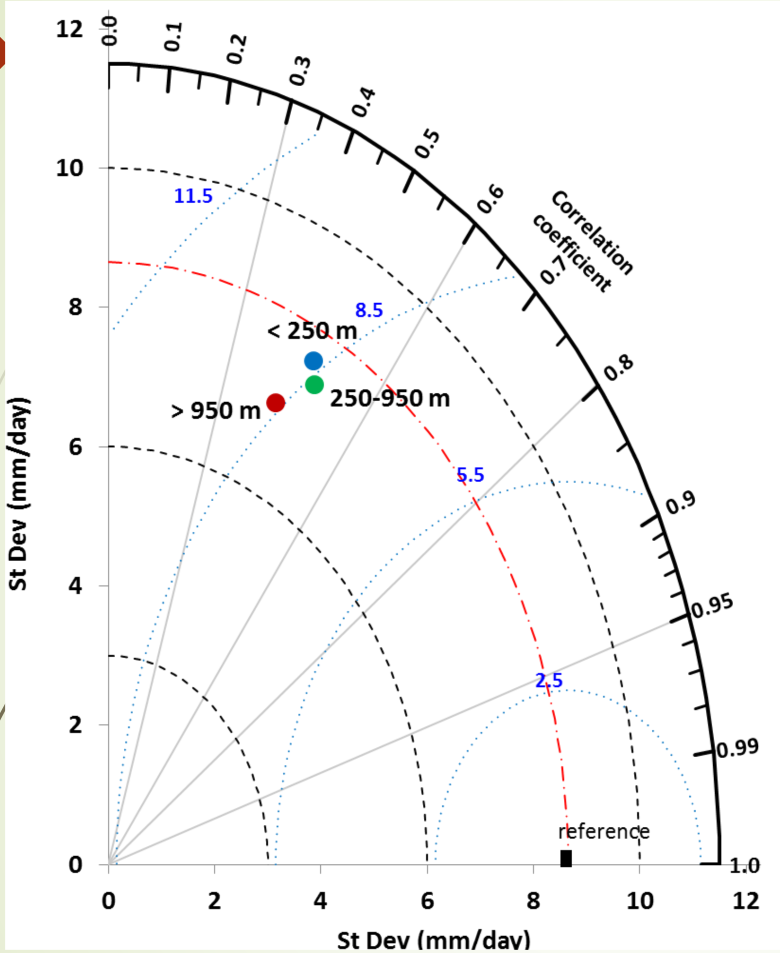
$$S_{EZ} = S \frac{\sum_{t=d}^{t=d-l} \sum_{i=1}^{i=n} S(i,t)}{\sum_{t=d}^{t=d-l} \sum_{i=1}^{i=n} G(i,t)}$$

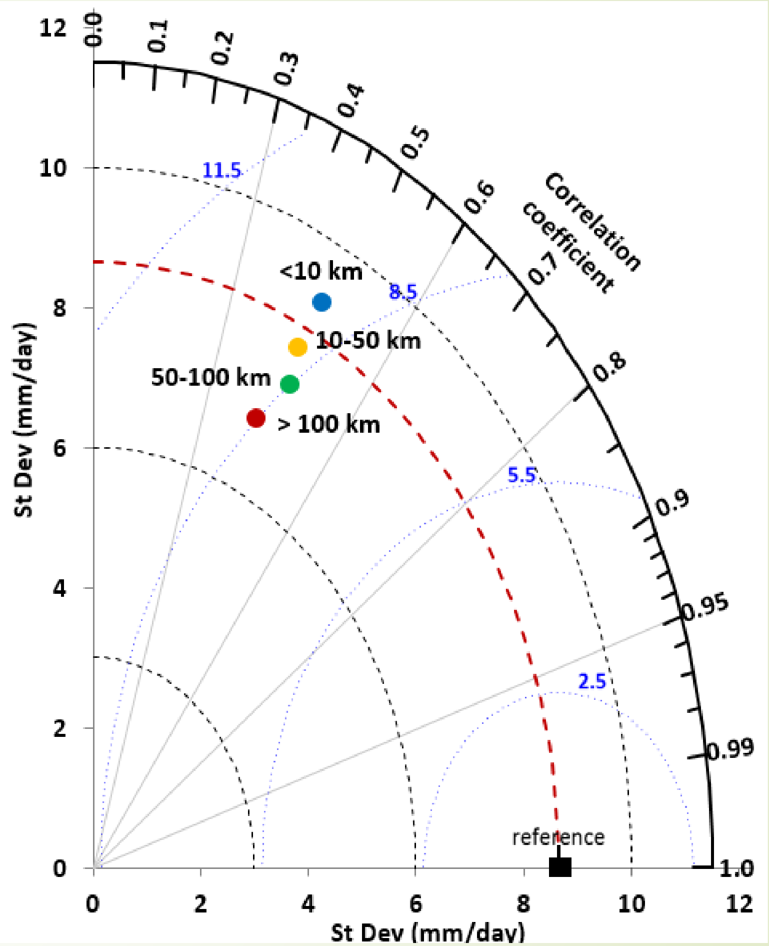
Where:
G = daily gauge based rainfall observations
i = gauge location
d = selected day
t = julian day number
l = length of a time window for bias calculation

Bias correction factor

- Bias correction factor is calculated for a certain day
  - only when a minimum of five rainy days were recorded
  - within the preceding 7-day window
  - with a minimum rainfall accumulation depth of 5 mm
  - otherwise no bias is estimated (i.e. a value of 1 applies as bias correction factor).
- This approach implies that bias factors change value for each station for each 7-day period.
- A time window of specified length moves forward in the time domain.

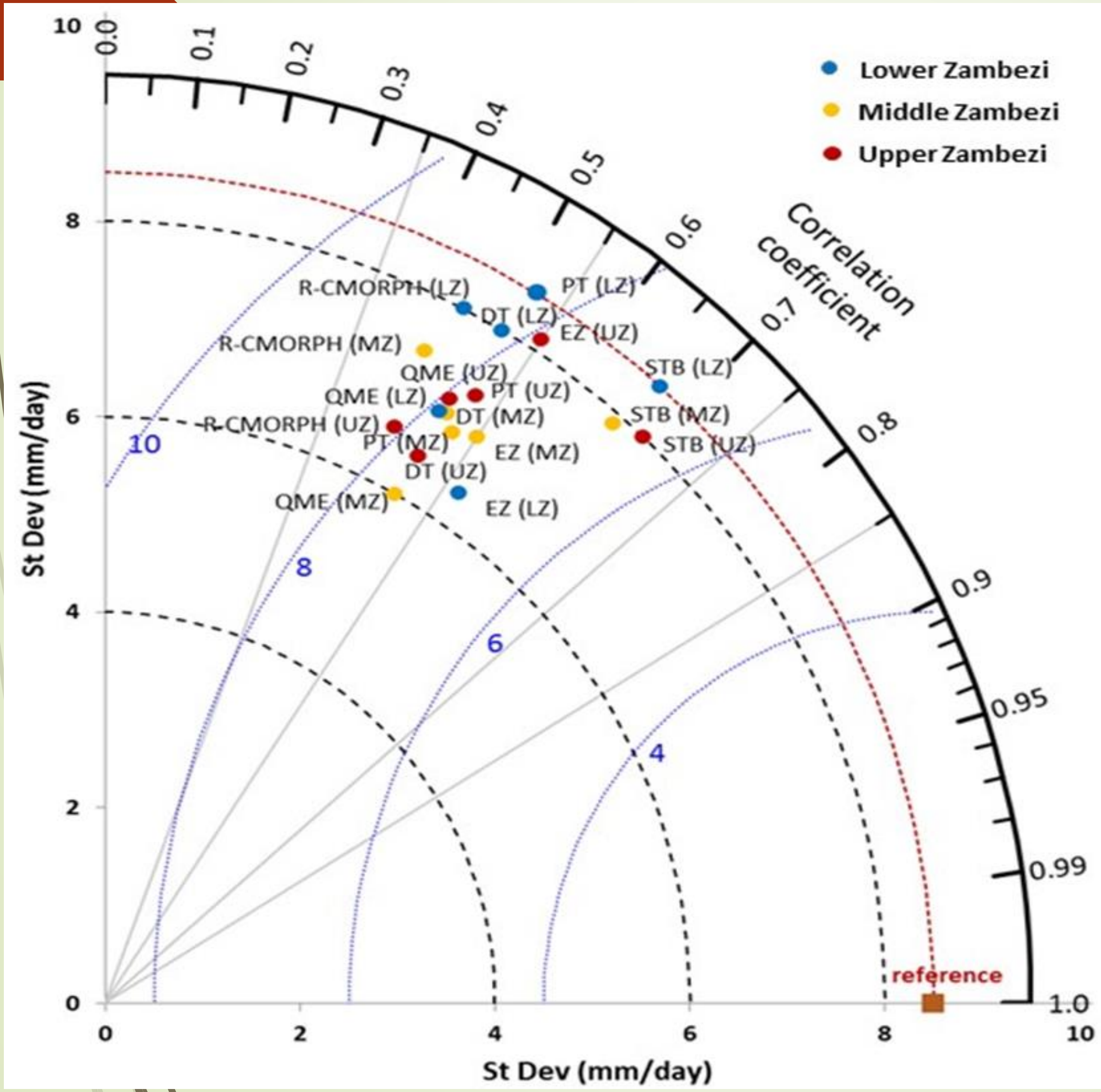
Topographic influences for CMORPH and gauge rainfall





- The CMORPH rainfall estimates in the Zambezi Basin are not significantly affected by elevation.
- Performance of CMORPH is not distinctly related to distance of a large water bodies in the Zambezi Basin.

Bias correction of CMORPH and gauge rainfall



- Removing bias (%) in CMORPH is by achieved by STB and EZ.
- Average bias correction of 0.97 % and 3.6 % in the whole basin respectively

Bias correction (%) for respective rainfall rate classes

- More effectiveness in reducing the percentage bias for light rainfall and moderate rainfall than very high rainfall

Key points on bias correction

- ❑ The temporal aspect of SRE bias is more important than the spatial aspect of bias in the Zambezi Basin.

- ❑ The multiplicative bias correction schemes (STB and EZ) outperform the power function and additive correction schemes

- ❑ Single best bias correction for entire Zambezi basin cannot be selected.

- ❑ The issue of the time window may not be suitable for Zambezi basin
  - ✓ only when a minimum of five rainy days were recorded
  - ✓ within the preceding 7-day window
  - ✓ with a minimum rainfall accumulation depth of 5 mm

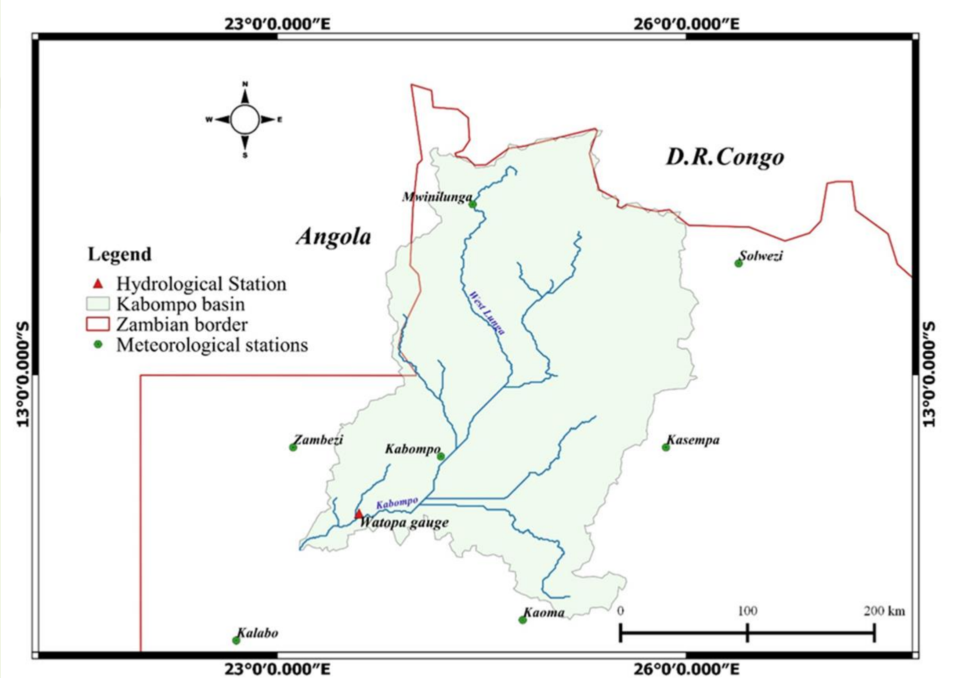
Hydrologic evaluation of bias corrected CMORPH rainfall estimates at the headwater catchment of the Zambezi River

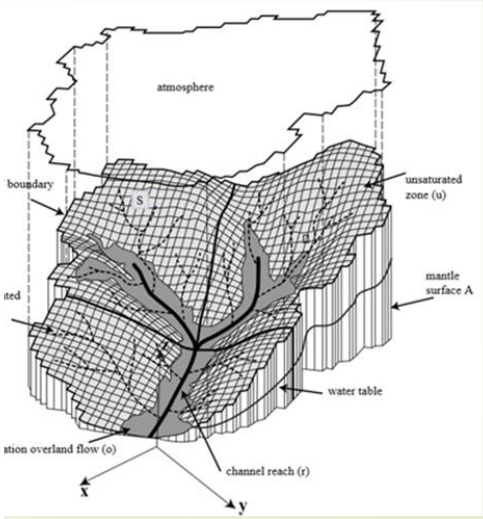
Hydrologic evaluation of bias corrected satellite rainfall

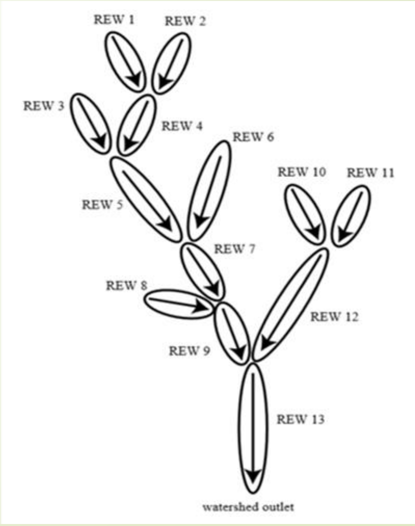
The specific objectives are:

- to calibrate and validate the REW hydrological model by gauge based rainfall and discharge in the Kabompo Basin

- to evaluate how the performance of REW model used for streamflow predictions is affected when bias corrected satellite data is used to drive the model.

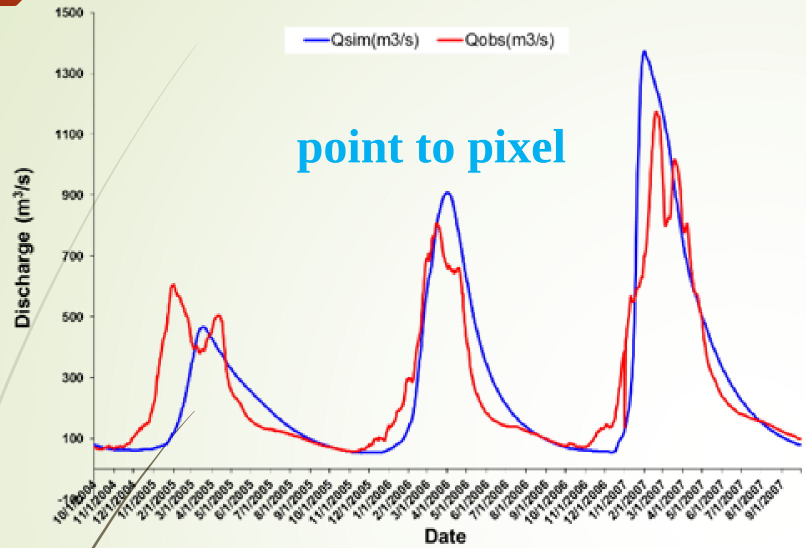


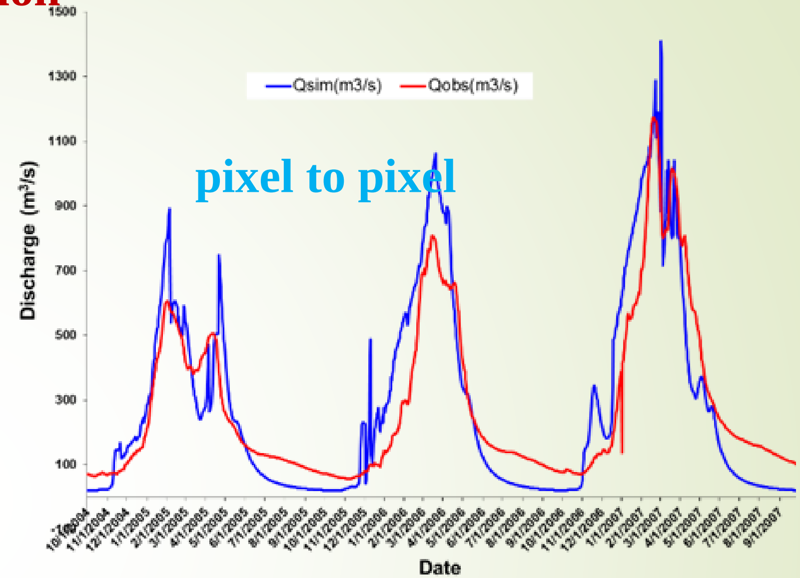




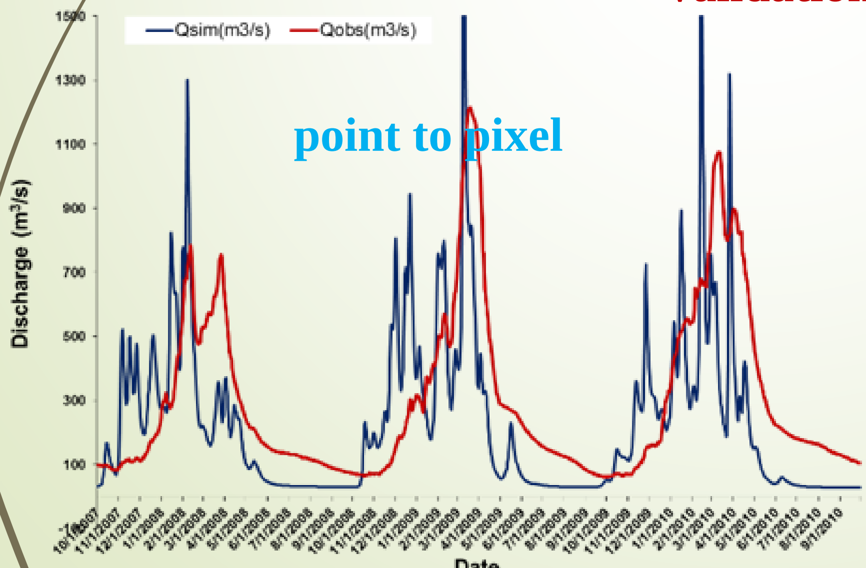
Bias correction for point to pixel and pixel to pixel

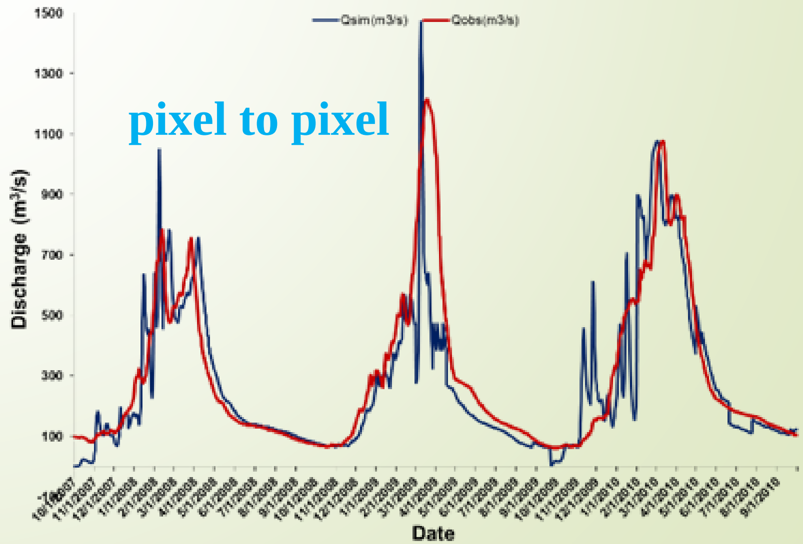
Calibration



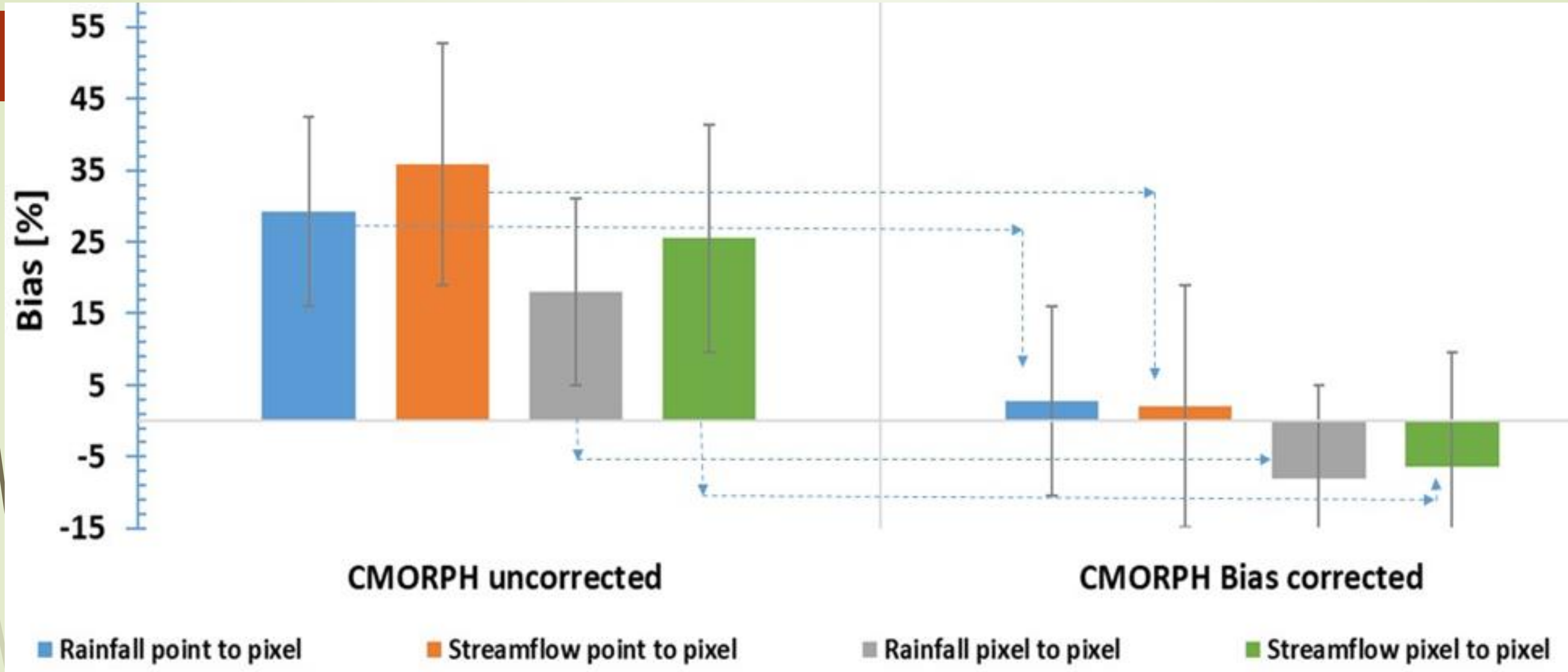


Validation





Error propagation



- Amplified bias in the streamflow simulation using uncorrected CMORPH (41 % increase for the pixel-to-pixel rainfall estimate).
- Substantial reduction in bias (29 %) after bias correction (from rainfall to streamflow) in the pixel-to-pixel rainfall estimate.
- With bias correction, bias amplification was reduced (from −13 % rainfall bias to only −17 % streamflow bias).

Key points on Hydrologic evaluation

- The REW runoff model translates small rainfall errors to larger streamflow errors.
- The magnitudes of such error amplifications became smaller for bias corrected satellite data than those for the uncorrected satellite rainfall
- REW calibration procedure compensated for rainfall input errors by changing the optimum values of model parameters as rainfall input changes.
- CMORPH satellite rainfall has good potential for useful application to hydrological simulation which is a useful merit for regions where networks of raingauge rainfall observations are sparsely distributed.

Propagation of CMORPH rainfall errors to REW streamflow simulation mismatch in the Upper Zambezi Basin

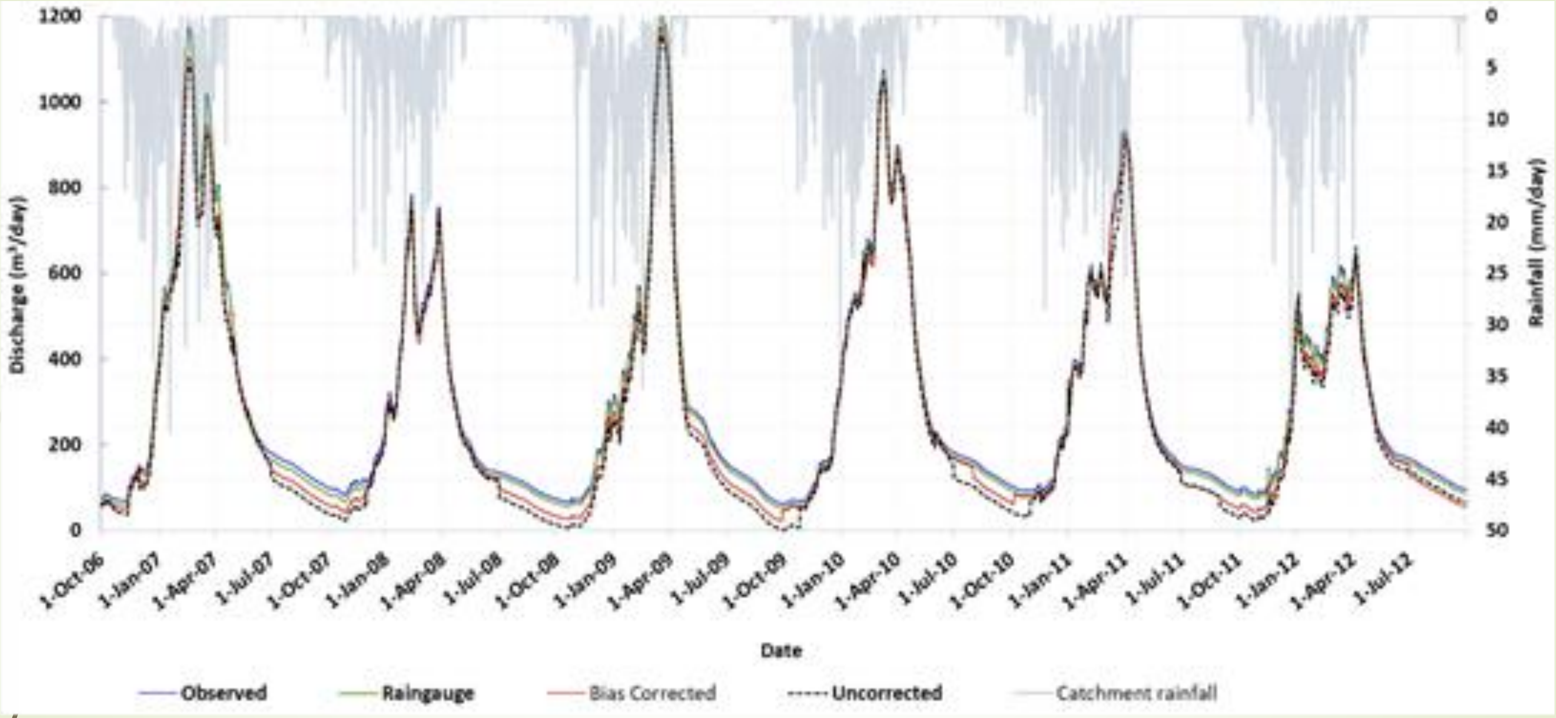
Methodology

- Multi-objective calibration is performed for
  - streamflow modelling
  - hydrograph shape and volume
  - combinations of specific hydrograph characteristics
  - for assessments of water balance composition and closure.

- The Epsilon Dominance Non-dominated Sorting Genetic Algorithm II (ε-NSGAII) algorithm was applied (Yang *et al.*, 2014) to all cases to optimize model parameters of the rainfall-runoff model.

- The main purpose of the genetic based search algorithm is optimisation of parameter values by fitting simulated streamflow hydrograph variables to observed counterparts by multi-objective functions.

Performance of CMORPH rainfall in hydrological modelling



- *Simulated hydrographs for respective rainfall data sources after rerunning ε-NSGAII algorithm for Y-function for the period 2006-2012.*

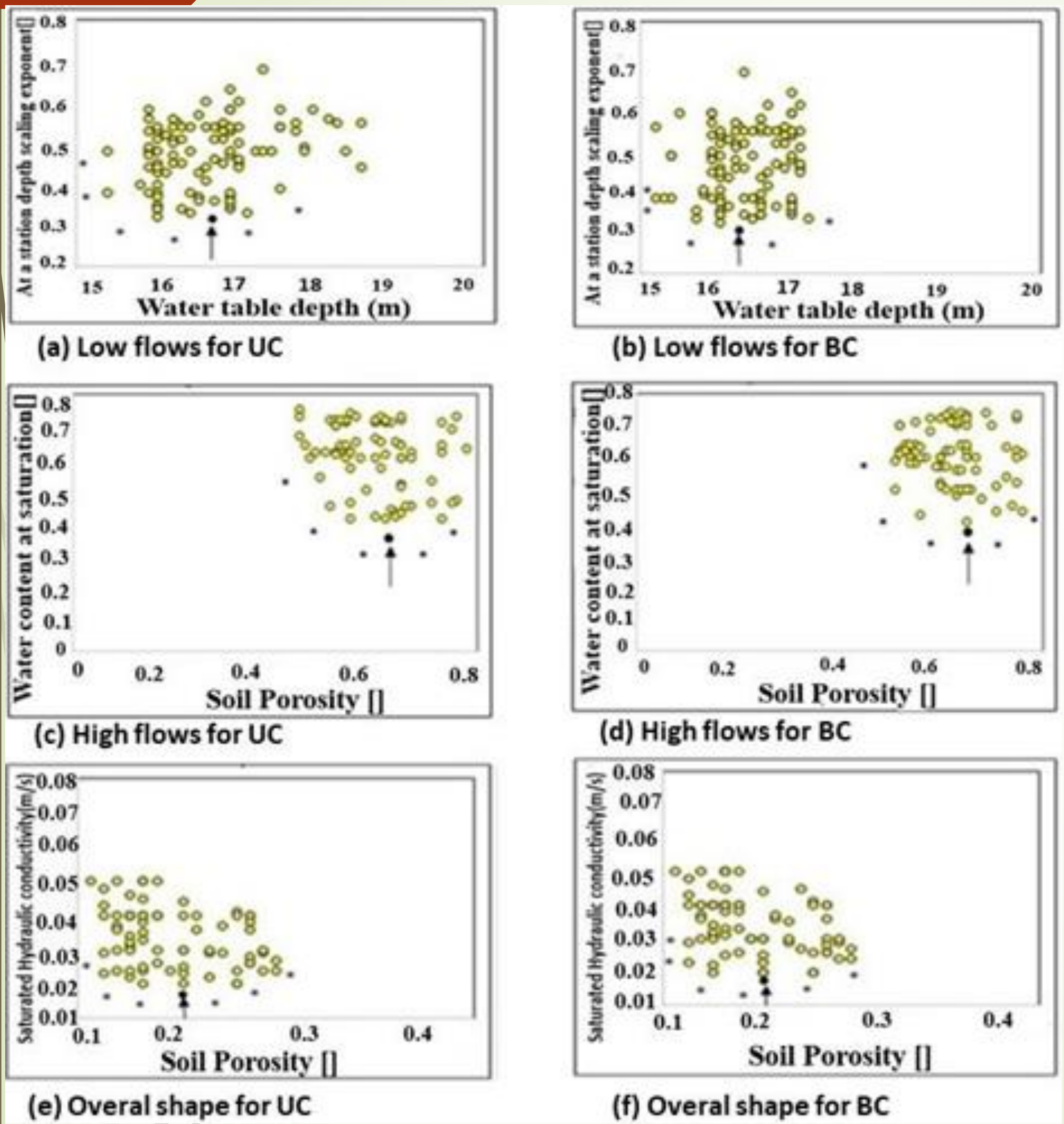
- *The catchment rainfall is also shown on secondary axis.*

Water balance components and parameter optimization

Parameter	Water balance Component (mm) and Objective function	Rain gauge	Bias corrected	Uncorrected
Soil Porosity		0.50	0.55	**0.54**
Saturated Hydraulic Conductivity [m^3/s]		0.006	**0.0058**	0.0005
Water Content at Saturation []		0.6	**0.55**	0.50
	Rainfall	3621	**3635**	4300
	ET_a	2850	2827	**2866**
	Streamflow	718.8	**710.8**	750
	Residual/rain (%)	1.44	**2.67**	15.91
	Y	0.76	**0.72**	0.55

Pareto distributions for sensitive parameters:

water content at saturation and soil porosity



An improved performance for bias corrected CMORPH rainfall input compared to uncorrected CMORPH as well as various degree of performance for low flows, high flows and overall shape.

The in-situ rainfall input has much better performance.

Key points on error propagation

- For uncorrected CMORPH, use of multiple objective functions resulted in substantial augmentation of rainfall error to cause streamflow simulation mismatch whereas for bias corrected CMORPH, such resulted in attenuation of error.

- Analysis for water balance composition has great potential to improve application of satellite precipitation products in water management and decision making in the Zambezi basin.

- This study advises optimization of model parameters for each respective rainfall input data source so to identify outcomes and effects of respective rainfall data sources on the simulated water balance composition and closure.

Recommendations

- Regulators and river basin managers to develop extensive experimental observational networks that are capable of monitoring the variability in meteorological and hydrological processes controlling the runoff generation processes relevant for water resources management

- Find a single and robust best bias correction scheme for the entire Zambezi basin

- Further optimization of model parameters for each respective rainfall input data source so to identify outcomes and effects of respective rainfall data sources on the simulated water balance.