Client:
The World Bank

NORTH GHANA SUSTAINABLE DEVELOPMENT, DISASTER PREVENTION AND WATER RESOURCES MANAGEMENT

FLOOD HAZARD ASSESSMENT WHITE VOLTA

Final Report– Deliverable 10

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HKV CONSULTANTS

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1 Introduction

1.1 Background

Ghana is one of the countries in West Africa most affected by multiple hazards in Sub-Saharan Africa, particularly droughts and floods occur frequently. Ghana is a focus country for disaster risk reduction activities of GFDRR (Global Facility for Disaster Reduction and Recovery). Since 2007, floods along the White Volta River have been a recurrent annual phenomenon due to heavy rainfall in the basin and (partly) coinciding with spilling from upstream Bagré reservoir in Burkina Faso. The floods of the last four years rank 1st , 4th, 7th and 8th highest in the series of Nawuni station at the White Volta since 1936. These floods affect development and livelihood in the three northerly regions of Ghana but on the other hand bring fertile sediments to the floodplains.

The government of Ghana is committed to provide long-term solutions in the three regions of the North and in particular to initiate a comprehensive development plan to support economic growth opportunities in that region. As part of that effort a project was initiated targeting water and particularly flood management, following re-occurring floods in the three Northern provinces. Its main component is a study providing technical assistance to the Government of Ghana for coping with this problem.

The study will investigate the scale and severity of flood hazards, the exposures of various assets and communities and assess the effectiveness of structural and non-structural measures to reduce or eliminate flood damages in the future. Results of this analysis will support the National Strategy for Disaster Prevention and development plans for the growth and development of the North, including development partner supported projects such as the Northern Growth Project financed by IFAD and the African Development Bank.

With this as background, HKV CONSULTANTS was appointed by the World Bank to perform a Flood Hazard Assessment study for the White Volta River.

1.2 Scope of work

The scope of work for this study includes the following:

- Flood hazard modelling for the White Volta from the Ghana-Burkina Faso border to Lake Volta, including vulnerable reaches of the main tributaries;
- Flood risk assessment by combining the flood hazard with the vulnerability of the communities and land use in the flood prone areas;
- Assessment of the effectiveness of structural and non-structural flood management/protection measures;
- Flood forecasting and input for a Flood Early Warning System (FEWS);
- Provision of basic input to the development of the Emergency Preparedness Plan, and
- Training of staff of the various stakeholders in the development, application and operation of the modelling tools to be prepared and use of the modelling results through on-the-job training of scientific staff and through a workshop for users of FEWS output.

The study will produce the following deliverables:

1. An inception report, spelling out methodology and roadmap for project implementation.
2. A GIS database including the applied topographical (DEM/DTM), land use and developed inundation extent, depth and duration maps, flood hazard and flood risk maps.
3. A hydrological database including all raw and validated meteorological and hydrological data used in the project.
4. A combined hydrologic and hydraulic model of the White Volta and its tributaries for flood flow simulation including 3 licenses for model use and adaptation.
5. A FEWS of the White Volta basin for forecasting of flood levels, including 3 licenses for system use and adaptation and a web-page for dissemination of the forecasting results.
6. A mid-term report on the development, calibration and validation of the hydrological and hydraulic models.
7. Inundation extent and duration maps of the 2007 – 2010 flood on the White Volta and its tributaries.
8. Flood hazard and flood risk maps on flood extent and duration maps for floods on the White Volta and its tributaries of selected return periods of 2, 5, 10, 25 and 50 years. Three copies of such plasticized maps covering the district is required of 1:25,000 scale maps for each district assembly and for all stakeholders in the Steering Committee 1: 50,000 scale flood hazard/risk maps.
9. Workshop for FEWS output users.
10. **Final Report, summarizing the Project findings and recommendations with annexes on:**
    a. **Hydraulic model development, calibration and validation;**
    b. **Hydrologic model development, calibration and validation;**
    c. **Development and operation experiences with White Volta FEWS;**
    d. **Genesis of floods on the White Volta;**
    e. **Flood hazard and flood risk mapping;**
    f. **Effectiveness of structural and non-structural flood management/prevention measures;**
    g. **Input for Emergency Preparedness Plan;**
    h. **Workshop contents and participation.**

This final report describes project findings and recommendations with annexes on points a. to h. as described under deliverable 10. The report does not describe the findings of the FEWS-operation (part of e) and the final workshop (part of h) as they are reported separately in the FEWS-Volta evaluation report.

2 Data

2.1 General

The data collection and validation process was extensive. A detailed description is available in the Hydrological database report [HKV, May 2012] and the GIS-database report [HKV, May 2012]. This chapter summarizes the process.

2.2 Meteorological data

Meteorological data was collected from the Ghana Meteorological Institute (GMET). Figure 2-1 shows the stations for which data was provided (left) and stations for which data was available and useful for the focus period 2000-2010.

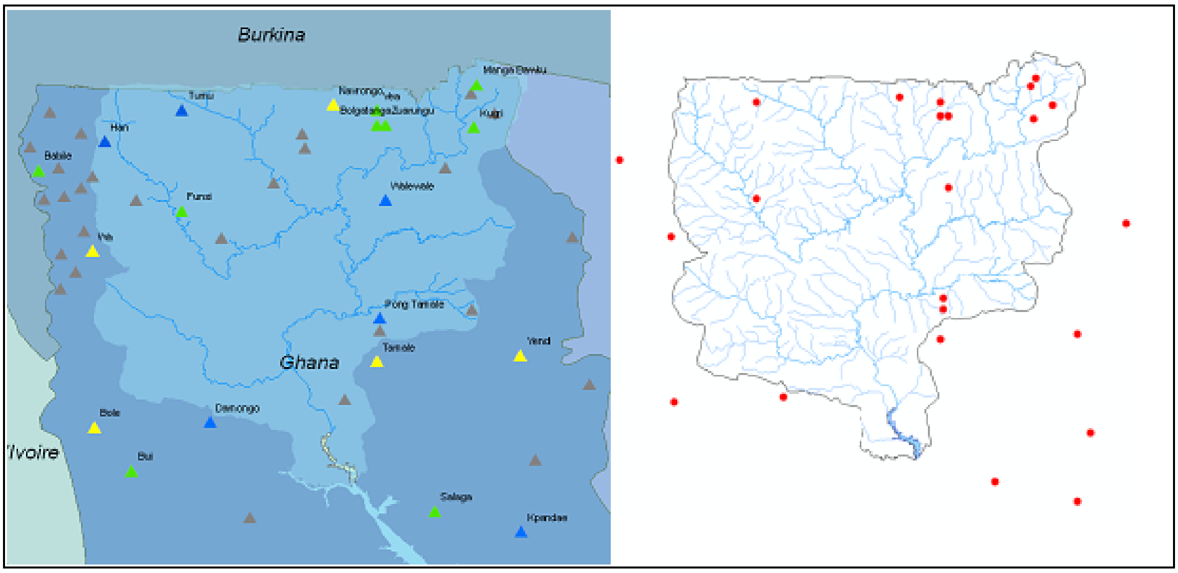


Figure 2-1 Left: Locations of the synoptic (yellow), Agro (blue), CLIMD (green) and rainfall stations (brown). Right: Location of the 23 stations at which daily time series with meteorological data are available for the period 2000 to 2010

Daily precipitation data was analyzed, validated and completed for the period between 2000 to 2010. The stations that were used in this project are summarized in the table below.

Station Name	**LONGITUDE**	**LATITUDE**	**ELEVATION M+NLD**
Binduri	-0,3	10,97	210,3
Bole	-2,48	9,03	299,5
Bolgatanga	-0,85	10,78	213,4
Damongo	-1,82	9,07	190,4
Funsi	-1,98	10,28	-999
Garu	-0,17	10,85	237,7
Kpandae	-0,02	8,43	187
Kugri	-0,28	10,77	228
Manga Bawku	-0,27	11,02	248,9

Navrongo	-1,1	10,9	201,3
Pong Tamale	-0,83	9,67	182,8
Salaga	-0,52	8,55	167,6
Tamale	-0,85	9,42	183,3
Tumu	-1,98	10,87	313
Vea	-0,85	10,87	183,1
Wa	-2,50	10,05	322,70
Walewale	-0,8	10,35	167,6
Yendi	-0,02	9,45	195,2
Zuarungu	-0,8	10,78	213,3
Bimbila	0,07	8,85	219,5
Cherponi	0,28	10,13	173
Savelugu	-0,83	9,6	170
Babile	-2,82	10,52	304,70

Table 2-1 Meteorological station overview in the White Volta basin

For calculation of the evapotranspiration, data on temperature, wind speed, relative humidity and sunshine hours of five synoptic gauging stations operated by GMET was collected, validated and completed. The reference potential evapotranspiration was calculated applying the Penman Monteith formula. GMET also calculates the reference potential evapotranspiration applying an empirical formula, that is not documented however. These figures differ significantly from figures found in literature and calculated by us on basis of the Penman Monteith formula. We therefore decided not to make use of the reference potential evapotranspiration data calculated by GMET and to proceed with the data calculated with the Penman Monteith formula.

2.3 Hydrological data

The Hydrological Service Department (HSD) is responsible for the monitoring and maintenance of the hydrological data in Ghana. Figure 2-2 shows the hydrological gauging stations for which data was available in this study. Buipe was not used at all, Nakong and Nangodi were used to validate and correct water level data from other downstream gauging stations. Table 2-2 summarises the stations assessed in this project.

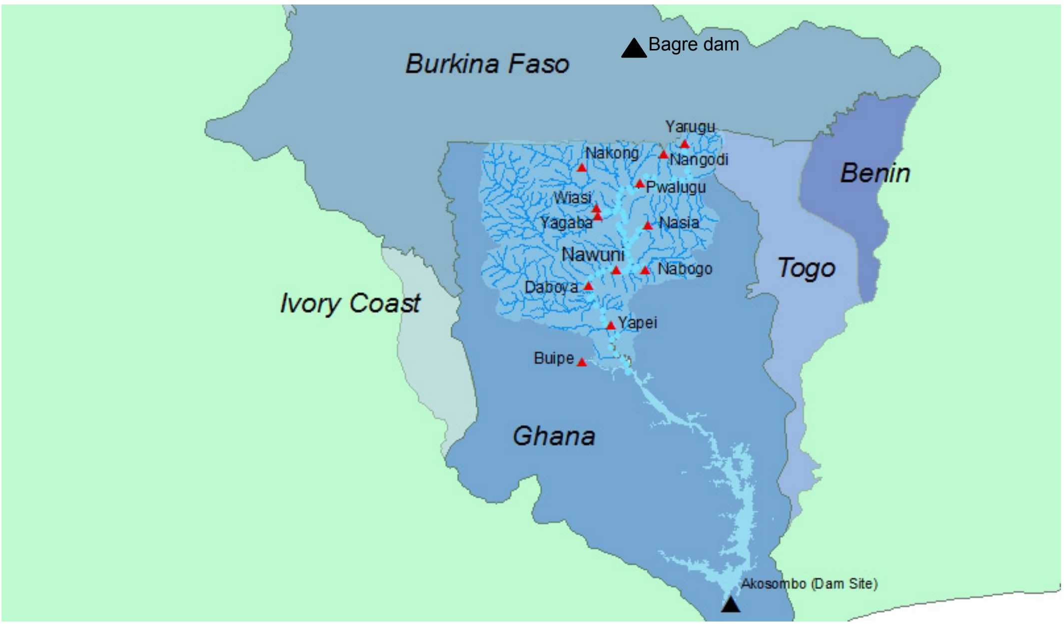


Figure 2-2 14 relevant gauging stations in the project area in the White Volta River basin

Figure 2-3 shows that water levels in 1971 and 2004 up to 2007 are available for most gauging stations during flood periods. However 1971 is only suitable for analysing the effects of bed level changes over the years. It is therefore proposed to use 2004-2007 for calibration and validation of the 1D-hydraulic model. Historical flood maps available in that period can be used to calibrate and validate the 2D-model. As stated above meteorological data is available and reliable for that period as well.

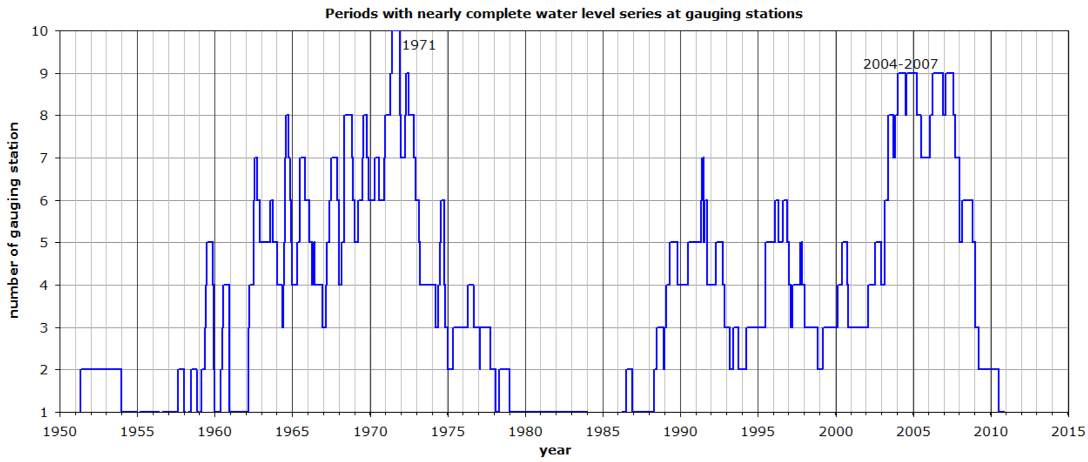


Figure 2-3 Overview of time periods with the number of available water levels at all gauging stations

Water level data is validated and completed for this period.

Rating curves and discharge series received from HSD were not reliable and therefore reconstructed, based on the hydraulic model and validated water levels.

All raw and corrected hydrological and meteorological data is stored in the WIS-Volta database.

					Water level		Discharge	
Station name	**River**	**Lat**	**Long**	**Gauge zero M+NLD**	**start**	**end**	**start**	**end**
Yarugu Old	White Volta	10.98	-0.39	Not available	7-12-62	2-28-99	5-1-58	4-12-73
Yarugu Kobori	White Volta	10.93	-0.38	167.24	1-1-98	12-31-07	7-9-01	6-16-04
Pwalugu	WhiteVolta	10.58	-0.85	125.40	5-1-51	5-31-09	6-25-70	11-18-04
Nawuni	WhiteVolta	9.70	-1.10	96.44	5-8-53	12-31-10	6-26-90	6-26-03
Daboya	WhiteVolta	9.54	-1.38	87.00	4-18-62	1-31-11	1-1-80	12-1-08
Yapei	WhiteVolta	9.14	-1.16	77.42	1-8-64	5-31-08	10-8-65	5-30-96
Nangodi	RedVolta	10.88	-0.61	Not available	7-1-58	10-15-78	8-14-75	9-13-05
Nakong	Sisili	10.75	-1.45	Not available	6-25-65	12-31-08	8-14-75	9-14-05
Wiasi	Sisili	10.33	-1.30	126.26	6-1-62	12-31-07	6-26-70	8-8-05
Yagaba	Kulpawn	10.25	-1.28	124.73	2-20-58	12-31-08	4-4-70	12-9-05
Nasia	Nasia	10.15	-0.77	108.23	5-1-51	5-31-09	6-24-90	10-11-08
Nabogo	Nabogo	9.70	-0.80	101.84	4-1-62	5-31-09	5-1-58	12-9-01
Buipe	BlackVolta	8.77	-1.45	Not available	1-8-64	5-31-09	8-14-75	9-14-05
Akasombo Dam	LakeVolta	6.311	0.067	Not available				
Bagre Dam	WhiteVolta	11.47	-0.561	Not available				

Table 2-2 Hydrological station overview in the White Volta basin

2.4 GIS-data and surveys

The following GIS-data was collected and described in more detail in HKV report GIS-database, May 2012 deliverable 2:

- A Digital Elevation Model (DEM) covering the whole Volta basin was collected and used to develop the hydrological models. This DEM is based on SRTM satellite data.
- A more detailed DEM was developed for the flood prone area that is covered by the hydraulic model. This DEM is based on SPOT satellite data, further improved by a terrestrial survey of the altitudes in the field.
- Land sat images that show the historical flood extent.
- GIS-data from several sources including Land-use maps, catchment areas, administrative information and so on.

A bathymetrical survey of the White Volta and its main tributaries provided us with the cross sections necessary for the hydraulic model (Annex 2, deliverable 2). The gauge zeros of the hydrological gauging stations were re-leveled by terrestrial field measurements (Annex 3, deliverable 2).

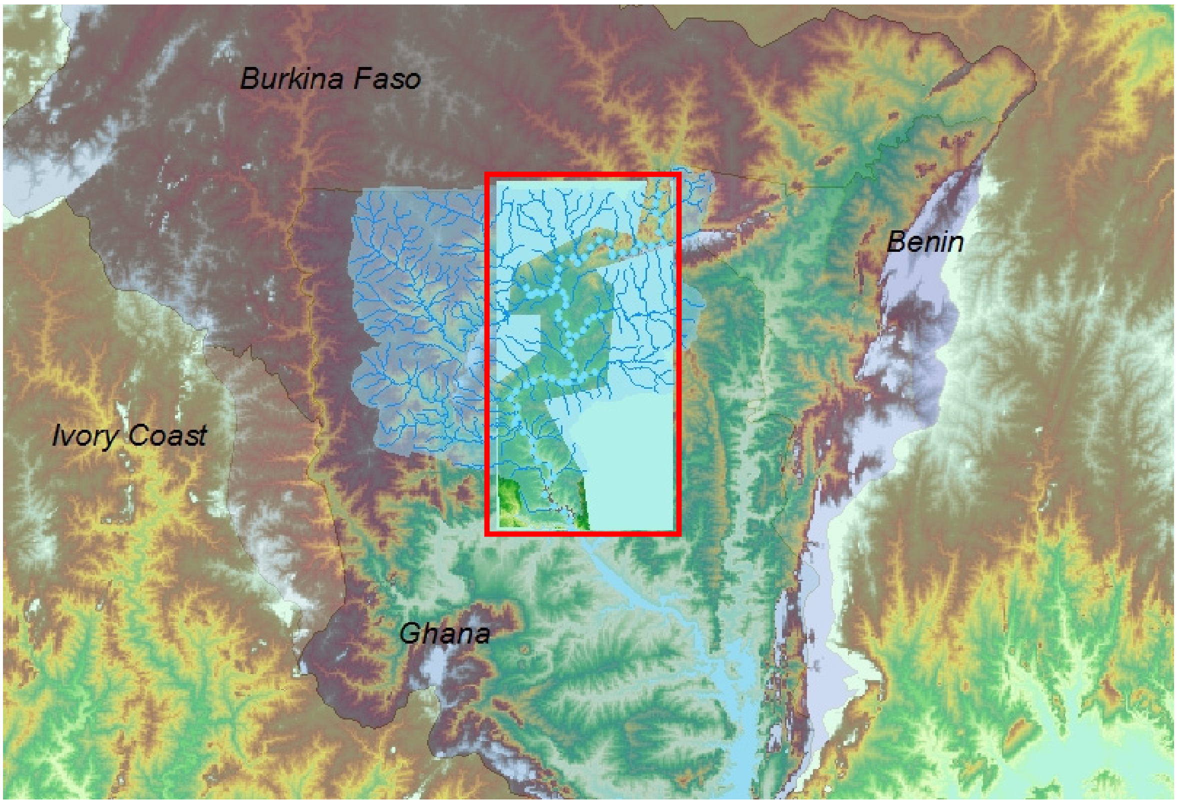


Figure 2-4 The area covered by the SRTM DEM and the SPOT DEM (inside the red rectangle)

3 Models used

3.1 General

The model of White Volta catchment consists of a hydrological (rainfall runoff or RR) component, a one-dimensional hydrodynamic component and a two-dimensional hydrodynamic component (Figure 3-1). The hydrological models of the blue catchments are calibrated on the available discharge data from the hydrological database. The pink and green (representing various small streams that flow directly into White Volta) are un-gauged. The hydrological model parameters of these catchments are based on the calibrated models and the catchment characteristics.

The hydrological models of the tributaries serve as boundary inflow to the 1 dimensional hydrodynamic model of White Volta River. The upstream boundary at Yarugu is defined as a discharge series. The downstream boundary is the Lake Volta water level as measured at the Akosombo dam. This location was chosen because no other (closer) station measuring the Lake Volta water levels was available.
The 2D model is an extension of the 1D model with the improved digital terrain model as illustrated in Figure 3-1.

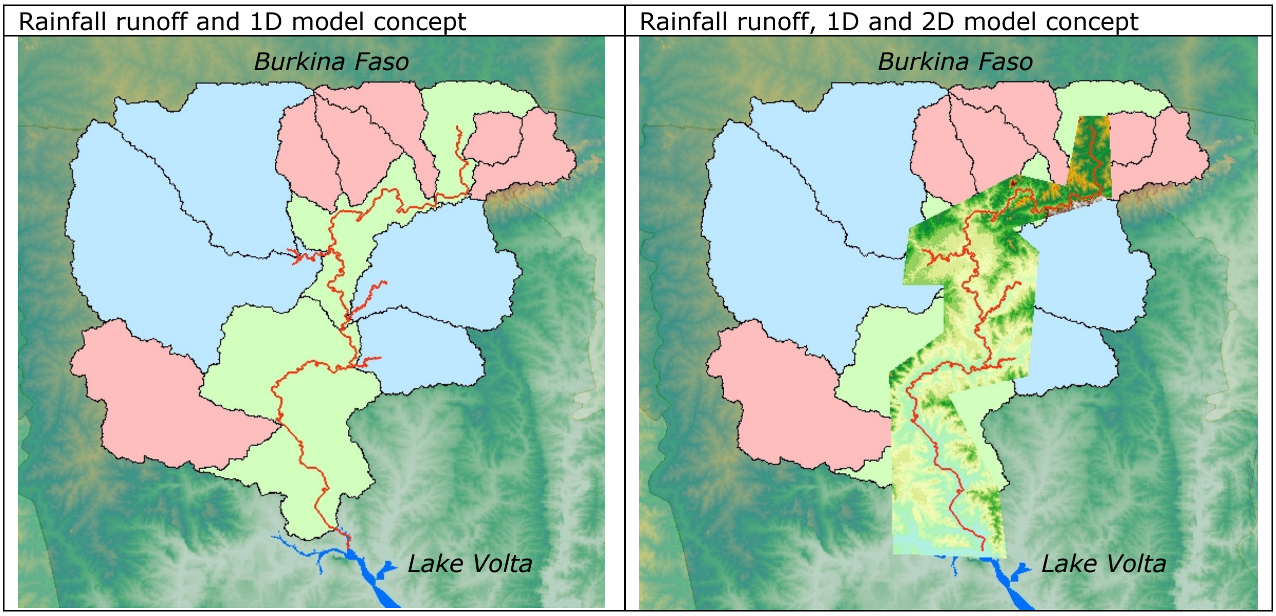


Figure 3-1 Rainfall runoff, 1-D and 2-D model concepts of White Volta basin

The models of the White Volta catchment are used for the following purposes:

1. For Flood forecasting a combined hydrological and 1D hydrodynamic model is applied.
2. Inundation maps are determined with the 1D and 2D hydrodynamic models.
3. Flood mitigation measures are assessed using the 1D hydrodynamic model.
4. The flood genesis is analysed with the 1D hydrodynamic model.
5. Rating curves are at the gauging station locations are determined with the 1D hydrodynamic model.

The Sobek modelling platform version 2.12.003 is used to build the models. The Sacramento module is used as rainfall runoff module in Sobek. See appendix B and C for more details on

Sobek and Sacramento. We refer to the technical Sobek manual available within the help function in any installed Sobek version. The technical manual describes in detail the algorithms and equations used in Sobek and Sacramento.
Report deliverable 4 (HKV 2012) describes in more detail the set-up, calibration and validation of the hydrological and hydraulic models.

3.2 Hydrological model

3.2.1 Data processing

Hydrological and meteorological data
The Sacramento rainfall-runoff model requires precipitation and reference evapotranspiration (ET_{ref}) as input parameters. Discharge and/or water level data is required for the actual calibration of the model.
For this study a time window between 2000 and 2010 was chosen to calibrate the rainfall runoff models. This window was selected, because for this period the most complete and continuous data series are available. This data was validated during the previous phases of the project (HKV, 2012, deliverable 3). Precipitation, reference evapotranspiration and discharge time series were used for modelling purposes. The precipitation and discharge data is available on daily basis whereas evapotranspiration is available on monthly basis.

The meteorological data is assigned to the basins by using Thiessen polygons (HKV, 2012). Due to the sparse amount of meteorological stations, single stations cover large amount of terrain (Table 3-1).

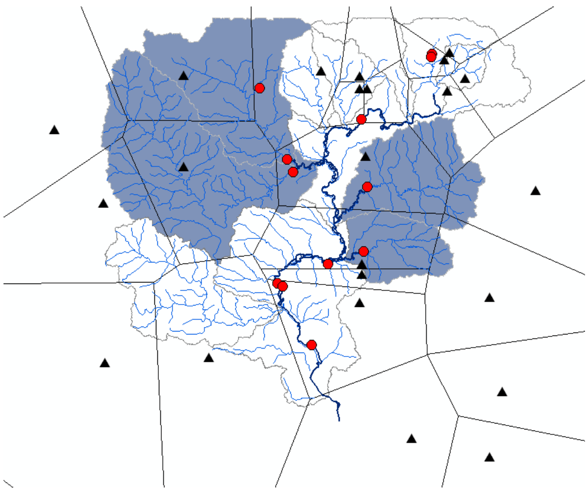


Figure 3-2 The gauged sub basins in blue plus the Thiessen polygons overlay based on available meteo stations

River	Gauging station	Catchment size (km^2)	Meteostations
Sisili	Wiasi	9500	3
Kulpawn	Yagaba	10600	4
Nabogo	Nabogo	1950	2
Nasia	Nasia	5175	5

Table 3-1 The four gauged basins and the location of the gauging station (Carrier 2009 and HKV 2012)

Discharge data for the remaining six tributaries is not available. However, the Red Volta enters the White Volta between the gauging stations of Yarugu and Pwalugu. By using the difference in discharge between these two locations some information about the Red Volta discharges can be derived. The same principle applies to the Mole River, which enters the White Volta between the gauging stations of Daboya and Yapei. The ungauged basins are described in more detail in Report deliverable 4 (HKV, 2012).

Topography and geology

The SRTM digital terrain model is used to determine the slope and average height of the modelled catchments. The slope of the White Volta tributaries is relatively low with an average of 1.17 degrees. Especially within the sand- and mudstone region the area is relatively flat. The relief in general is limited. Ranging from approximately 500 masl in the hills of the Kulpawn basin to +/- 60 masl around lake Volta.

The vegetation cover and anthropogenic influence is heterogeneous within the catchments ranging from savannah to cultivated woodlands (Carrier et al., 2009). A sharp divide can be distinguished within the White Volta catchment when looking at the geology (Figure 3-3). There are two main types to consider (Carrier et al 2009): regions with a soil consisting of Voltonian deposits (sandstone and/or mudstone) and regions with a granitoid rocky soil (Carrier et al., 2009).

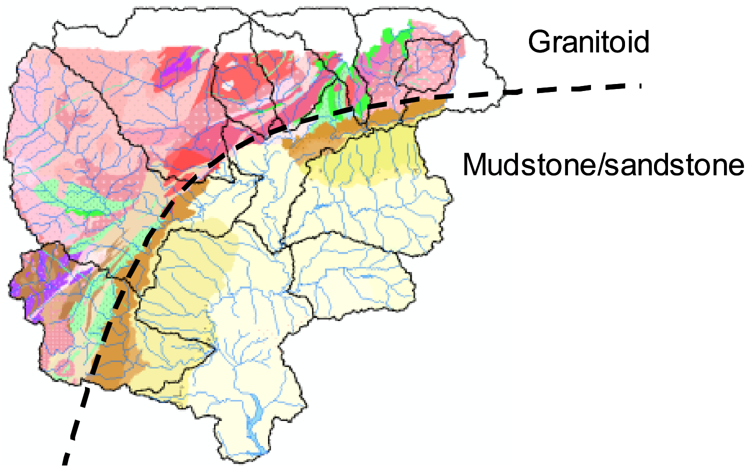


Figure 3-3 The sharp 'geological' divide within the White Volta catchment with the granitoid areas in red and the sand- and mudstone regions in yellow and brown (Carrier et al., 2009)

The geology influences the behaviour of the discharges. The hydrograph of the Kulpawn and Sisili, both (partly) located on the granitoid soils show a more spiky precipitation influenced behaviour. Whereas the Nasia and the Nabogo, both located on the mud and sandstone, show a more gentle graph (Figure 3-4). This information is used to interpret the results and to determine the initial parameter values.

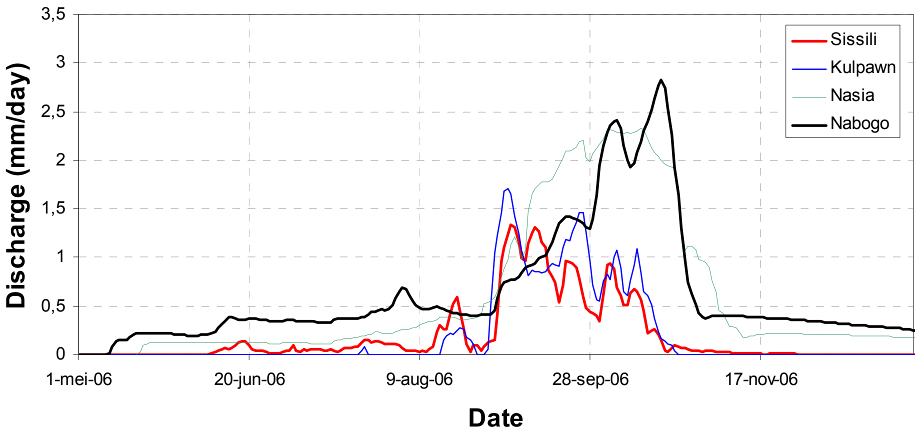


Figure 3-4 The hydrographs for 2006 (discharge in mm/day) of the four gauged basins

A more detailed description of the White Volta Basin can be found in Moniod et al., 1977, Carrier et al., 2009 and Termes 2011/2012.

3.2.2 Model development

Each of the tributaries was modelled as a separate lumped rainfall/runoff model. Although the density of the meteorological stations is low, several meteorological stations can be found within or near the separate basins. The basins surface was assigned to a meteorological station by using Thiessen polygons (Figure 3-5). The purpose of this is to account for the spatial variation in precipitation into the models.

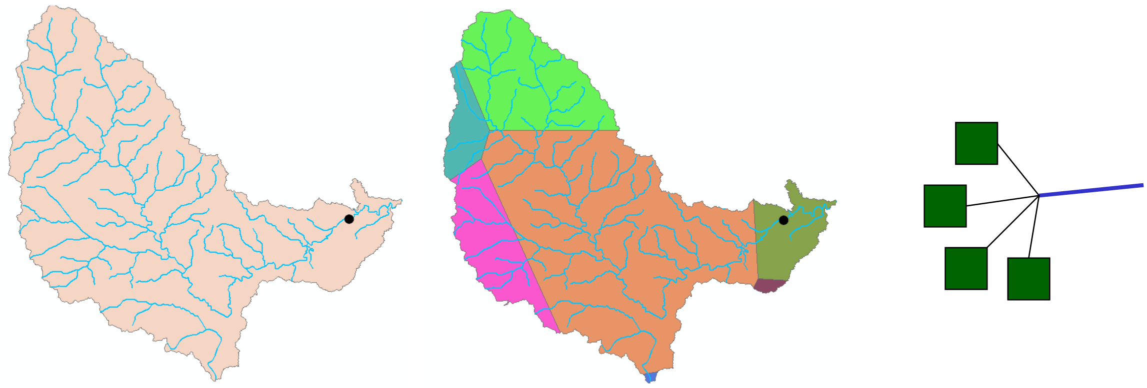


*Figure 3-5 By using Thiessen polygons the surface of the basins was assigned to the different meteorological stations within or nearby the catchment. **Left:** Kulpawn basin **middle**: Divided by Thiessen polygonsl **Right:** Rainfall-Runoff schematisation*

3.2.3 Calibration process

To optimize the model performance a calibration process is required. To generate the best model results the following strategy was applied.

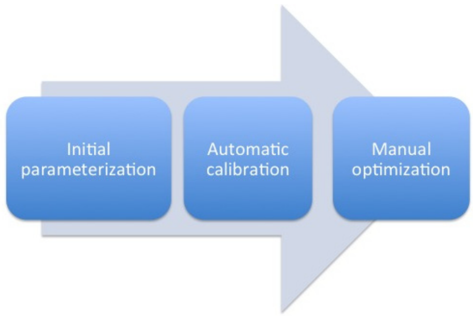


Figure 3-6 Strategy for the calibration process

Initial parameterization

A first estimation of the parameters, and the range in which the values of the parameter should be found, is based on basin characteristics. Part of the Sacramento input parameters can be derived from analysing the hydrograph; others can be determined based on area specific characteristics (i.e. soil types, land use classes etc.).

Automatic calibration

Automatic calibration processes can be used to optimize the model performance. The process of finding an optimal solution for the objective function (i.e. Nash Sutcliff, Root Mean Square Error etc.) by changing the model parameters within a present range is done automatically. The objective function assesses the difference between the model output and the infield-measured values.

A wide range of algorithms is available for this purpose. For this study the simplex algorithm as developed and applied in previous HKV studies (Botterhuis & Klopstra, 2004) was used.

Manual optimization

If the automatic calibration does not result in acceptable or not yet optimal results the models can further be calibrated manually to increase the model performances and find the optimal result.

Calibration criteria listed according to calibration priority are:

1. Timing of peak;
2. Peak discharges;
3. Water balance (expressed in volume or runoff);
4. Base flow.

The timing criterion was focussed upon during the calibration process, because timing is the most important aspect within flood forecasting.

Calibration application White Volta basin

The discharges used to calibrate the hydrological models with are reconstructed with the rating curve derived from hydraulic model, as described in paragraph 4.2.3 in Deliverable 3 (HKV, 2012).

The model runs start in 2000 to be sure that the initial model state in 2003 does not influence the calibration process. It appeared that data available to estimate the acceptable range of calibration parameters was sparse. Some data on recharge and storage capacities was derived from Carrier et al. 2009.

Initially the models were calibrated automatically using the downhill simplex algorithm and the root means square error (R^2) as the objective function. After that the models were fine tuned

manually. By changing (i.e. increasing or decreasing) the parameters an optimal solution was sought after. Calculated peak discharges, base flow, volumes and timing of the peak were compared to observations to check model performances.
During the calibration process a sensitivity analysis was performed, which is described in Report deliverable 4 (HKV, May 2012).

3.2.4 Calibration and validation results

Gauged basins

Within the final model results one can separate the Sisili and Kulpawn from the Nasia and Nabogo basins, both in discharge as in model performances. In general, the RR models tend to underestimate the calculated discharged volume for the latter two and overestimate the discharges for Sisili and Kulpawn. Table 3-2 shows the observed and calculated catchment ***runoff (volume divided by surface)***. The results show that 2003 provides good results for all stations. Nabogo shows the best results for the different years.

	Nabogo			Nasia			Kulpawn			Sisili		
Date	Q_{obs} (mm)	Q_{calc} (mm)	Diff	Q_{obs} (mm)	Q_{calc} (mm)	Diff	Q_{obs} (mm)	Q_{calc} (mm)	Diff	Q_{obs} (mm)	Q_{calc} (mm)	Diff
2003	478	422	12%	244	241	1%	197	203	-3%	85	99	-16%
2004	340	338	1%	182	96	47%	53	80	-51%	43	63	-47%
2005	259	294	-14%	120	77	36%	25	39	-56%	30	40	-33%
2006	237	253	-7%	154	65	58%	51	77	-51%	47	113	-140%
2007	640	438	32%	250	384	-54%	102	179	-75%	96	155	-61%

Table 3-2 Observed and modelled runoff in mm/year between 2003-2007(Nasia and Nabogo taken for the whole year, Kulpawn and Sisili from start till end of observed discharge)

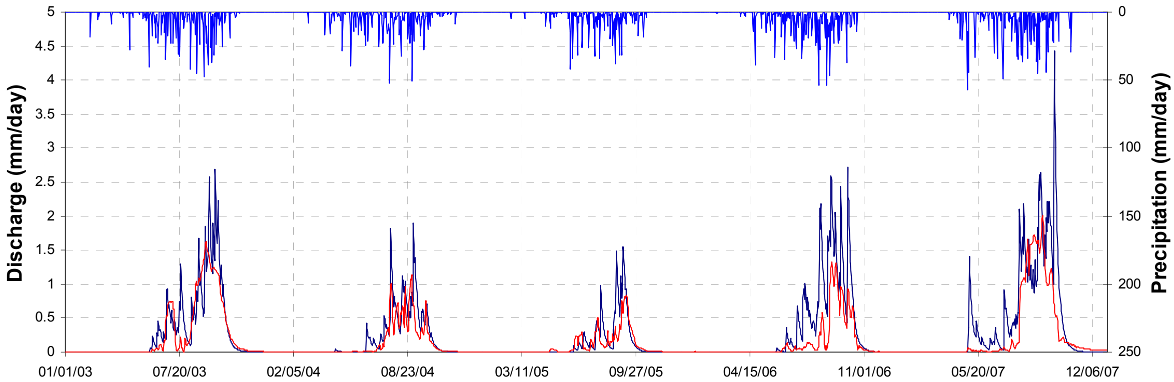
During the calibration process, it became clear that when focussing on optimizing the ***mass balance*** the ***timing of the peak*** would be delayed. When optimizing ***time to peak***, the error in ***volume*** increased. It was therefore decided to focus on the timing and peak discharge seen its importance to flood forecasting. The resulting correlation between observed and simulated discharge volumes are illustrated in Table 3-3 as an R^2 value with 1 being a 100% correlation (for the complete year). Because the calibration focussed on the time to peak the results are not optimal, especially for Sisili and Kulpawn. Again, Nabogo performs very well.
The ***base flow*** hardly plays a role in the discharge regime of the tributaries. The baseflow is smaller than the uncertainty caused by rainfall and evaporation data, which is estimated between 1 mm during low flow situations and 6 mm during peak flows. The baseflow is estimated less than 1 mm.

	R^2 2003	R^2 2007
Sisili	0.74	0.52
Kulpawn	0.55	0.59
Nabogo	0.96	0.90
Nasia	0.76	0.63

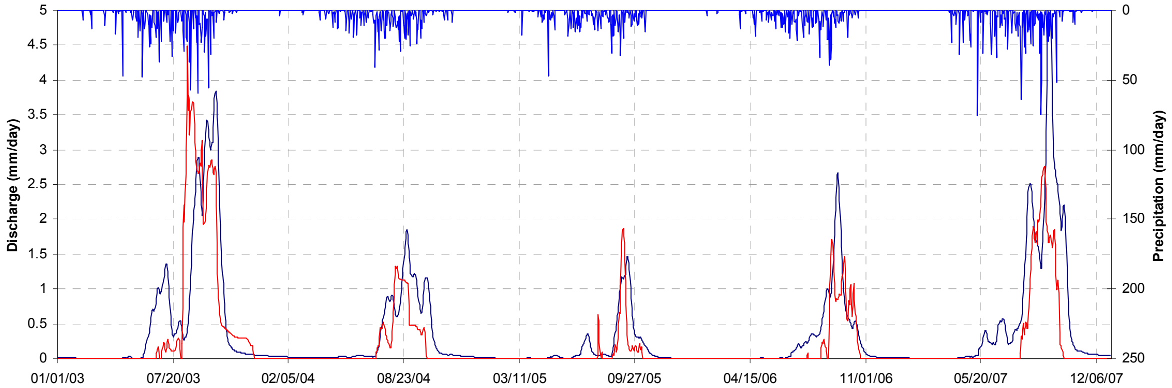
Table 3-3 R^2 of the four gauged basins for the years 2003 and 2007

When observing the results for ***timing and peak discharges*** the model performs better as can be observed in Figure 3-7, where measurements and model outputs are plotted.

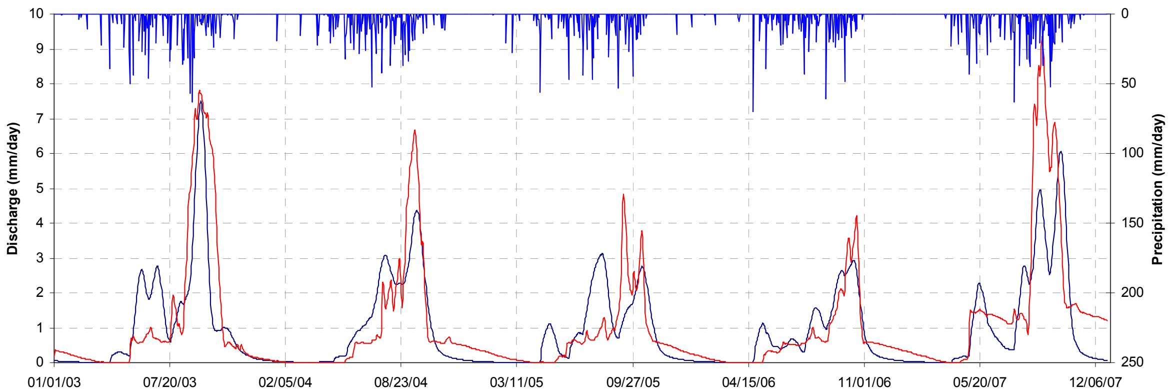
Sisili



Kulpawn



Nabogo



Nasia

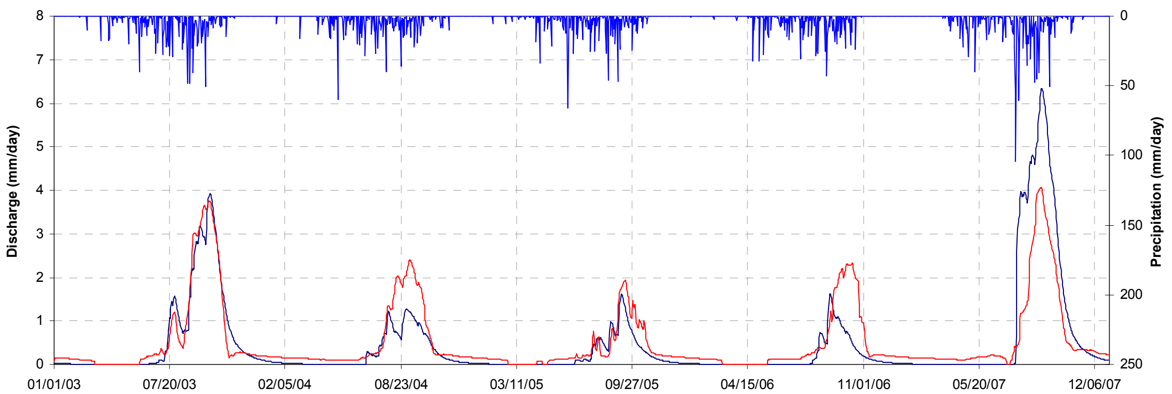


Figure 3-7 The calibration results for Sisili, Kulpawn, Nabogo and Nasia (model results in blue, observations in red)

Within the catchments of the tributaries, only small amounts of water are discharged compared to the incoming precipitation. The majority of the water leaves the system through evapotranspiration. The loss by evapotranspiration can be up to 80%-90% of the total precipitation. This implies that precipitation data errors might influence the discharge results quite drastically. Table 3-4 shows an example of the precipitation, evaporation and discharge on Sisili river in 2007.

	Sisili	
	Mm^3	mm
Aug, Sept, Oct, 2007		
Precipitation	6751	534
Evaporation	5149	407
Discharge (measured)	781	62

Table 3-4 Example: comparison between precipitation, evaporation and discharge for three (wet) months in 2007 for Sisili River

Non-gauged basins

The final calibrated parameter sets can be found in HKV Deliverable 4 and 6 report [October, 2012]. The parameter sets of the calibrated models were used for the non-gauged basins (Table 3-5). The parameter set of the Sisili basin was used for most of the other non-gauged basins. It was decided that, due to the similar geological conditions (granitoid), this was the most pragmatic option.

Basin	Parameter set
Tamne	Sisili
Tono	Sisili
Morago	Sisili
Atankwidi	Sisili
White Volta Lateral 1	Nasia
White Volta Lateral 2	Sisili
White Volta Lateral 3	Sisili

Table 3-5 Calibrated parameter sets where used to model the non-gauged basins. The parameter set of the Sisili acted as most important reference

Red Volta & Mole River

Initially the parameterisation of the Kulpawn was used for the Mole River and the Sisili for the Red Volta. The parameter sets for the Red Volta and the Mole River were slightly adapted. This was done based on observed difference in discharge at the Yarugu and Pwalugu gauging stations and Daboya and Yapei, corrected for propagation times. However this data was only of use to estimate the order of magnitude, due to irregularities within the observed differences (i.e. negative values) as can be observed in Figure 3-9.

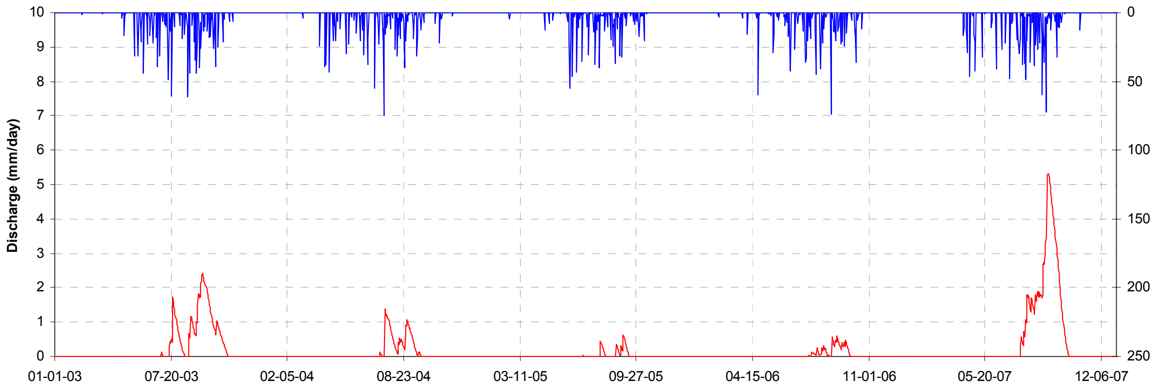


Figure 3-8 The calibration results for the Red Volta

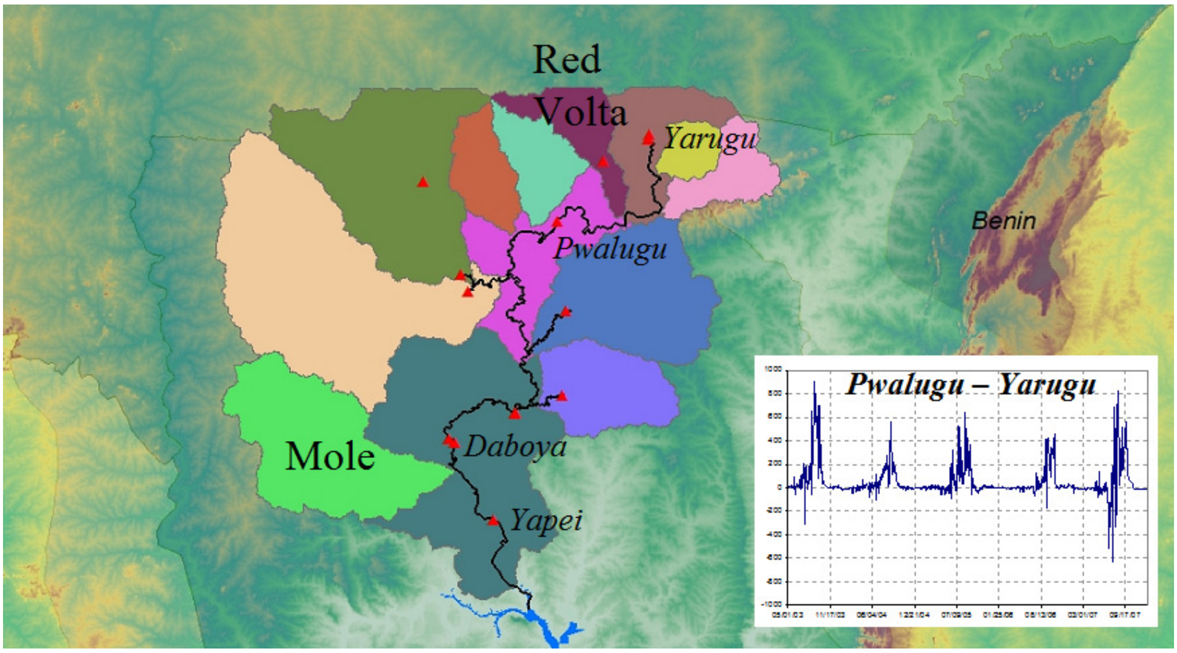


Figure 3-9 The difference between the Yarugu and Pwalugu gauging station to optimize the parameterisation of the Red Volta showing negative values

Validation with 1D model

The rainfall runoff models are validated by replacing all 1D-model inflows with rainfall runoff generated inflows (except for Yarugu Kobori). In Figure 3-10 and Figure 3-11 the results are shown for Nawuni and Daboya, both located downstream of the four calibrated RR-catchments. The figures show the measured water levels, the water level calculated with measured inflow (1D_Hyd) and calculated water level with inflow determined with the rainfall runoff models (RR_Hyd). In general the results are satisfactory. The results also illustrate periods in which water levels have registered a peak, but the measured precipitation apparently did not (like August 2003). In general it can be concluded that the water levels on the White Volta are calculated accurately, despite the lack of rainfall data that cause inaccurate RR-results on (some) tributaries.

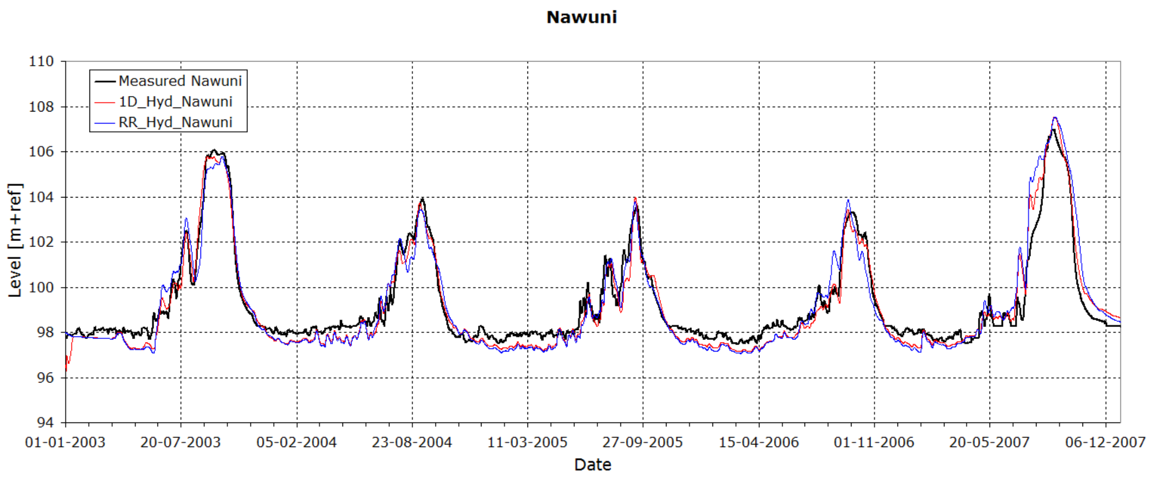


Figure 3-10 Water level at Nawuni calculated with inflows from the RR-models

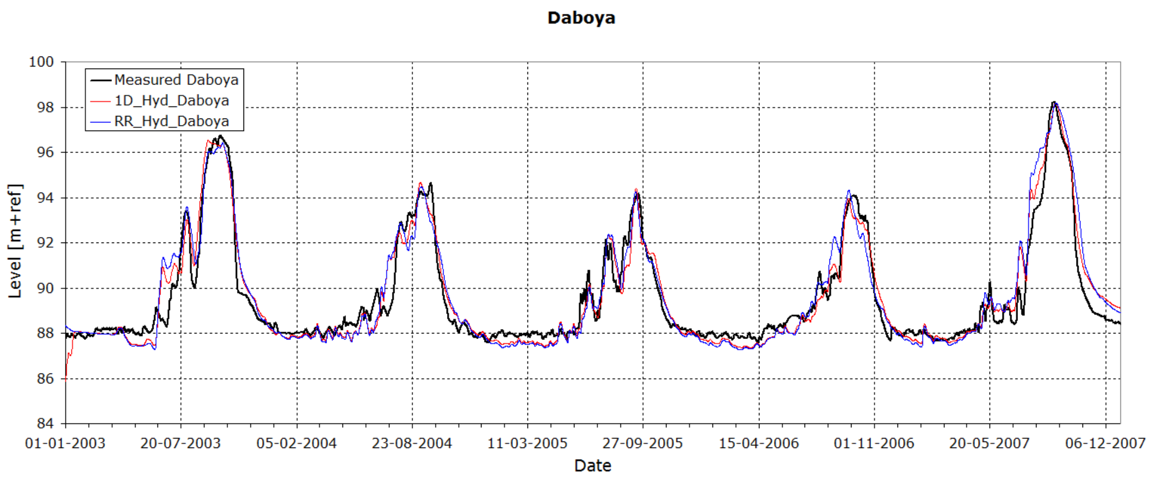


Figure 3-11 Water level at Daboya calculated with inflows from the RR-models

3.3 Hydrodynamic model

3.3.1 Data processing

The following data was processed before schematising the hydrodynamic model:

River network

Alignment of rivers: the alignment of the river axis was received from WRC. After checking the alignment with Google Earth it was clear that the river axis needed improvement. The river axis of the White Volta and the main tributaries was re-measured during the bathymetrical survey and cross-checked with Google Earth and the historical land sat flood maps. The figure below illustrates the corrected alignment in blue and the river alignment from WRC in black.

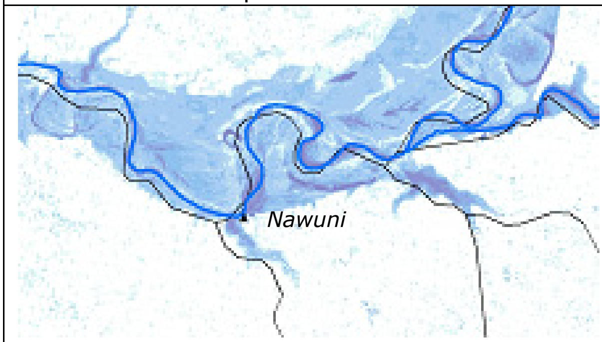
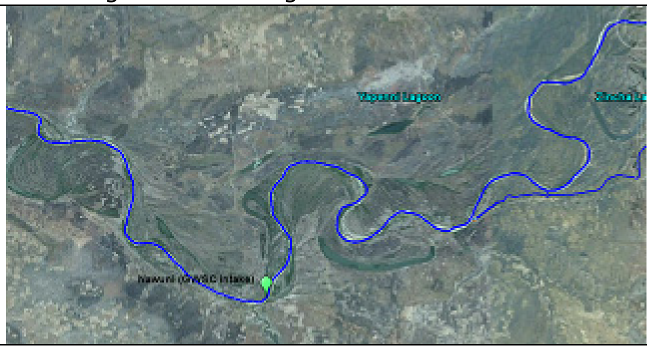
Historical flood maps in ArcGIS	River alignment in Google Earth
	

Figure 3-12 Satellite data used for river alignment

The White Volta is a very natural dynamic river with a complex inundation pattern where old river arms are inundated during different flood levels. Some old branches retain water and some transport it. In order to simulate this effect with a 1D-model a quasi 2D model approach was used. This means that the floodplains in which the old river arms are located are also schematised as river branches in the 1D-model. Again the historical flood extent maps were helpful in this exercise. The network of branches was drawn up in ArcGIS. Figure 3-13 below shows a combination of main channels (blue) and floodplains (red) around the confluence of the Kulpawn and White Volta rivers. The flow direction is indicated with arrows.

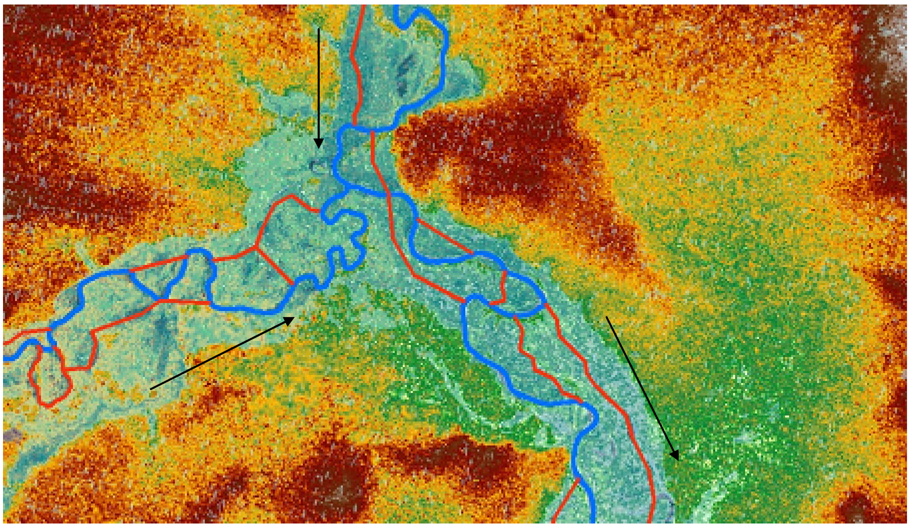


Figure 3-13 Sobek river network

Cross-sections

The cross-section locations in the main channel were defined in the inception phase. The cross-section locations of the floodplains were selected based on the floodplain network as defined in Figure 3-14. The locations are illustrated as green points.

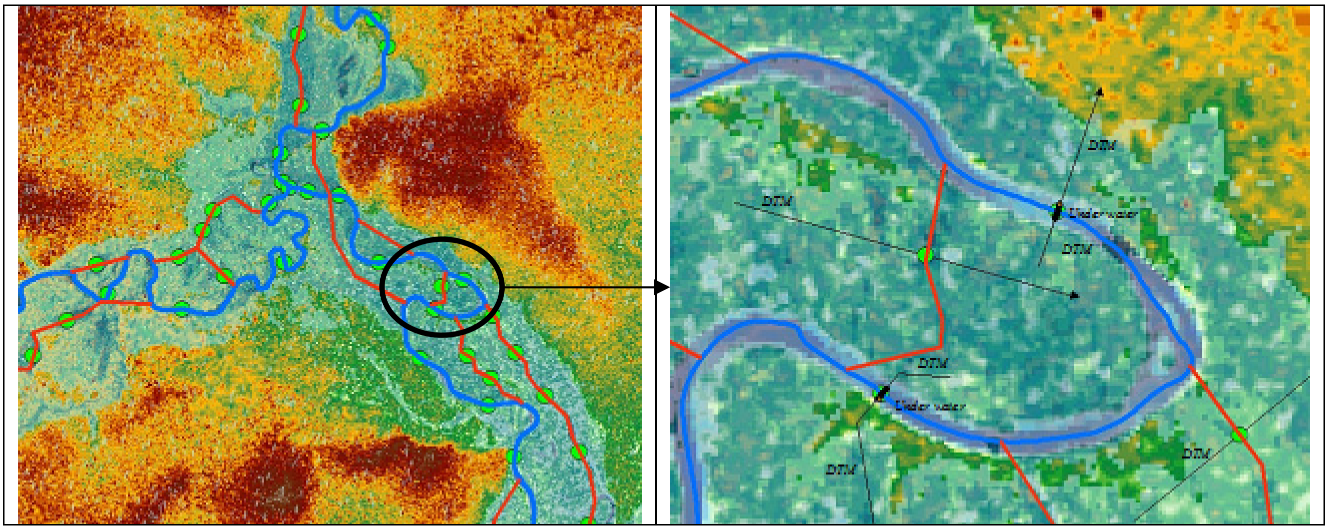


Figure 3-14 Cross-sections in the Sobek river network: main channel in blue, floodplain channel in red

The geometry of the cross-sections in the main channel is a combination of underwater cross-sections as measured during the bathymetry survey and the improved DTM (also see Report deliverable 2, HKV 2012). The cross-section locations in the floodplains are placed on the floodplain branches. The geometry of the floodplain cross-sections is taken from the DTM. Figure 3-14 shows this in detail. The underwater geometry fits relative well with the DTM, which is also illustrated in Report deliverable 2, HKV 2012.

Structures

The locations of all relevant hydraulic structures like reservoirs, bridges and weirs were collected from field observations and Google Earth. The geometry was estimated using photos and the DTM.
The bridges of Pwalugu and Yapei were included in the model as *Pillar structures*. The bridges of Yarugu, Wiasi, Yagaba, Nabogo and Nasia were not included as they are boundaries of the model.

Landuse and friction

The landuse map was collected from the HAP database (Report deliverable 2, HKV 2012) and used to determine the (initial) bed friction values for the 1D and 2D models.

Hydrological data

Water levels, discharges and rating curves were collected and processed as described in Report Deliverable 3 (HKV, 2012). The inflow from ungauged catchments as well as direct runoff catchments to the White Volta are calculated by hydrological models (see chapter 3.2). The inflow from the gauged catchments as well as the inflow at Yarugu was derived from the reconstructed rating curves as described in Report Deliverable 3 (HKV, 2012).

3.3.2 Model development

Sobek can import shape-files as model objects. The geometry of the objects can be easily imported as flat text. When the model data collection and specifically the data processing is finalised all model data can be imported:

- The main channel and floodplain network;
- The cross-section locations and geometry;
- Hydraulic structure locations and geometry;

- Model boundaries (inflows), lateral inflows and lateral distributed inflows;
- Lake Volta is included in the model as well. The downstream boundary is the water level just upstream Akosombo dam.

Figure 3-15 shows a screen dump of the 1D model and a detail around Nawuni gauging station.

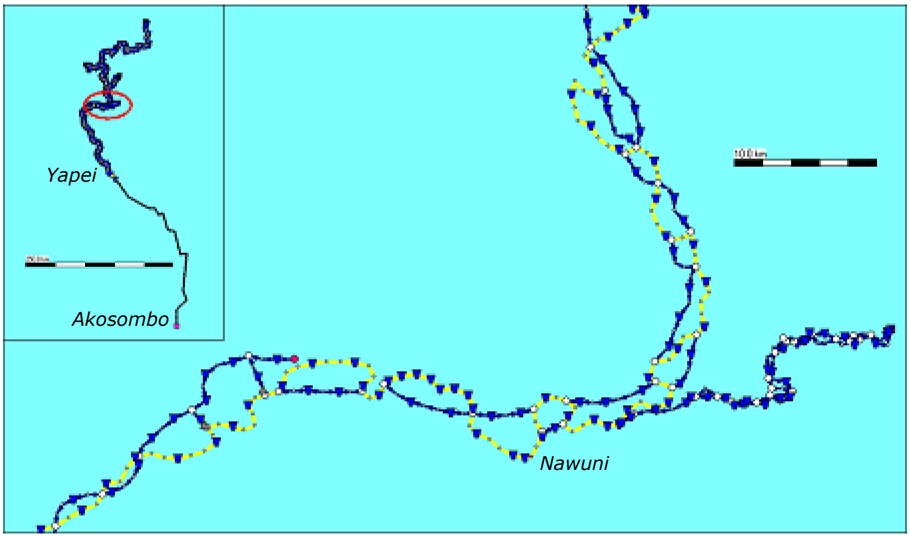


Figure 3-15 Screen dump Sobek model

3.3.3 Calibration process

Based on the availability and reliability of the data it was decided to calibrate and validate the 1D model for the period of 2003-2007. Especially 2003 and 2007 are extreme flood events, with 2007 recorded as one of the highest ever.
The calibration was carried out by changing the roughness coefficients of the cross-sections in the main channel branches, consisting of two riverbanks and the main channel, and the floodplain branches as illustrated in Figure 3-16. The roughness values differ between the floodplain branch, main channel and riverbank. This results in 3 roughness sections in the river. The river stretch between 2 consecutive hydrological gauging stations are given the same roughness values. It was decided to use manning values because:

- they represent the influence of water depth on the roughness values and
- we based our (initial) roughness values on internationally accepted values from Manning's n for Channels (Chow, 1959 and appendix F).

The roughness values of the calibrated and validated 1D model are shown in Table 3-6.

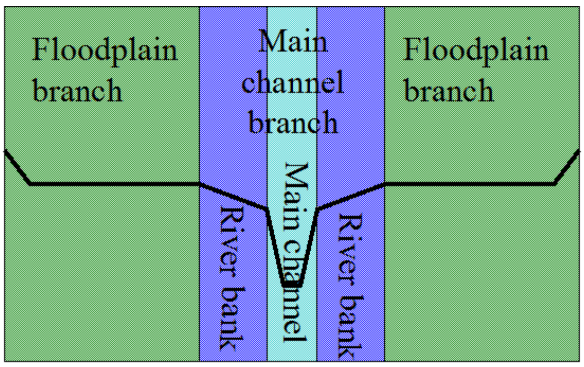


Figure 3-16 Roughness sections in the White Volta cross-sections

Section	Main channel	River bank	Floodplain
Lake Volta - Yapei	0.0303	0.0955	0.063
Yapei - Daboya	0.0321	0.105	0.063
Daboya - Nawuni	0.0371	0.104	0.07
Nawuni - Pwalugu	0.0495	0.135	0.095
Pwalugu - Yarugu	0.0301	0.126	0.084
Nabogo	0.0451	0.1101	0.141
Nasia	0.0482	0.126	0.165
Sisili	0.049	0.0903	0.143
Kulpawn	0.048	0.1202	0.142
Daboya side-channel	0.0442	0.121	not available

Table 3-6 Roughness values after the calibration process

Some of the relative high values are justified by the fact that:

- The White Volta floodplain is densely vegetated in the wet period. The floodplains are covered with high savannah grass and scattered bushes.
- The banks of the rivers are covered in very dense vegetation.
- The tributary floodplains retain more water, expressed in the high floodplain manning values.

Figure 3-17 From left to right: Upper White Volta and Nabogo, floodplains and Lower White Volta

3.3.4 Calibration and validation results

The calibration focussed on the flood of 2003, as this data was assumed most reliable. The 2007 flood was used to recalibrate where necessary. The medium flood years 2004-2006 were used

to validate the model results. The flood peak value was used as the main calibration criterion of which the results are summarised in Table 3-7. The results show the difference in meters between the maximum measured and calculated water level. Unreliable data in the measurements cause large differences and are left empty in the table below. The explanation is described further below. The contract states a calibration criterion of 0.30 m. The table below shows that most stations meet this criterion.
Timing of the peak and the rise and fall of a flood wave were taken into account during the calibration and validation process as well. However they were assessed based on visual inspection of the results. Figure 3-18 shows an example of the measured and calculated water levels at Nawuni gauging station. Appendix E shows all measured and calculated water levels in graphs.

	Difference [m]					
Station	**2003**	**2004**	**2005**	**2006**	**2007**	**Average station**
Yarugu	-0.26	-0.10	-0.23	-0.20	0.05	-0.15
Pwalugu	0.47	1.80	0.30	0.02		0.65
Nawuni	0.28	0.17	-0.43	-0.12	-0.53	-0.13
Daboya	0.21	0.00	-0.23	0.14	0.06	0.04
Yapei	-0.23					-0.23
Wiasi	0.02	0.04	0.12	0.02	0.08	0.06
Yagaba		0.06	0.01	-0.03	-0.05	0.00
Nasia	0.35	0.20	0.02	0.23	0.02	0.20
Nabogo	0.21	0.42	0.06	0.13	-0.22	0.12
Average total	-0.02	-0.03	-0.29	-0.20	-0.03	-0.11

Table 3-7 Calibration and validation results 2003-2007, measured – calculated water levels [m]

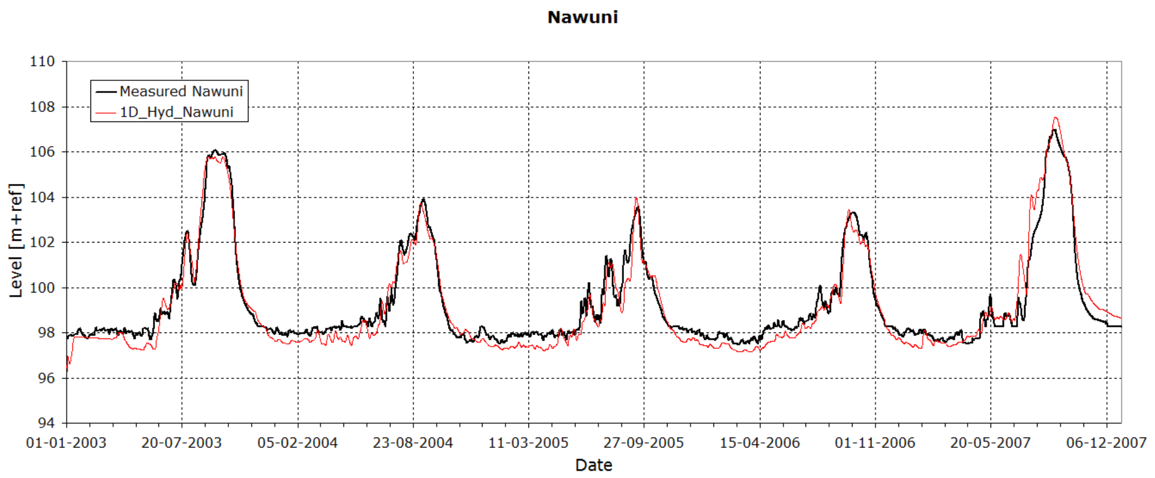


Figure 3-18 Measured and calculated water levels, Nawuni, 2003-2007

The calibration and validation results are satisfactory both in absolute value as well as in timing. In the following list the results for the different gauging stations are explained in more detail:

- Yarugu shows good results because the discharge is derived from the rating curve constructed with the hydraulic model.
- The flood at Pwalugu is dominated by inflows from the Red Volta and the White Volta (at Yarugu). The Red Volta discharge is calculated with a rainfall runoff model and therefore

less accurate compared to inflows directly based on measured data, like at Nasia or Yarugu. This causes differences between the measured and calculated water levels at Pwalugu. On the other hand, some of the peaks are simulated very well.

- The calculated water level at Nawuni is very similar to the measured water levels. The difference during the 2007 flood peak is relatively high and caused by a large inflow from the Red Volta, resulting from intense rainfall, but not registered in the water levels. This trend is visible in the water levels at Pwalugu as well.
- The calculated water level at Daboya is very similar to the measured water levels.
- Yapei shows good results for 2003, however the floods of 2004-2007 show a higher calculated peak and volume. This is caused by recording errors at Yapei. Figure 3-19 illustrates this: when comparing the measured water levels at Daboya (assumed correct) and Yapei closely, the flood wave at Yapei seems to be missing several peaks.

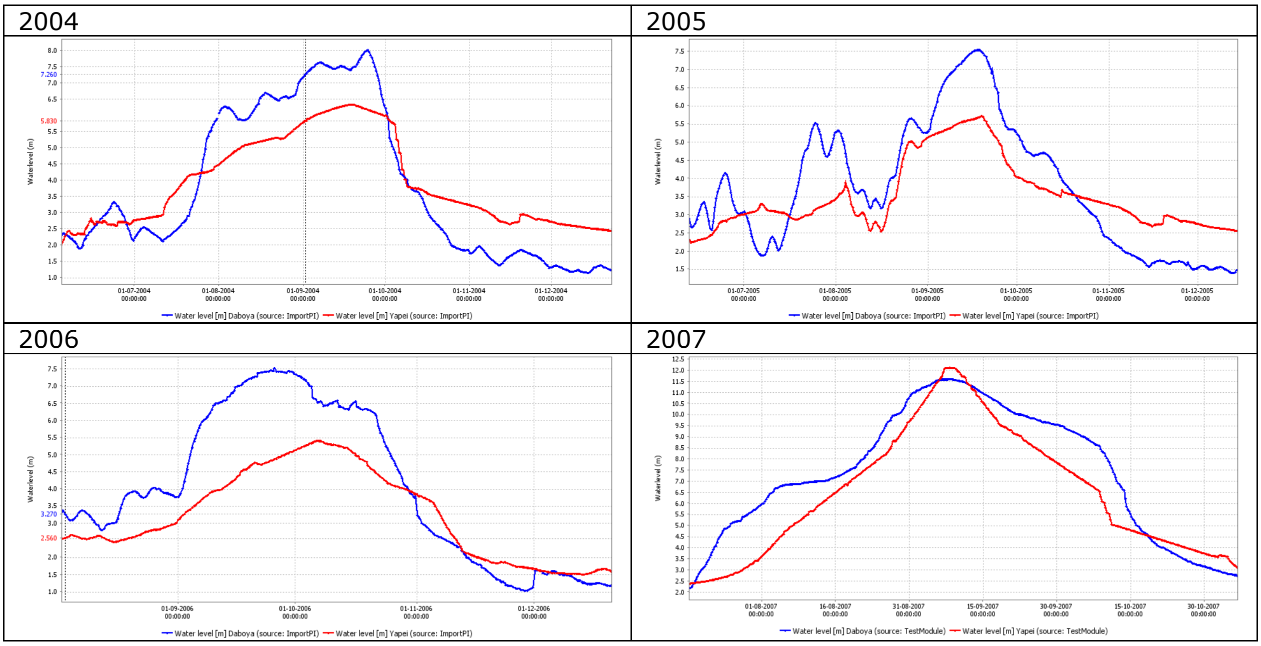


Figure 3-19 Measured water levels Daboya (blue) and Yapei (red) 2004-2007

- Yagaba showed a relative large difference between the measured and calculated maximum peak water level for 2003. This is caused by several very high water level values in mid August 2003. Since surrounding hydrological and meteorological stations cannot explain this peak, it was assumed doubtful and not taken into account in the calibration process, which is why the difference in Table 3-7 shows no value for Yagaba 2003.
- In general Yagaba and the other tributary stations Wiasi, Nasia and Nabogo show results very similar to the measured water levels because the discharge is derived from the rating curves constructed with the hydraulic model.
- The calibration and validation process focussed on high flows, resulting in associated roughness values. These values are not always valid for low flows, as the results show especially for the gauging stations on the tributaries (Wiasi, Nabogo, Nasia and Kulpawn) The Sobek version we used does not have the possibility to vary roughness values depending on the flow level. The hydraulic model was not used to construct the lower part of the rating curve.

The table below shows the differences in timing of the peak for 2003 and 2007 for the different hydrological stations on the White Volta. The tributaries have hardly any timing difference as their input is derived from the measured water level series.

	Difference [days]	
Station	**2003**	**2007**
Yarugu	0.00	0.00
Pwalugu	3.50	0.50
Nawuni	0.00	-1.00
Daboya	-3.00	-2.25
Yapei	-1.75	-3.00

Table 3-8 Calibration and validation results 2003-2007, measured – calculated time of peaks [days]

3.4 Extension with 2D module

Once the model calibration and validation is finished the 1D hydrodynamic model is extended with a 2D-module. The extension implies the following steps:

- Remove the floodplain area from the 1D-model,
- Import the DEM. The original DEM as described in GIS-database report deliverable 2 (HKV, 2012) used a 20x20 m grid. An analysis was made to determine the optimal grid size to be used in the 2D-model because a 20x20 m grid leads to unworkable computation times. We assessed 20, 100, 200 and 400 m grid cell sizes and concluded that 200 m grid provides the best results in terms of computation time and calculated results.
- Import the roughness grid based on land use maps. The roughness values used were based on the manning roughness from Chow. Appendix F shows these roughness values, the values used in the 2D-model and the visualisation of the roughness grid.

The 1D2D model was calibrated on the historical flood extent of 2003, especially because a satellite image is available from the 2003 flood extent 1 day after the peak occurred at Nawuni. The flood of 2007 was used as validation period. Some of the 2D validation results are illustrated in Figure 3-20, Figure 3-21 and Figure 3-22. The 2D calculations represent the historical flood extent and measured water levels very well.

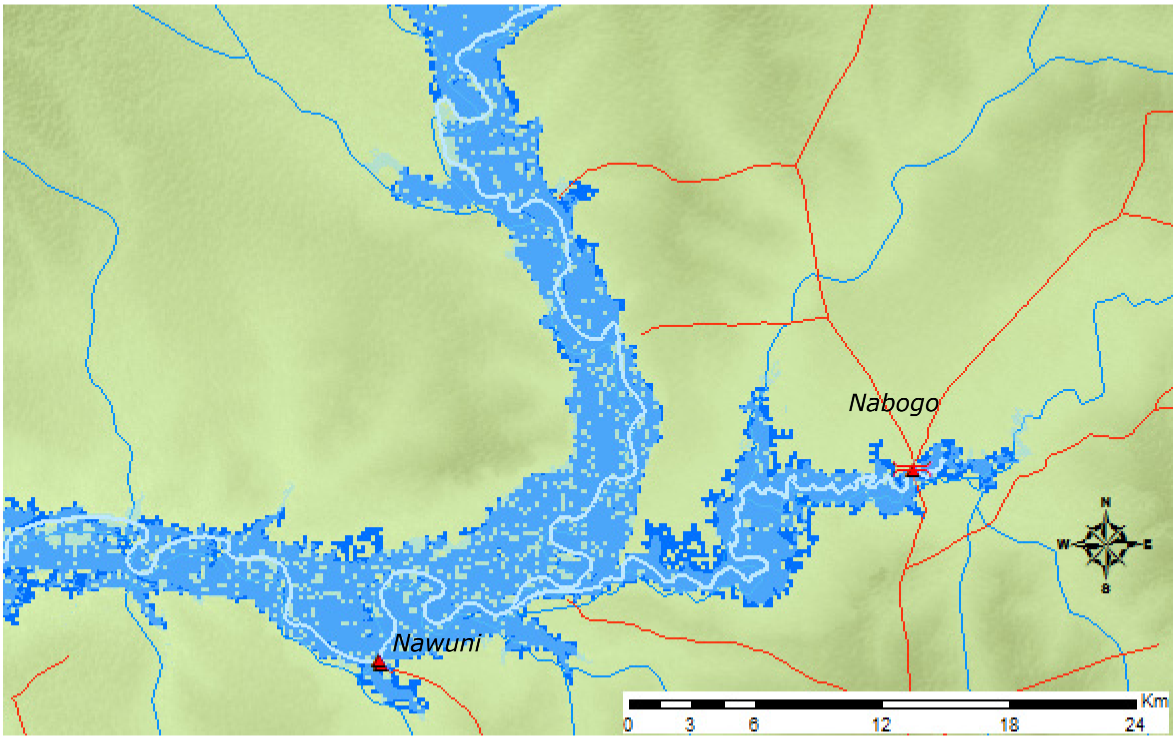


Figure 3-20 Landsat image 2003 (light blue) and 2D model results (dark blue) Nawuni – Nabogo 1:250000

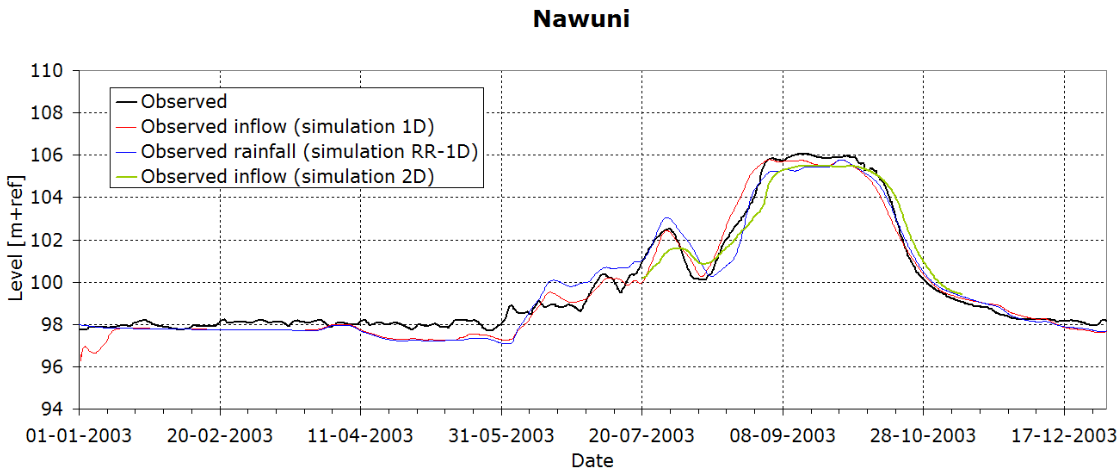


Figure 3-21 Water levels 2003 compared with 2D model at Nawuni

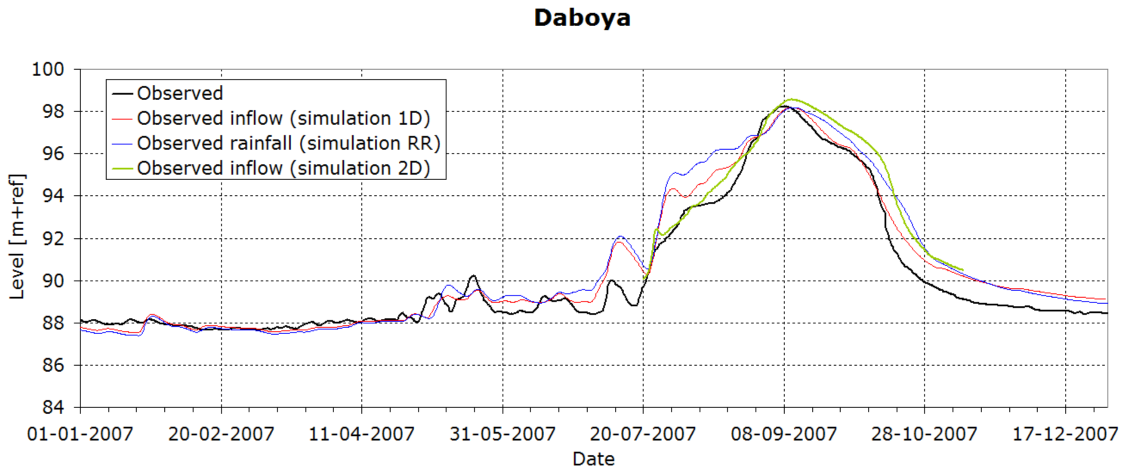


Figure 3-22 Water levels 2007 compared with 2D model at Daboya

3.5 Conclusions

Rainfall runoff models

The rainfall runoff model results show us that the individual models do generally not perform well especially when looking at the values of simulated peak discharges. This is mainly due to lack of data (station coverage) and system information, like the amount of water that is retained and evaporated. Especially the Sisili and Kulpawn Rivers are sensitive to uncertain input data and associated parameter settings. The hydrological model of Nabogo river on the other hand performs acceptable.

Better data can be acquired by installing more meteorological stations. GMET is installing (or planning to install) new automatic stations. They also recently installed a rainfall radar near Accra and intent to extend the radar coverage to North-Ghana in the future as well. These developments will help to improve the estimation of rainfall quantities as well as spatial rainfall variation in the project area. This information will improve the rainfall runoff model results.

The Red Volta is the largest tributary of the White Volta but not properly gauged for some time. This makes it impossible to properly calibrate the RR-model of the Red Volta. Nangodi gauging station on the Red Volta is not operational, partially because flash floods frequently destroy the gauge. A more robust gauge should be re-established at Nangodi or a gauging station just downstream of the confluence between the Red and White Volta will make Red Volta discharges available in the future.

When replacing the measured hydraulic model inflows at Sisili, Kulpawn, Nasia and Nabogo with rainfall runoff simulation inflows, the hydraulic model simulates historical river water levels very similar compared to the measurements. This means that whilst some of the individual rainfall runoff models do not perform well, the combination of all rainfall runoff models lead to very good White Volta water levels.

It is noted that the hydrological models were improved and updated as described in appendix K.

Hydrodynamic 1D-model

The hydrodynamic model performs well especially for the 2003 flood. Due to lack of data, mainly at Yarugu Kobori, it was not possible to properly simulate 2008-2010. It is strongly recommended to find or reconstruct the historical hydrological data for this station. When

applying the average discharge of 2007 at Yarugu Kobori for the years 2008-2010, the results are acceptable as shown in Figure 3-23.
In general it is essential to make and keep Yarugu Kobori operational, as it is the most important gauging station of the White Volta catchment in Ghana. An extra gauging station between Pwalugu and Nawuni should be installed as well. Apparently this station called Kpasenkpe exists, however the status is not clear (also see Report Deliverable 3, HKV 2012).

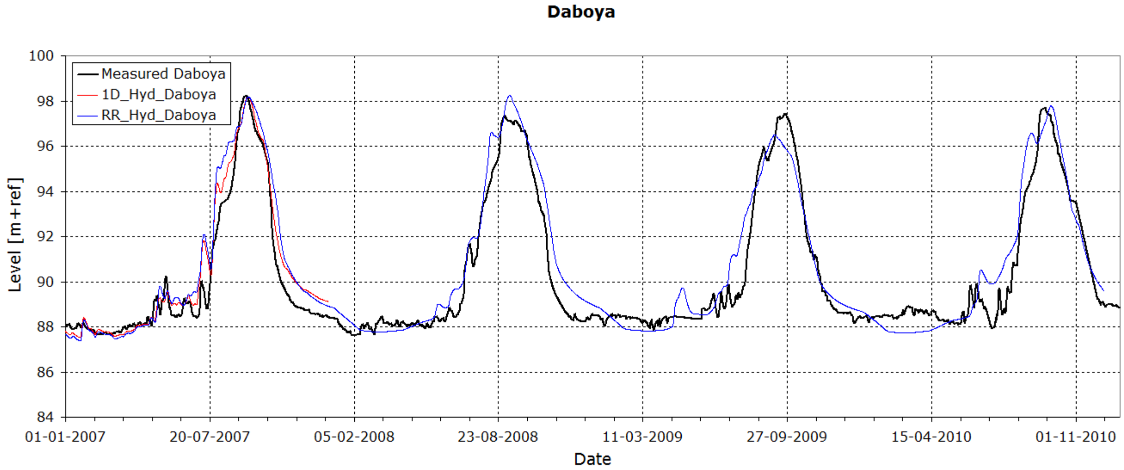


Figure 3-23 Water levels Daboya 2007-2010 with average 2007 inflow at Yarugu Kobori (RR_Hyd_Daboya)

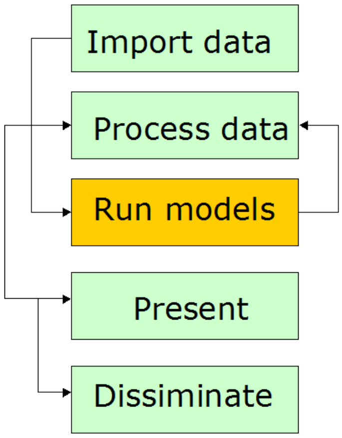
It is also recommended to improve the data availability around the confluence of the Black and White Volta. The hydrological stations in this area are hardly operating or removed. The model boundary is located at lake Volta, but the calibration starts at Yapei and upstream from there. When trying to model this area properly the Black Volta should be taken into account as well.

Hydrodynamic 2D-model

The model results of the 2D model very good both in calculated absolute levels as well as in flood extent. Improvements can be made when new satellite images become available from future flood events. At the moment satellites fly more frequent over Ghana, which increases the chance of satellite images capturing future floods in their full extent just after the peak.

4 FEWS-Volta

4.1 General



FEWS-Volta was developed in two main phases. First a Water Information System (WIS-Volta) was built in which all collected and processed hydrological and meteorological data was stored until 31-12-2010. Next WIS-Volta was extended with a forecasting module, making it possible to calculate (semi-automatically) real time forecasts. This result is called FEWS-Volta.
WIS-Volta consists of modules that import, process, present and disseminate data. FEWS-Volta uses the same modules and additionally uses a module that runs the hydrological and hydrodynamic models.

4.2 Step 1: WIS-Volta

4.2.1 Import data

Data can be imported via so called *FEWS-PI files*. These are xml-files that can be generated with a spread sheet. When the files are placed in a folder the operator can run the import task and the data included in the FEWS-PI files will be placed in the *Basic* folder. The import routine only works when the parameters and locations imported exist in WIS-Volta.

The second option to import data is to manually add data in the table view. By activating the edit mode, data in the *Processed* folder can be added in the table that becomes available when proper location and parameter sets are selected. Copying and pasting between Excel and WIS-Volta is possible as well. The stakeholders were trained using this import method.

4.2.2 Process data

WIS-Volta has some basic data processing tools that were used in the project, mainly for water level series. Rainfall was processed outside WIS-Volta and the discharge series were reconstructed using the 1D flow model. Data processing included the following steps:

- All gaps in the water level series smaller than 48-hours were automatically filled using linear interpolation.
- In the edit mode outliers or other unreliable data can easily be spotted and removed, either from the table or directly from the graph.
- When all unreliable data is removed the gaps need to be filled. This can be done by:
  - Manually select one or more gaps in the table and select either linear or block interpolation.
  - Use other series during similar periods to fill the gaps. Water levels can be viewed according to their absolute or relative levels. Using relative levels makes it easy to compare different locations. It is recommended to copy the data series used to fill the gap to excel, transpose the series in order to connect properly to the connecting values.

And copy the data back into the WIS-Volta table. Figure 4-1 illustrates a gap fill at Daboya.

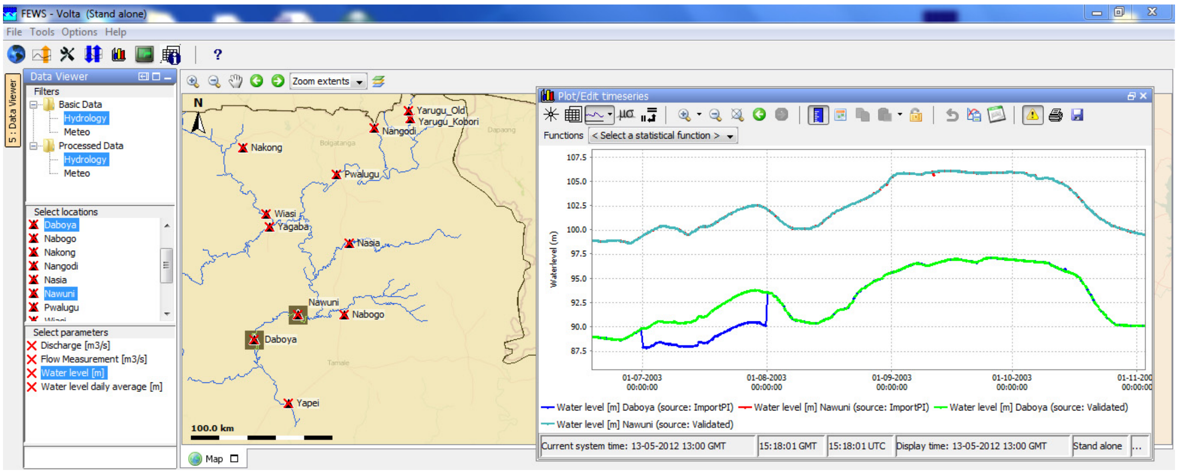


Figure 4-1 Water levels Daboya and Nawuni, basic and processed

Report deliverable 3 (HKV 2012) describes the data processing in more detail.

4.2.3 Present data

WIS-Volta has user-friendly data selection and viewing options. The user can select locations, data types and parameters from the filter and or directly from the map-interface. Once selected it can be viewed graphically and in tables. It is easy to include more data sets in the graph and table regardless of the parameter or location selected. Different graph windows can be viewed as well. The user can easily and quickly scroll through the data.
General statistics and basic statistical graphs can be selected as well. When doing so WIS-Volta always uses the data set that is visible within the graph.

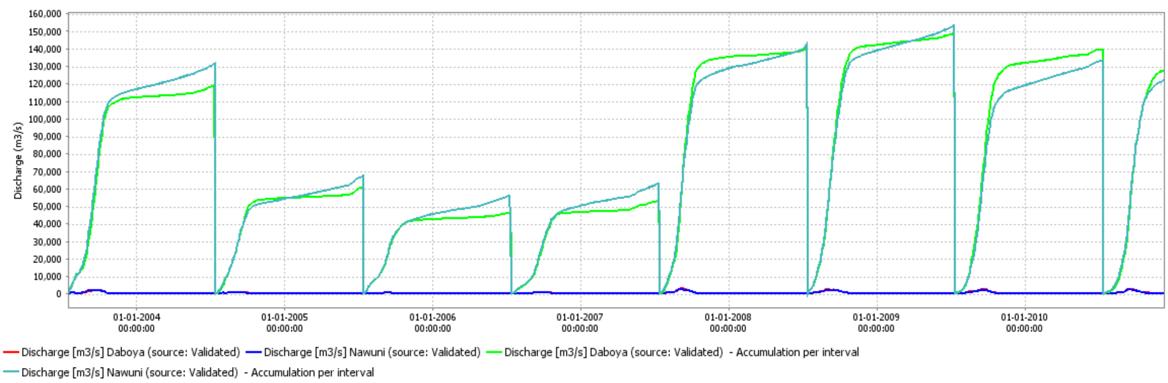


Figure 4-2 Example of a statistical function in WIS-Volta: accumulated discharges per year

4.2.4 Disseminate data

Data can be exported by:

- Copying and pasting to excel from the table view.
- Copying and pasting the graph picture.
- Exporting the graph picture as a file.
- Exporting the data series as a file.

In this format it is easy to disseminate data.

4.3 Step 2: FEWS-Volta

4.3.1 Import data

Precipitation

During the project it became clear that it was not possible to receive real time meteorological data or hydrological data from the gauging stations owned by GMET and HSD. Instead a daily meteorological forecast was made available through Institute for Meteorology and Climate Research, Karlsruhe Institute of Technology (KIT). The meteorological forecast is based on on MM5, version 3.6 and developed by Johannes Werhahn and Harald Kunstmann of the Atmospheric Environmental Research Division (IMK-IFU), also see http://www.imk-ifu.kit.edu/wetter/wettermenue_a.php. Appendix F describes the meteo forecast in more detail. Every morning FEWS-Volta downloads the 5-day precipitation forecast from an ftp-site (if internet connection is available) after which it can be imported by the forecaster.

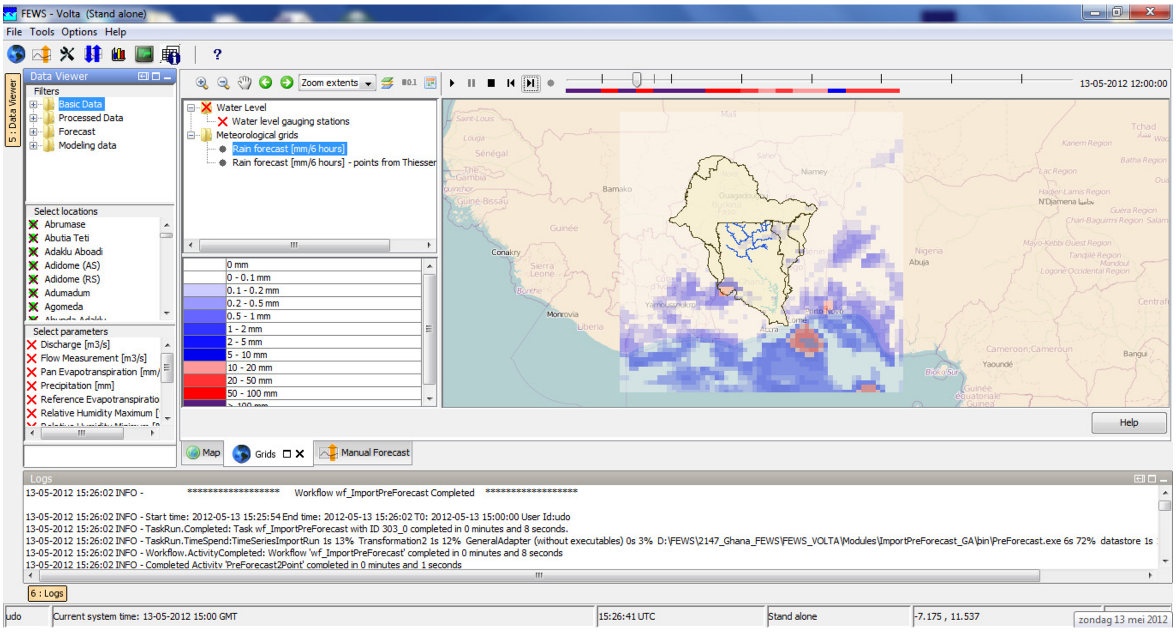


Figure 4-3 Meteoforecast made visible in FEWS-Volta

Evaporation

A default monthly-based evaporation series is generated derived from the evaporation as calculated within this project and described in Report Deliverable 3 (HKV 2012) and will be used for all RR-models.

Upstream boundary

- Discharge at Yarugu

The inflow at Yarugu can be calculated by using an estimation of the Bagre outflows. A monthly average discharge will be made available for the whole year. When Bagre dam is about to spill, Sonabel (operators of Bagre in Burkina Faso) provides a 2 weeks heads up. The FEWS-Volta operator needs to assess, in consultation with Sonabel and VRA, what the value and period of spillage is and must be able to *manually import* the values in FEWS-Volta.

- Water level at Yarugu

A second option to define the upstream boundary of the system are water levels at Yarugu, however these are more difficult to estimate and at this moment not measured as far as we know. They also need to be *manually imported* in FEWS-Volta.

Downstream boundary

The water level at Akasombo dam is available at VRA, who will send by mail, text or phone every day the water levels at Akasombo dam to the FEWS-Volta operator. The operator will manually input this measured value in FEWS-Volta. It is not a problem if the system lacks a few days of this data series because Sobek will simply use the most recent value and the water levels at Akosombo change very slowly during the year.

4.3.2 Process data

Precipitation

- Accumulate the 6-hourly data to daily data, needed to run the hydrological models.
- Convert the daily data to the relevant meteo stations by using a Thiessen aggregation to the relevant meteo stations.
- The meteo forecast series per station are combined with the meteo forecast from the previous days and rainfall measurements (not available at this moment). More recent forecasts overwrite previous forecasts, meteo measurements overwrite the forecast.

Other

- The three lateral distributed inflows calculated with the RR-model are divided by the length along which they are distributed in the White Volta 1D model.
- All necessary hydrological data is converted to 6-hourly data and converted to the proper Sobek format. 6-hourly data is needed to run the hydraulic model.

4.3.3 Run models

FEWS-Volta uses

- Rainfall runoff models from the White Volta tributaries and lateral distributed catchments.
- Hydraulic model of White Volta.

The models can be activated from the *Manual forecast* in FEWS-Volta. The model input and output can be checked as well, as illustrated below.

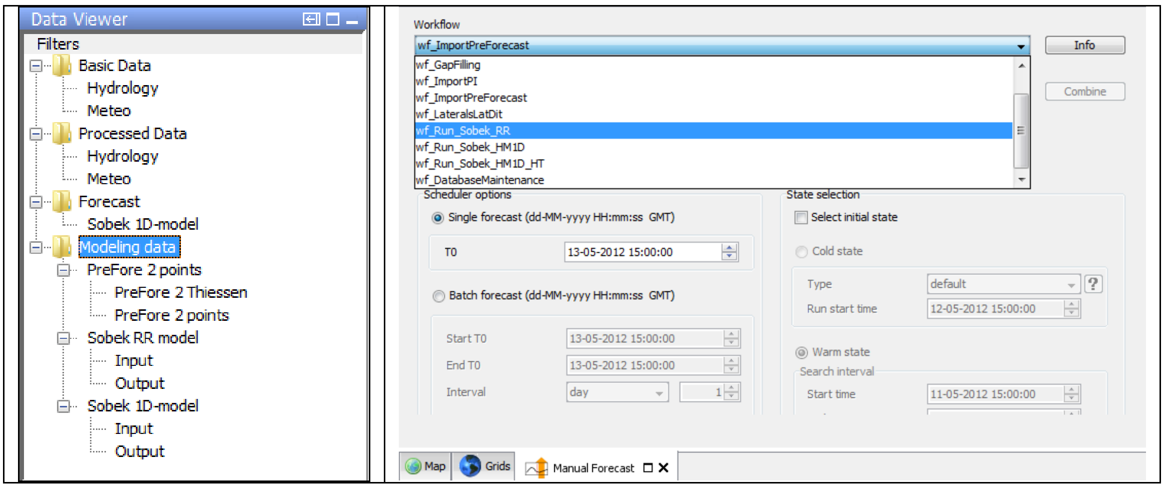


Figure 4-4 FEWS-Volta: operate models, checking model input and output

All default settings are related to the computer system time. At the moment this means that FEWS-Volta calculates a 7-day forecast with the 1D-model, based on 14 days hind cast, chosen as initialisation period. The RR-model calculates with a 2 years hind cast period. The initialisation period for the RR-model is much longer because:

- The processes modelled in the RR-model can influence model outcome for a very long period (more than a year, depending on the type of area).
- The RR-models have very short calculation times. In this case several seconds to calculate 2 years, for the whole White Volta. The hydraulic model calculates about 10 minutes for 21 days.

4.3.4 Present data

FEWS-Volta presents the water level forecast at the hydrological gauging stations. For each station a trigger was defined, based on the inundation calculations from the 2D model. The triggers were presented to the stakeholders and will be assessed during the 2012 rain season. When the trigger is crossed an alert is shown. The alerts are shown in the filter and in the map view.

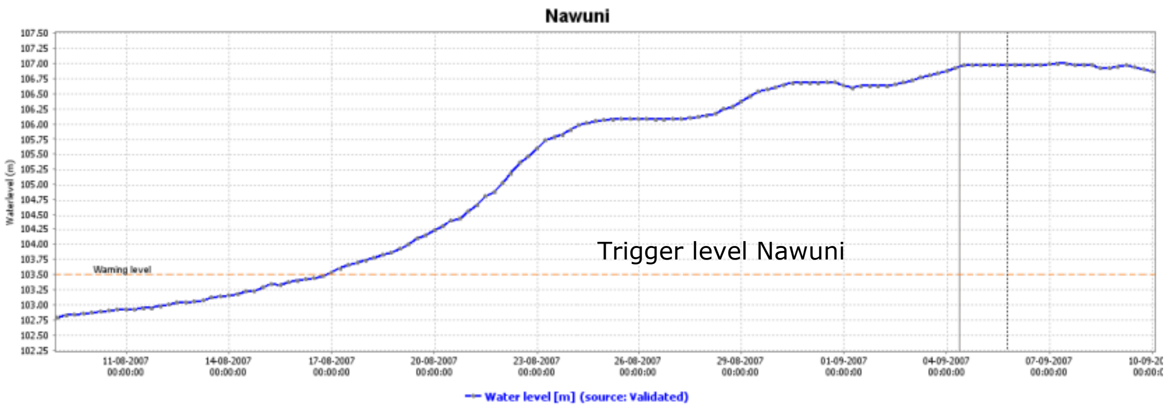


Figure 4-5 Crossing of the trigger level at Nawuni

The operator should check the results and decide whether he approves the forecast. When the operator approves the forecast he can export pictures or tables as described in the following paragraph.

4.3.5 Disseminate data

Data can be exported by:

- Copying and pasting to excel from the table view.
- Copying and pasting the graph picture.
- Exporting the graph picture as a file.
- Exporting the data series as a file.

In this format it is easy to disseminate data.
WRC is currently responsible for the forecasts and is able to put the forecasts on their website.

FEWS-Volta was made available to all stakeholders, however only the stakeholders with valid Sobek licenses will be able to reproduce the FEWS-Volta forecasts. At this moment it is not clear which institutes receive the final Sobek licenses.

4.3.6 Advantages FEWS-Volta

FEWS-Volta was set-up as a robust system, flexible and easily extendable by implementing the following:

- When no internet is available values can be imported manually and a forecast can still be made.
- When internet is available after being offline for some time, the system automatically picks up all data that was not imported yet.
- FEWS-Volta merges the meteo-forecast with the observed precipitation. When precipitation measurements are available (in the future) it will be taken into account.
- The user can choose whether to use discharge at Yarugu Kobori as a boundary condition or water levels. FEWS-Volta can also be easily extended with real time water level data for instance when the hydro-argos station at Yarugu Kobori will make real time water level data available.
- Multiple forecast runs can be made using different parameter values.
- Historical runs can be made as well using the historical database as described by WIS-Volta.

The FEWS-Volta forecasting procedure in which the stakeholders were trained is described in Appendix G.

4.4 FEWS-Volta experiences and recommendations

FEWS-Volta can be used to support relevant institutes to make flood forecasts- The forecasts and interpretation of the forecast need to be carried out by experts with experience in the field of meteorology and or hydrology, especially in the field of floods. They need to assess the forecast accuracy and how the forecast will develop over the coming days. They also need to distinguish the areas for which the warnings are valid. The latter can be done by using the flood hazard maps and 2D inundation simulations, which clarify to some extent what the inundation characteristics are like for different flood situations (see Report Deliverable 2 HKV, 2012 and paragraph 6.
The forecaster should decide whether to inform NADMO and what information is made available. At the moment all relevant stakeholders have the knowledge and equipment to create a flood forecast. However it is essential that all stakeholders realise and agree that the forecasting team from one institute is responsible for the forecasts, at the moment WRC.
When NADMO receives flood warning information it can inform the relevant municipalities and mobilise the necessary men and materials. Flood risk maps can be used to support evacuation of people and property.

FEWS-Volta is operational, mainly based on available real time rainfall forecasts (IMK-IFA, 2012). The forecast accuracy will be assessed in or after the 2012 rain season. In any case additional real time hydro-meteorological data will improve the forecast. Potential real time data flows are:

- Hydro-Argos stations on the White Volta, most important one being Yarugu Kobori. Some are already installed but not operational, some are planned to be installed. FEWS-Volta can be easily extended with new hydrological stations.
- GMET plans to install automatic stations. It is recommended to plan them in areas that are not properly covered at this moment, also see the conclusions in Report Deliverable 3 (HKV, 2012). It is recommended as well to make the data from the current stations real time available. FEWS-Volta is already set up in such a way that it automatically uses measured rainfall data if available.
- GMET is installing rainfall radars in Ghana. When this becomes available in North-Ghana FEWS-Volta can use this data to improve the forecasts. It is also possible to combine measured radar values to improve spatial distribution and measured ground stations to

improve the precipitated values. Such a combination can typically be configured in the FEWS-Volta software.

- When hydro meteorological data becomes available in real time on large scale, it is possible to set-up the system in such a way that the model results are assimilated (in this case replaced) with the most recent and accurate data available. For FEWS-Volta this would be the easiest assimilation method. A more pragmatic method to collect real time hydrological data is to provide the gauge readers with mobile phones and let them send real time water level data to Accra HSD office.
- Measured satellite rainfall data is available via TRMM (see http://trmm.gsfc.nasa.gov/) and can be included in FEWS-Volta. In October 2012 TRMM data was included in FEWS-Volta, also see HKV, FEWS-Volta Evaluation report (November 2012).

In discussion with all stakeholders it was concluded that HSD had the proper mandate to carry out the forecasts, but not the capacity. WRC was therefore assigned to carry out the flood forecasts for now. NADMO being the recipient of the forecasts also plays an important role in this. The sustainability of flood forecasting in Ghana can only be secured when proper institutional settings and capacity is available.

The forecast lead time for the larger part of White Volta is more than 3 days. However, when using Yarugu Kobori as model input, the forecast lead time between Yarugu and Pwalugu is limited to 0-1.5 days. To increase the lead time a proper discharge forecast or measurement from Bagre is needed in combination with the discharge from the catchment downstream Bagre, including the tributary Nouhao in Burkina Faso.

The models and parameters in FEWS-Volta are based on data available until 2010. The real time system has started in April 2012. As the RR-model that feeds the forecast uses 2 years to initialise, it is recommended to collect or reconstruct the data available for 2011. At this moment 2010 is used as initialisation period. In October 2012 TRMM data was used to fill this gap, also see HKV, FEWS-Volta Evaluation report (November 2012).

As stated before, FEWS-Volta will be evaluated during the 2012 North Ghana rain season. This should provide more information about accuracy and lead time, based on which new conclusions and recommendations will be made, also see HKV, FEWS-Volta Evaluation report (November 2012).

5 Flood genesis

5.1 Comparison of floods

The White Volta catchment in Ghana is still a relatively natural river, despite the two large reservoirs Bagre and Akasombo. When the wet season starts the soil will first absorb most of the rain. When the precipitation exceeds the evapotranspiration and storage is filled, the river discharge starts to build up. When the floodplains begin to inundate, old river arms start transporting water or retain it. This causes the floods along the White Volta and in the Nasia, Nabogo, Kulpawn and Sisili tributaries to build up gradually during the wet season, indicating that a *single* rainfall event does not trigger a flood.
The accumulation of rainfall events during the wet season is the main cause of floods in the White Volta project area. The water increase normally starts in August and takes at least a month to arrive at its peak. All relevant gauging stations in the project area show this trend except Yarugu Kobori, which is more steep and dominated by Bagre outflows, and the Red Volta, which reacts faster on rainfall events due to its steep slope and the narrow shape of its catchment.

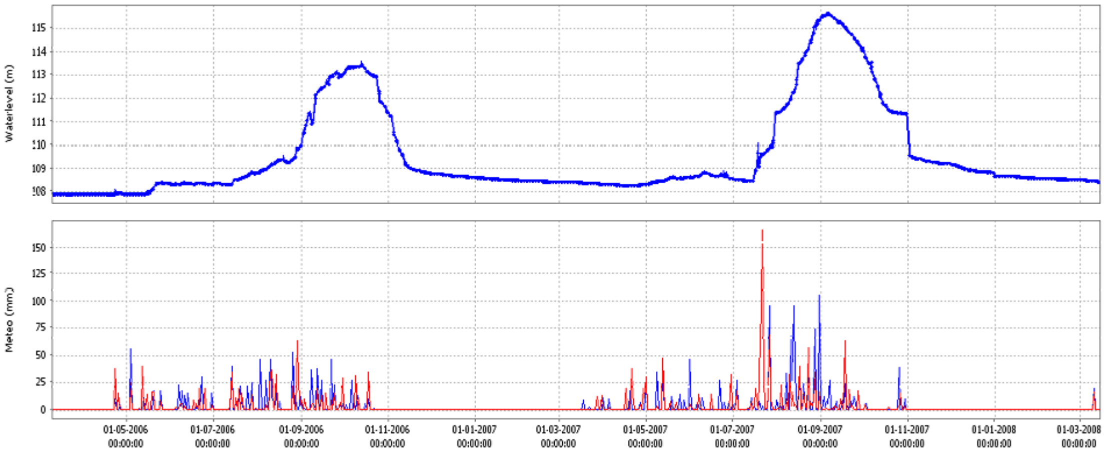


Figure 5-1 Gradual water level increase on Nasia during the wet season

The difference between an extreme flood event like in 2007 and a medium flood like in 2006 is mainly that in the 2007 wet season more rain precipitated and rapid succession of rainfall events occurred more often. The latter results in higher saturation of the soil and more surface runoff. Figure 5-2 illustrates this, showing the average annual precipitation for all 23 gauging stations in the area. The years during which floods occurred 2003, 2007, 2008, 2009 and 2010 show higher accumulated values compared to the years where floodplains were hardly flooded (2002, 2004, 2005 and 2006). Appendix H shows the difference from the annual average precipitation from the period 2000-2010. The "wet" years show more rain on most stations. The figure in appendix H illustrates as well which areas received most rain: 2003 shows relative high precipitation rates in the whole area, while 2007 shows even higher precipitation in the northern part.

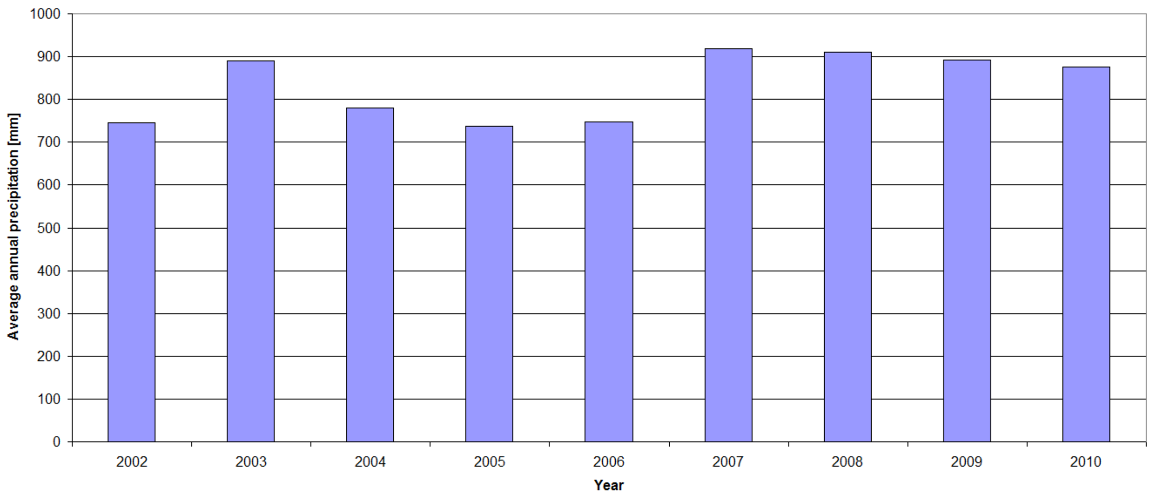


Figure 5-2 Average annual rainfall from the 23 meteo stations

5.2 Contribution of the different inflows

The contribution of the different inflows are made clear in Figure 5-3 showing the accumulated water volumes during the flood years of 2003 and 2007 at the different gauging stations and the tributary total (Wiasi, Yagaba, Nasia and Nabogo summed). The figure shows especially large differences in the upstream stations at Yarugu and Pwalugu, caused by substantial more rain in the northern part of the Volta basin in 2007 compared to 2003. Spilling of the Bagre dam also adds to the 2007 volume. The continuous volume increase in downstream direction is caused by the large runoff catchment that contributes to the Ghanaian part of the White Volta, also see Figure 5-3.

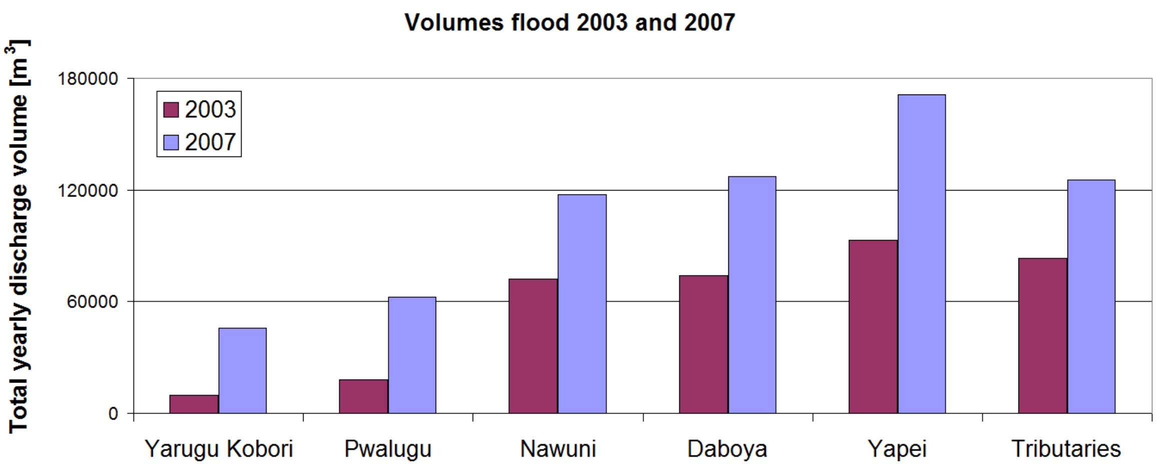


Figure 5-3 Volumes 2003 and 2007 floods at hydrological gauging stations

The effect of each inflow on the flood levels in the project area is determined by analysing the water level decrease of the maximum water levels when removing or decreasing the inflow and described in the following paragraphs.

Inflow from Burkina Faso

The Bagre dam releases water to keep the reservoir water level below 235 m+ref. Sonabel, the company that manages Bagre notifies the Ghanaian authorities 2 weeks before the expected spillage date. Figure 5-4 shows the estimated discharge at Yarugu Kobori when Bagre would not have spilled in 2007, assuming the water would have been stored in the reservoir.

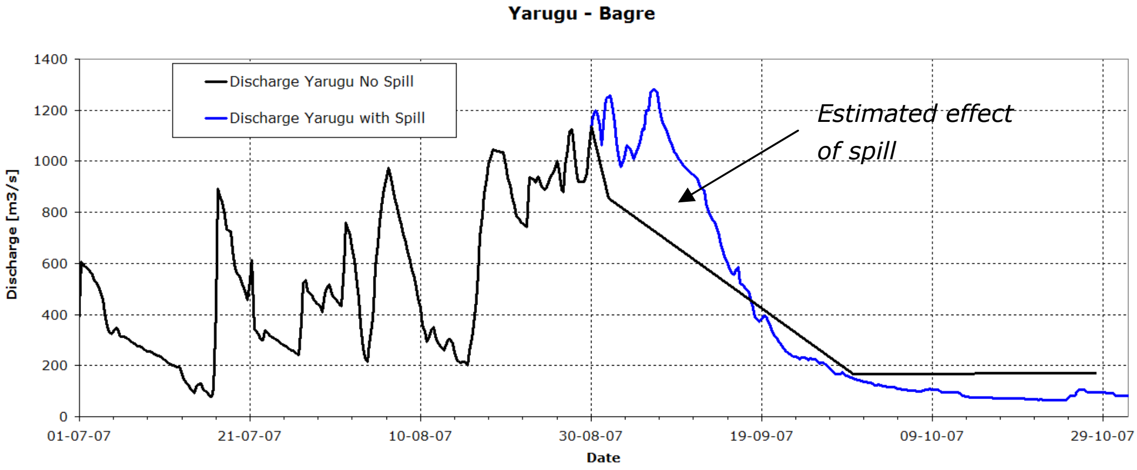


Figure 5-4 Discharge 2007 with and without Bagre release in 2007

A relative large tributary called Nouhao flows into the White Volta Just upstream of the border with Burkina Faso. The catchment between Bagre and Yarugu also discharges water. The effect of the total inflow from Burkina Faso is illustrated by removing the complete inflow from Burkina Faso as shown.

Both scenarios were simulated with the hydraulic model and the effect on the maximum water levels in 2007 was determined. Figure 5-5 shows the effect: the Bagre spill caused almost 1 m water level increase in 2007 between Yarugu and Pwalugu, however the effect is minimal downstream of the confluence with Kulpawn. The total inflow of water from Burkina Faso lead to a maximum increase of 6 m, minimised to 1 m downstream of the Kulpawn confluence. This shows us that spilling of the Bagre dam is not the biggest flood contribution to the Ghanaian part of the White Volta.

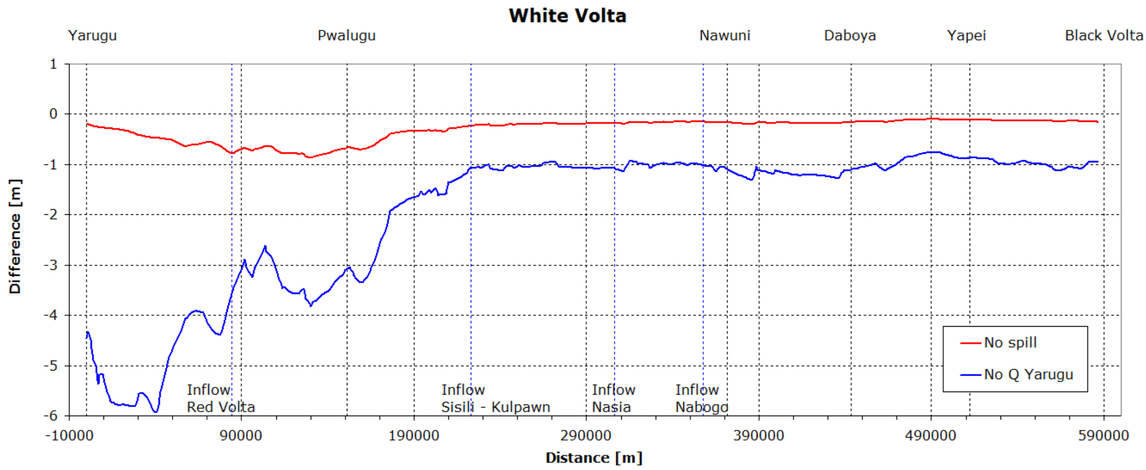


Figure 5-5 Effect of inflow from Burkina Faso on White Volta maximum water levels

The effect of the 2007 Bagre spill on the area downstream of the Kulpawn confluence, where the flood risk is higher, cannot be seen in the flood extent. The upper White Volta are is less prone to floods in general and the effect of the Bagre spill on the flood extent is limited as well as shown in Figure 5-6.

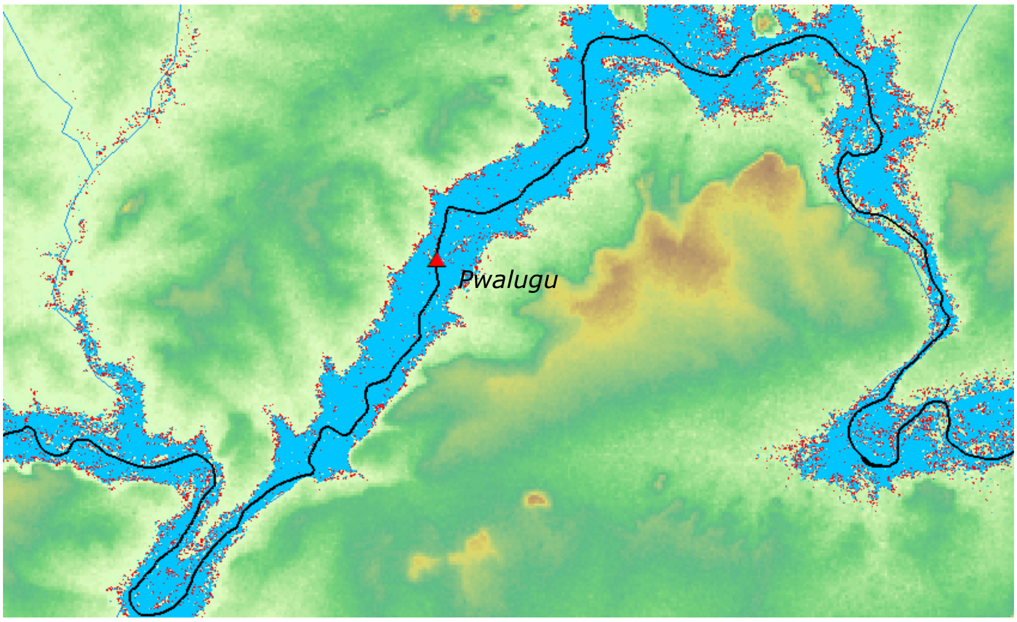


Figure 5-6 Effect of Bagre spill on the upper White Volta: blue without spill, red extra extent with spill

Large tributaries

The tributaries form a large part of the total flood wave volume, but are individually not dominant. Figure 5-7 and Table 5-1 below illustrate the effect of the larger tributaries on the White Volta. The Red Volta is a relatively steep river in which flash floods develop due to heavy local rainfall. The Red Volta is the largest tributary in the White Volta.

Tributary	Maximum [m]	Average [m]
Sisili	0.22	0.18
Kulpawn	0.35	0.30
Nasia	0.45	0.30
Nabogo	0.18	0.15
Red Volta	1.80	0.50
No spill Bagre	*0.22*	*0.13*

Table 5-1 Effect of the tributaries and Bagre on White Volta water levels between Kulpawn confluence and Lake Volta

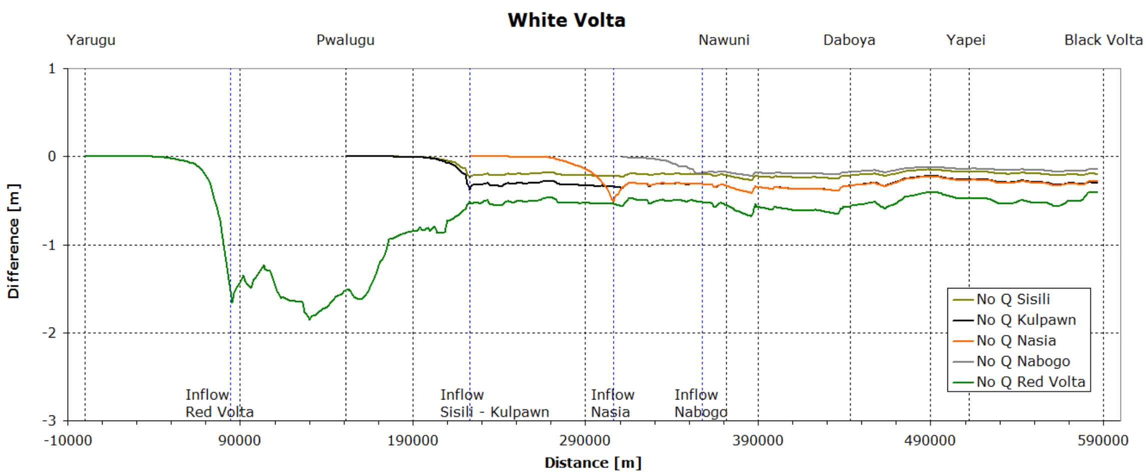


Figure 5-7 Effect of the main tributaries on White Volta maximum water levels

Backwater effect

High levels on the White Volta River cause increased water levels on the mild sloped Nasia and Nabogo Rivers and coincide with increased or even peak discharges on the Nasia and Nabogo Rivers. Figure 5-8 shows that the backwater effect on both tributaries is similar and the backwater length extents further than the model boundaries at Nasia and Nabogo. The figure shows that 1 m water level difference leads to 0,5 m water difference at the gauging stations of the tributaries.

The backwater length by the White Volta on Kulpawn River is less than 15 km, which means that floods on the Kulpawn are caused mainly by the tributary flood waves. The backwater length of Kulpawn on Sisili River is about 7 km.

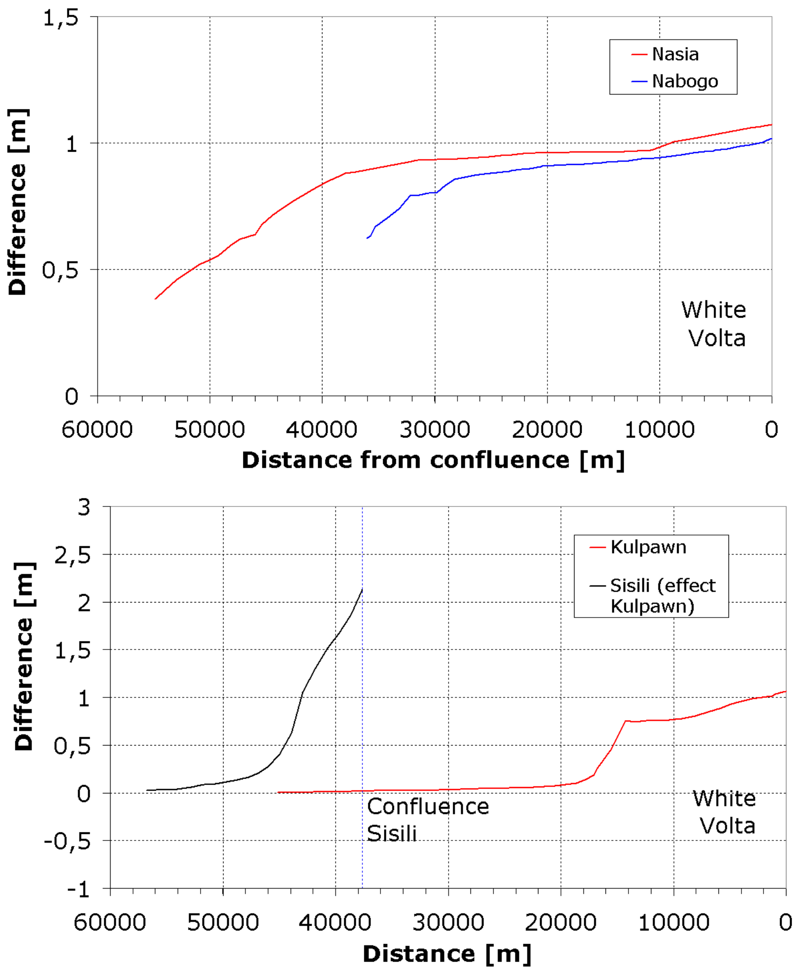


Figure 5-8 Backwater effect on the main tributaries

The backwater effect of Lake Volta can cause the flood level on White Volta to increase, however this was not the case between 2003-2007 because the lake levels were relatively low. The maximum backwater effect of Lake Volta is illustrated in Figure 5-9 and shows that the effect is negligible at Yapei.

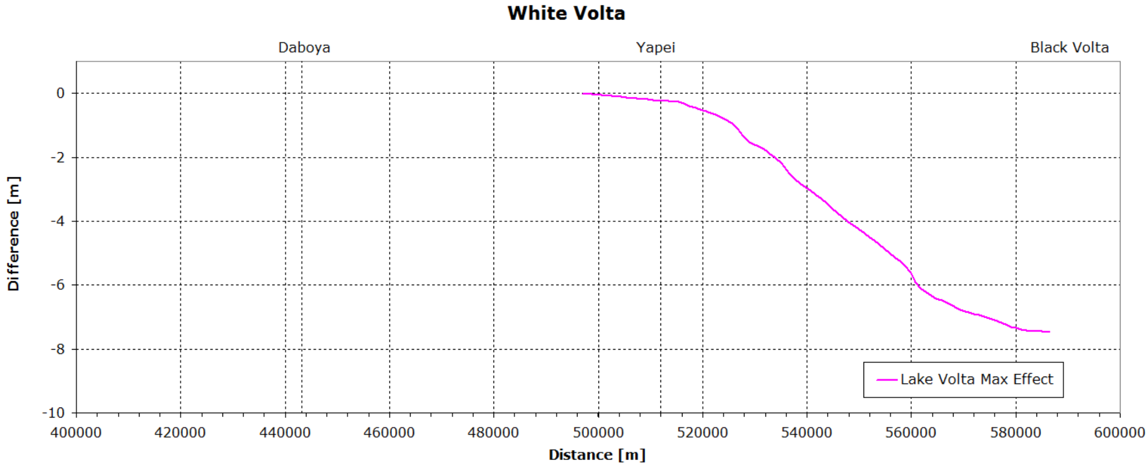


Figure 5-9 Backwater effect of Lake Volta

5.3 Conclusions

Single events do not cause floods, accumulation and rapid succession of rainfall events do. Spilling of the Bagre dam has limited influence, however during finalisation of this project extremely large and long spilling from Bagre resulted into floods around Yarugu. Downstream Pwalugu the flood wave was dissipated and effects were limited. The total inflow from Burkina Faso mainly affects the sector between Yarugu and the Kulpawn River confluence.

Flood waves on the tributaries and on the White Volta are gradually build up during the same period in the wet season lasting more than a month. This means that the flood waves of the tributaries and White Volta always coincide. On the other hand, single tributaries have limited influence on the White Volta. Flood mitigation measures in tributaries therefore have no flood relieve effect on the White Volta River, except when flood mitigation measures are taken in all tributaries.

6 Flood hazard and risk mapping

6.1 Method hazard maps

Flood hazard maps are defined as maps that show the danger of flooding as a result of the coincidence of probability and intensity of a flood event. This means that in order to develop flood hazard maps we need to define the frequency of occurrence which can be done with:

- Long-term discharge data. It was concluded that long-term discharge series cannot be reconstructed.
- Scenarios based on historical rainfall data and models. It was concluded that long-term rainfall series could not be reconstructed.
- Annual flood peaks combined with estimation of the flood wave shape.
- Historical Landsat images. The images show very clearly what the extent of the floods during the last 10 years was.

It was decided to define the frequency of occurrence of the yearly historical flood events on basis of discharges at Nawuni (determined with the rating curve that was generated in this study), see Figure 6-1 and Table 6-1. The floods that occurred the last decade dominate the top 10 highest floods. The figure shows also that the top 5 floods have similar peak values with theoretical return periods ranging from 10 to 100 years approximately.

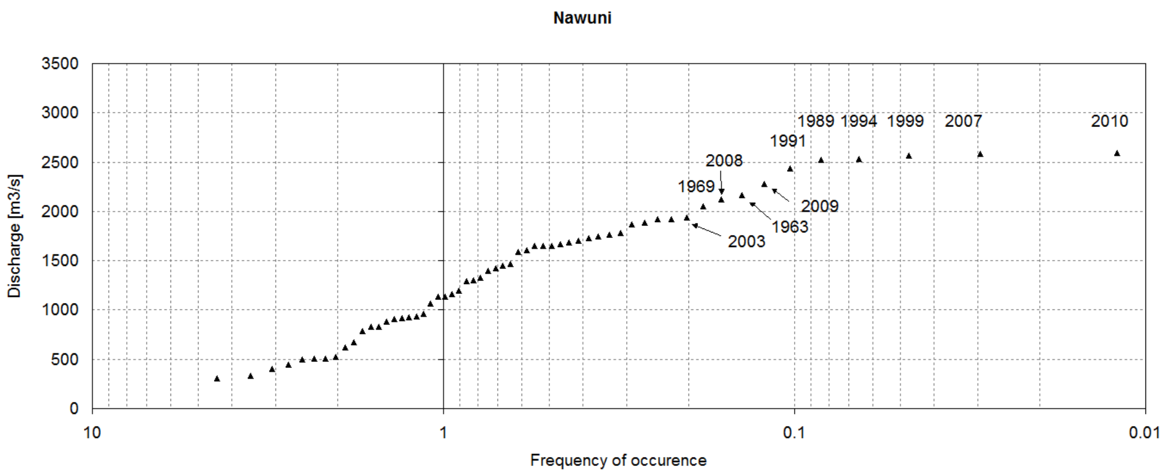


Figure 6-1 Return periods annual maximum discharges at Nawuni

Discharges at Nawuni are most reliable and complete. As an example Figure 6-2 shows the return periods of annual discharge maxima at Nawuni and Pwalugu. Clearly Nawuni contains more data. Also Pwalugu is influenced by local effects, while Nawuni is more representative for the complete Ghanaian White Volta catchment and most flood prone areas are in this part of the White Volta.

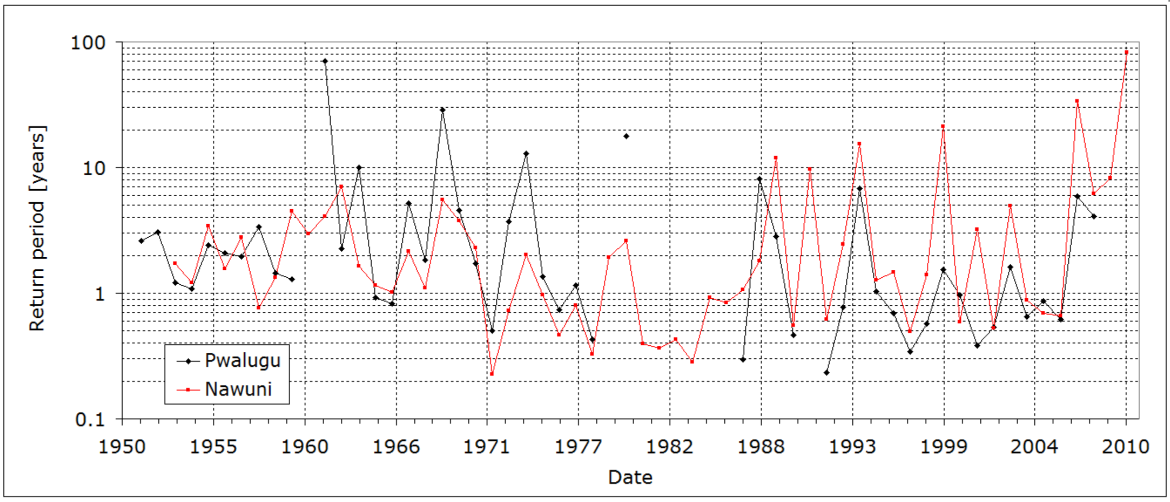


Figure 6-2 Return periods annual maximum discharges at Nawuni and Pwalugu

Discharge	Year	Return period	Discharge	Year	Return period	Discharge	Year	Return period
2593	2010	82.9	1685	1971	2.3	935	1986	0.8
2585	2007	33.9	1669	1967	2.2	924	1977	0.8
2562	1999	21.1	1652	1974	2.0	917	1958	0.8
2531	1994	15.3	1652	1979	1.9	907	1973	0.7
2523	1989	11.9	1652	1988	1.8	878	2005	0.7
2433	1991	9.7	1604	1953	1.7	831	2006	0.7
2280	2009	8.2	1588	1964	1.6	826	1992	0.6
2162	1963	7.1	1466	1956	1.6	789	2000	0.6
2122	2008	6.2	1451	1996	1.5	675	1990	0.6
2055	1969	5.5	1423	1998	1.4	617	2002	0.5
1940	2003	4.9	1395	1959	1.3	524	1997	0.5
1921	1960	4.5	1323	1995	1.3	510	1976	0.5
1921	1962	4.1	1297	1954	1.2	510	1983	0.4
1884	1970	3.7	1295	1965	1.2	499	1981	0.4
1866	1955	3.4	1199	1968	1.1	444	1982	0.4
1777	2001	3.2	1164	1987	1.1	403	1978	0.3
1759	1961	3.0	1131	1966	1.0	328	1984	0.3
1742	1957	2.8	1131	1975	1.0	309	1972	0.2
1725	1980	2.6	1063	1985	0.9			
1702	1993	2.4	961	2004	0.9			

Table 6-1 Maximum annual discharges at Nawuni and associated return periods

Flood hazard maps are required for return periods of 2, 5, 10, 25 and 50 years. From the figure and table above it can be concluded that maximum discharges and with that the flood hazard maps for 10, 25 and 50 years are very similar and can be represented by the 2007 flood extent map.
The 2003 flood represents the 1:5 years flood. The 1974 flood represents a 1:2 years flood event. Unfortunately due to lack of data it was not possible to simulate the 1974 flood event. Instead we decided to use 2003 as representative for a 1:2 years flood as well. This assumption is based on the relative increase of the flooded surface for different flood stages as illustrated in Figure 6-3. The figure shows a flood surface increase of 20% per meter water level increase.

The maximum discharges from 2003 and 1974 differ 288 m^3/s and the associated water levels 0.50 m, which is an approximate 10% difference in the flooded surface area.

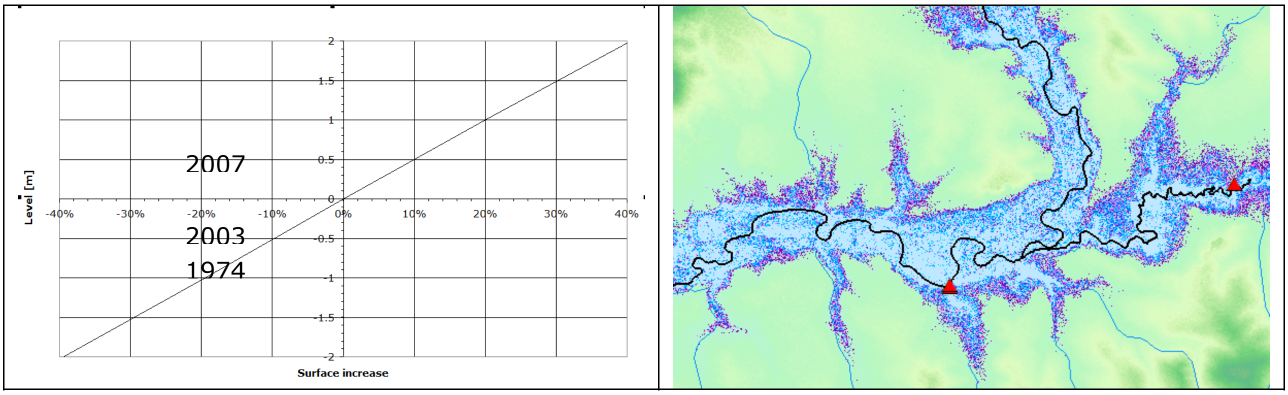


Figure 6-3 Surface increase for different flood stages: relative increase (left) and flood extent near Nawuni (right)

6.2 Landsat images as hazard maps

As described in the previous paragraph a set of historical satellite based flood images was collected for the floods between 2000-2010. The images show how many times certain areas were flooded during the last decade. This procedure is explained in more detail in Report GIS-database, HKV 2012.

6.3 Method risk maps

A flood risk map shows the potential adverse consequences of different flood scenarios. For the White Volta area the maps are built up with the following layers:

- Flood hazard maps showing the potential flood extent;
- Towns and villages with number of inhabitants;
- Roads and rivers;
- Digital Terrain Model or satellite image;
- Relevant objects like bridges or dams;
- District boundaries.

The flood risk is illustrated in a qualitative way when combining these layers in a map. Appendix I also explains which areas and communities are particular under flood risk.
The 2003 and 2007 calculated flood extents show computational blocks. We smoothened them for the purpose of visibility on the printed flood risk maps, also see Appendix I.

The land-use map as described in the GIS-database report [HKV 2012] is not very accurate and is therefore not taken into account in the risk maps.

6.4 Maps and results

The following maps were developed:

- Flood risk maps of the flood of 2007 showing the maximum water depth based on 2D calculations, representing 1:10, 25 and 50 years flood.
- Flood risk maps of the flood of 2003 showing the maximum water depth based on 2D calculations, representing 1:2 and 1:5 years flood.

- Flood hazard maps derived from all available historical flood extent images. These maps indicate how often flood prone areas were inundated during the last 10 years, based on 7 available flood images.
- Flood duration maps showing how long certain areas are inundated.
- Flood extent maps showing the flood extent and vulnerable areas for floods with a 2-5 years return period and 10-100 years return period, based on the smoothened calculated flood extent.

Based on several discussions with the stakeholders it was decided to:
- Make available all layers and maps in digital form as part of the GIS-database.
- Make available the flood extent in Google earth format, which enables the stakeholders to zoom in to their desired mapping scale.
- The flood extent maps of 2003, representative for 2-5 years return period and 2007, representative for 10-100 years return period will be provided at a scale of 1:50000 at A0 hardcopy format to the Client and relevant stakeholders.

Some examples are shown in appendix I. Additionally animations of the 2007 and 2003 floods illustrating the inundation process are available, also illustrated in appendix I. The maps are also described in the GIS-database report [HKV, 2012].

6.5 Conclusions

The flood hazard and risk maps that were developed show potentially flooded areas in terms of water depth as well as how often areas were flooded in the last 10 years based on 7 available flood images. Both maps show similar flood extents and clearly delineate the flood prone areas. The vulnerable areas at the moment are defined as towns, villages and infrastructure. The flood extent maps that were provided in hardcopy delineate the flood extent for 2-5 years return period as well as the flood extent for 10-100 years return period. All other maps and layers are available in digital format.

From the maps it can be concluded that little information is available about vulnerable areas: the land-use map is questionable and the locations of vulnerable objects like hospitals or schools are not known. Most vulnerable areas are (just) outside the flood prone areas. Based on this the question is where and how flood damages occur(red) in the region. During several discussions it became clear that more fieldwork is needed to properly map where vulnerable objects are located, like schools and hospitals. But also more historical data on flood impact is needed. This can only be done with large-scale field operations before and after floods. Field observations and satellite maps should be used to improve land-use maps in the future and to incorporate them in the risk maps.
The flood risk maps developed, methods used and recommendations provided in this study will be used by NADMO to develop flood hazard maps within a UN project NADMO has set-up, in which hazard maps (including flood hazard maps) for all of Ghana will be made. This is explained in chapter 8 as well.

7 Flood mitigation measures

7.1 General

In discussion with the stakeholders it was decided to assess the following flood mitigation measures:

- Flood retention in tributaries,
- Reservoir near Pwalugu, including analysis of reservoir operation,
- By-pass near Nawuni and
- Flood forecasting system.

The flood genesis shows that retaining water in the tributaries will not have much effect on the White Volta flood levels, except for the Red Volta, also see Figure 5-7. Retention structures in tributaries do reduce flood impact in the tributaries themselves. Several retention structures in Nasia River were analysed, because the flood risk map analysis shows that Nasia River has large flood prone areas as well as several villages that are at risk, as illustrated in Figure 7-1. Within the study Hydrological and hydraulic assessment Sisili and Kulpawn basin commissioned by Wienco Ghana Ltd (HKV, October 2012), the potential flood mitigation effect of a reservoir in the Sisili and Kulpawn was assessed as well.

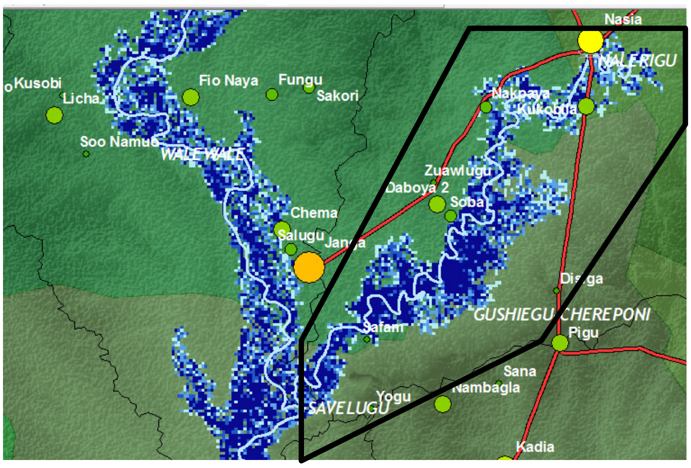


Figure 7-1 Flood risk Nasia River

The volume of water at Pwalugu is approximately 30% of the volume downstream the White Volta at Yapei. A reservoir near Pwalugu can store and manage this water volume and reduce the floods downstream Pwalugu. The Pwalugu reservoir, for which plans exists since the 90's is assessed and described in this chapter. The importance of proper operational rules of the reservoir is illustrated as well. A reservoir is de facto a structural measure, whilst the operation strategy of the reservoir can be seen as a non-structural measure.

The flood genesis shows that the effect of most flood mitigation measures decrease downstream of the confluence with Kulpawn River. A more effective measure for the area downstream of the Kulpawn are the construction of by-passes. A by-pass near Nawuni was analysed using the hydraulic model.

The flood genesis analysis concludes that floods on the White Volta occur due to gradual build-up of the flood during the wet season. A normal flood turns into an extreme flood by more rainfall events and less time between the events. It is possible to forecast these events and the resulting flood genesis. In other words, flood forecasting, a typical non-structural flood mitigation measure, can also reduce the flood impact drastically, with relatively little effort. However the accuracy and lead-time of the forecasts are very important parameters that define the efficiency of a forecasting system. During the next rain season the potential effect of FEWS-Volta will be analysed.

7.2 Retention in tributaries

Flood retention in tributaries can be carried out using different principles:

1. A retention area with a side weir inlet construction where water *only* inundates during high water levels can reduce a flood peak. The side weir is constructed parallel to the river and cuts off the peak of a wave if the inflow level is optimised for certain floods or operated based on a forecast of the flood wave that is expected. The principle of the flood effect is presented in Figure 7-2 as 1, where the peak is cut off (called *peak shaving*).
2. A reservoir with a fixed spillway can also mitigate floods, but mostly the smaller ones. During extreme floods the impounded area is filled up and the flood wave is hardly damped or mitigated. The red marked area (2) in Figure 7-2 shows that only the first part of the wave is stored, and that there is no effect on the peak level.
3. When a reservoir is operated larger flood waves might be mitigated as well, but this depends on the size of the flood, the reservoir capacity and especially the capacity that is reserved for flood mitigation. Most reservoirs also have an irrigation function where the objective is to store as much water as possible which conflicts with flood mitigation methods. The principle of an operated reservoir is presented as 3 in Figure 7-2: The blue line shows the reservoir outflow when a reservoir is operated: the reservoir is emptied during the rise of the flood, water is stored during the peak and flood water is released during the fall.

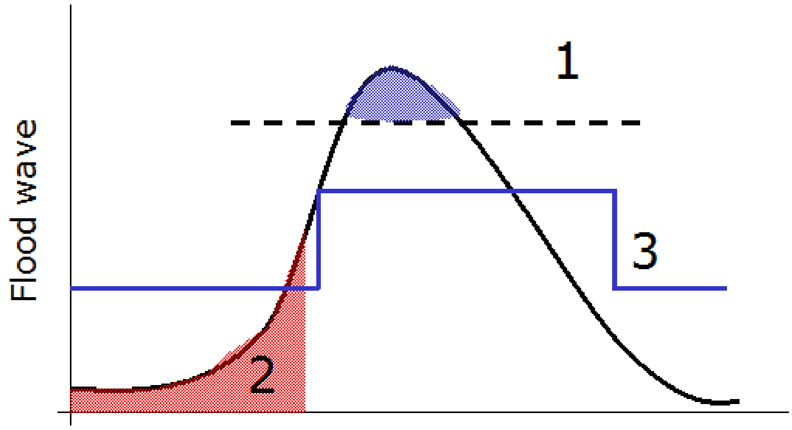


Figure 7-2 Principle of sire weir retention, retention with fixed inlet and operated retention area

The effect of measures 1 (side weir) and 2 (fixed reservoir) were assessed separately in the Nasia river. Measure 3 (operated reservoir) was analysed in the Sisili and Kulpawn basin according to HKV (October 2012).
Figure 7-3 shows the location of measures on the Nasia river: the retention area is confined by the south-north road through Nasia and higher grounds in the south. The reservoir dam is located at Nasia gauging station near the bridge. The reservoir area is confined by surrounding roads and higher grounds.

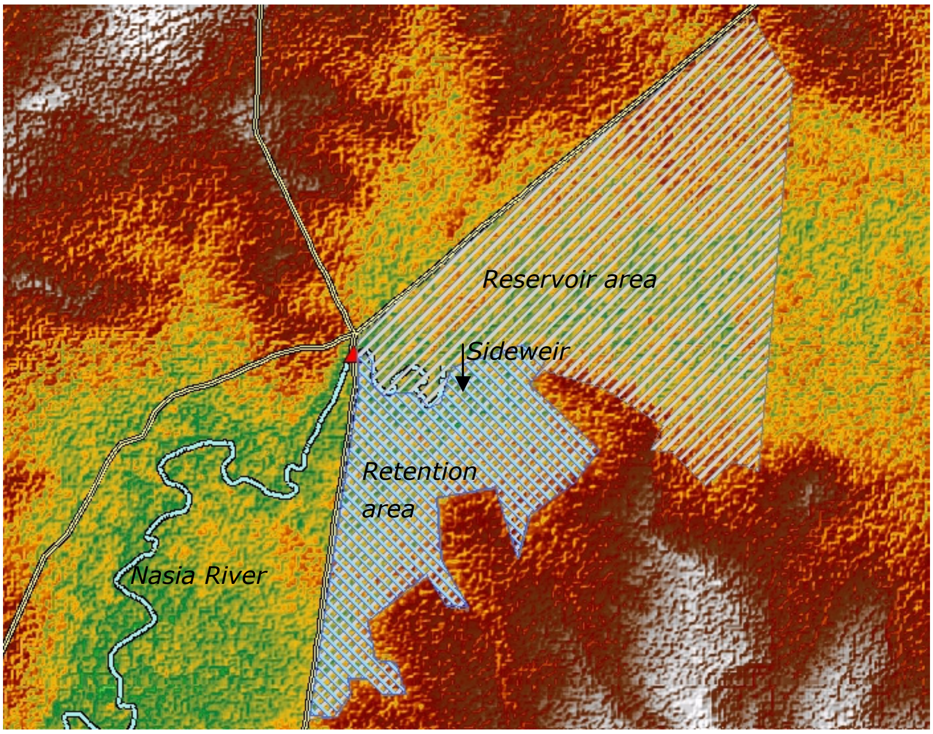


Figure 7-3 Location of retention area and reservoir near Nasia

Figure 7-4 shows that the reservoir stores water before the peak arrives. During the peak the reservoir is full and the maximum water level does not differ from the situation without a reservoir. The side weir crest level is fixed but optimised for the 2003 flood and results in a water level decrease of 0.3 m at Nasia slowly damping out in downstream direction.

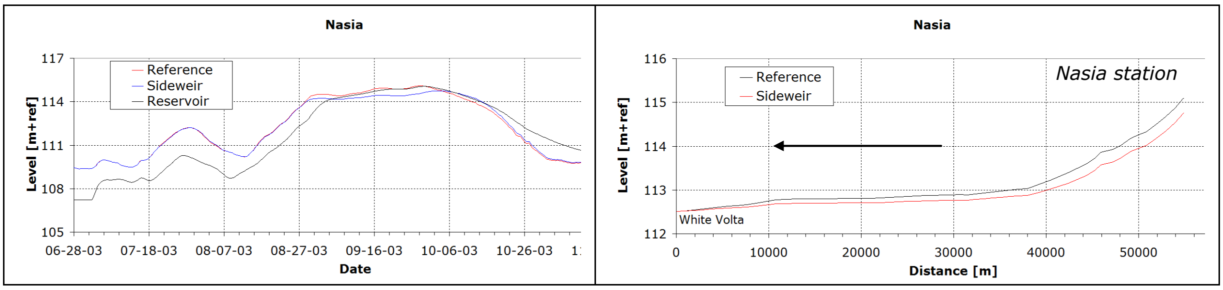


Figure 7-4 Effect retention area and reservoir on 2003 flood on Nasia river. Left: water level at Nasia station. Right: maximum water levels between Nasia station and White Volta confluence.

Several potential reservoir scenarios were defined in the Kulpawn River assuming a total reservoir capacity of 500 Mm^3. In order to illustrate the possible effect on floods we presented:

- Reservoir with a fixed spillway (fixed),
- Reservoir with operated spill gates (operated),
- Two reservoirs in cascade, both with a fixed spillway (cascade fixed),
- Two reservoirs in cascade, one with a fixed spillway and one operated (cascade fixed, operated),
- Two reservoirs in cascade, both operated (cascade (operated).

Figure 7-5 shows the effect on the 2007 flood wave at Yagaba for these different reservoir variants. The figure shows that most variants do not have effect on the maximum flood level in 2007, except for the operated cascade reservoir, which results in 2,5 m maximum water level decrease.

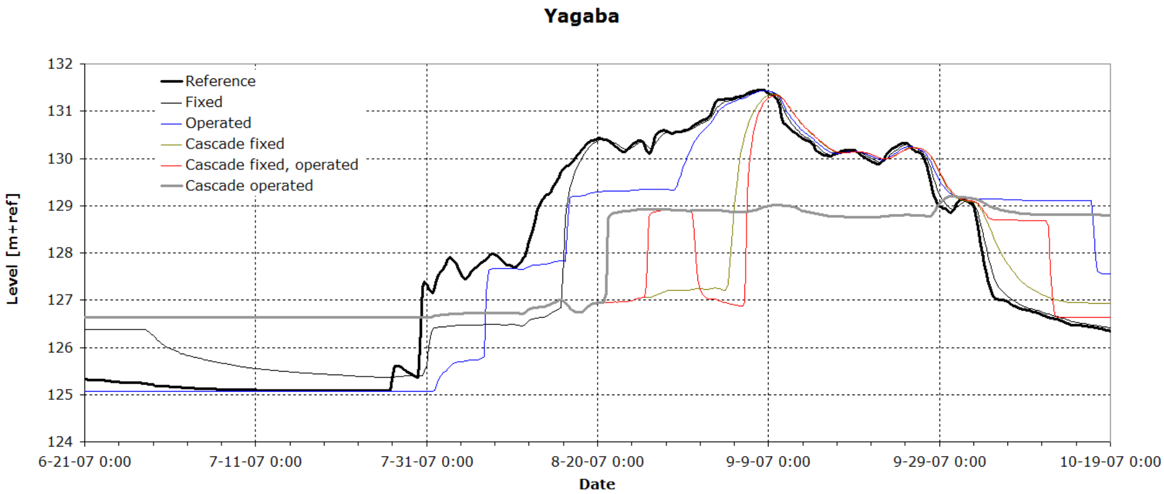


Figure 7-5 Effect of reservoir construction on 2007 floods at Yagaba, Kulpawn River

7.3 Pwalugu reservoir

7.3.1 General conditions

Two possible locations of the Pwalugu dam were analysed: Pwalugu West and Pwalugu East, as illustrated in Figure 7-6.

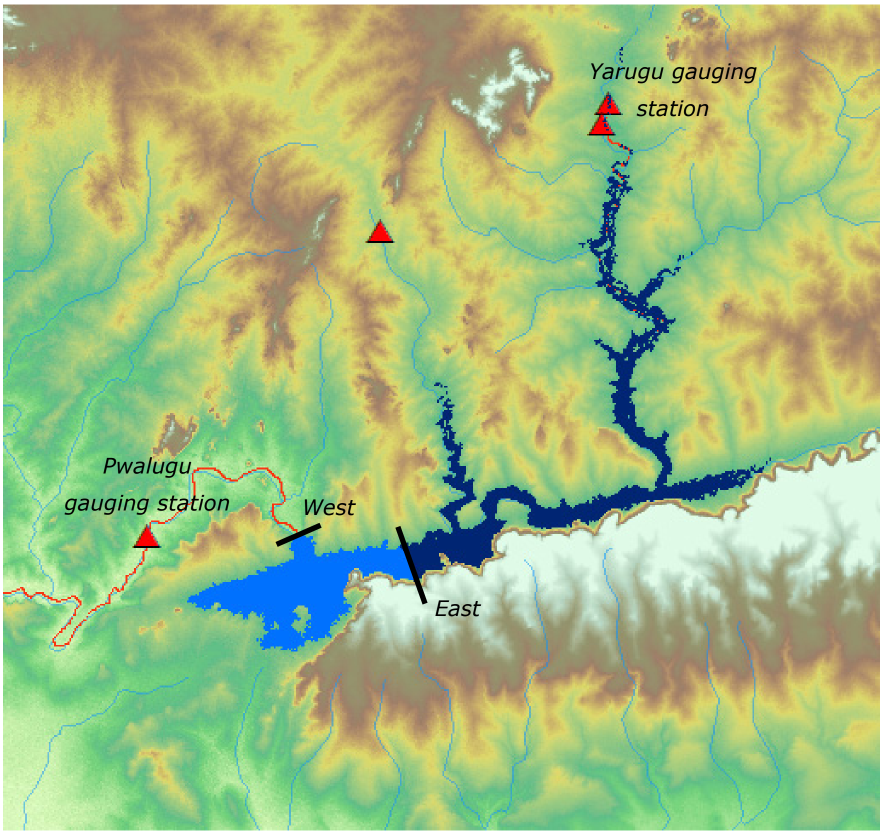


Figure 7-6 Potential reservoir locations Pwalugu West and Pwalugu East

The following assumptions were made based on information provided by the World Bank:

Parameter	Pwalugu West	Pwalugu East
Height	168 m+ref	168 m+ref
Surface	240 km^2	148 km^2
Volume	4729 Mm^3	1437 Mm^3
Turbine outflow	170 m^3/s	85 m^3/s

The following scenarios were defined, combined and calculated:

- Flood scenarios of 2003 and 2007 representative for 1:5 up to 1:100 years flood approximately,
- Two location variants, Pwalugu West (feasibility study) and Pwalugu East,
- Reservoir using only a fixed spillway (non-gated) at 168 m+ref and 200 m wide. This variant is not operated,
- Reservoir using a fixed spillway **and** gates to manage the reservoir outflow.

7.3.2 Results

The results are shown for the 2007 flood, location variants east and west, each showing the reference case (as it is now), a reservoir without operation using a fixed spillway as outflow structure and an operated reservoir using a fixed spillway and operated gates as outflow structures. Some of the resulting graphs are shown in the figures below.

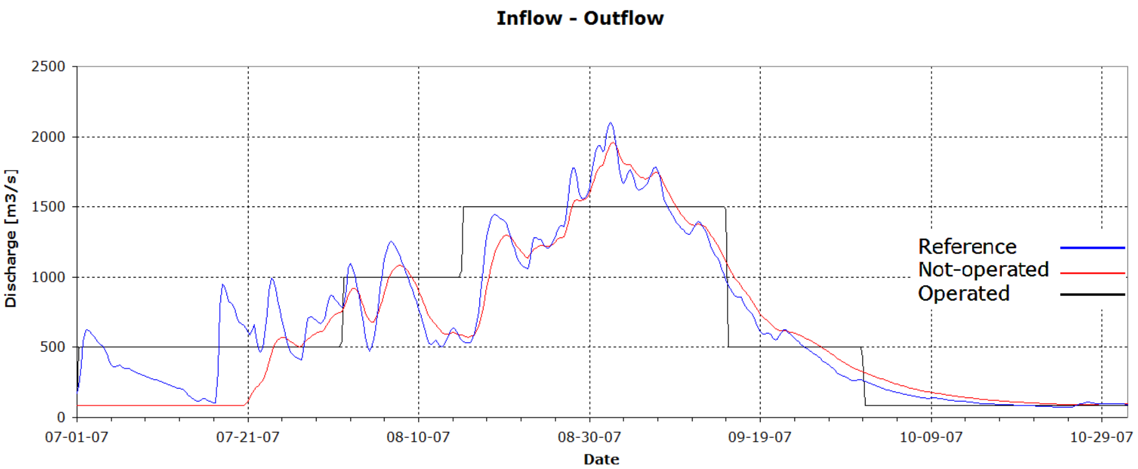


Figure 7-7 Pwalugu East: Compared to the reference case (no reservoir) the fixed spillway outflow shows hardly any change. The operated variant shows a decrease of the peak discharge of 25%.

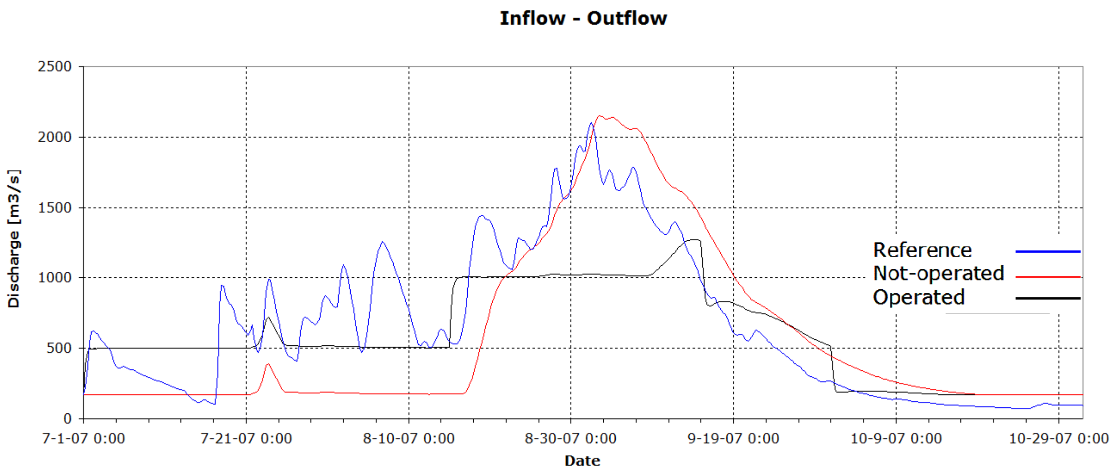


Figure 7-8 Pwalugu West: Compared to the reference case (no reservoir) the fixed spillway outflow worsens the situation. The operated variant almost halves the peak discharge. The reservoir level is shown for the fixed variant.

An analysis on the downstream effects was conducted for the Pwalugu West Variant. The effect is shown in the side view figure below. The figure shows the difference between the maximum water levels with and without an operated reservoir at Pwalugu West. The difference is the highest between the reservoir and the confluence of the Kulpawn River. After that the effect remains about 1 m.

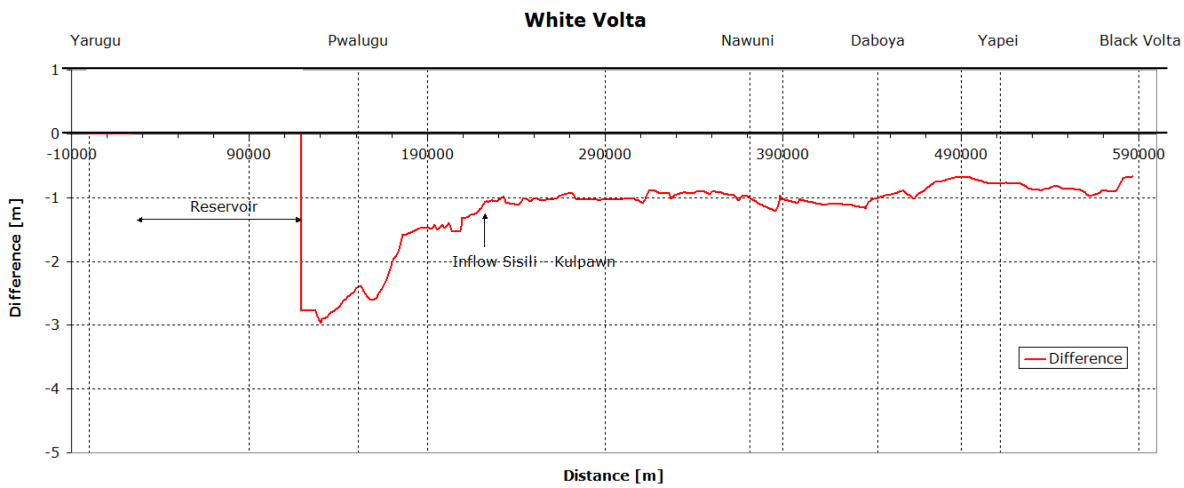


Figure 7-9 Pwalugu West: Decrease of maximum water levels for the 2007 flood

The effects on the flood extent are shown in Figure 7-10 below and confirms the side view analysis. The light blue shows the flood extent with Pwalugu West operational, the dark blue is the estimated 2007 flood extent. The total flooded surface along the White Volta decreases with about 10% the flooded volume decreases about 20%. This includes a decrease of 0.5 up 1 m in the flood prone Nasia and Nabogo rivers. There is hardly any effect in the Kulpawn catchment, as already concluded in the flood genesis analysis.

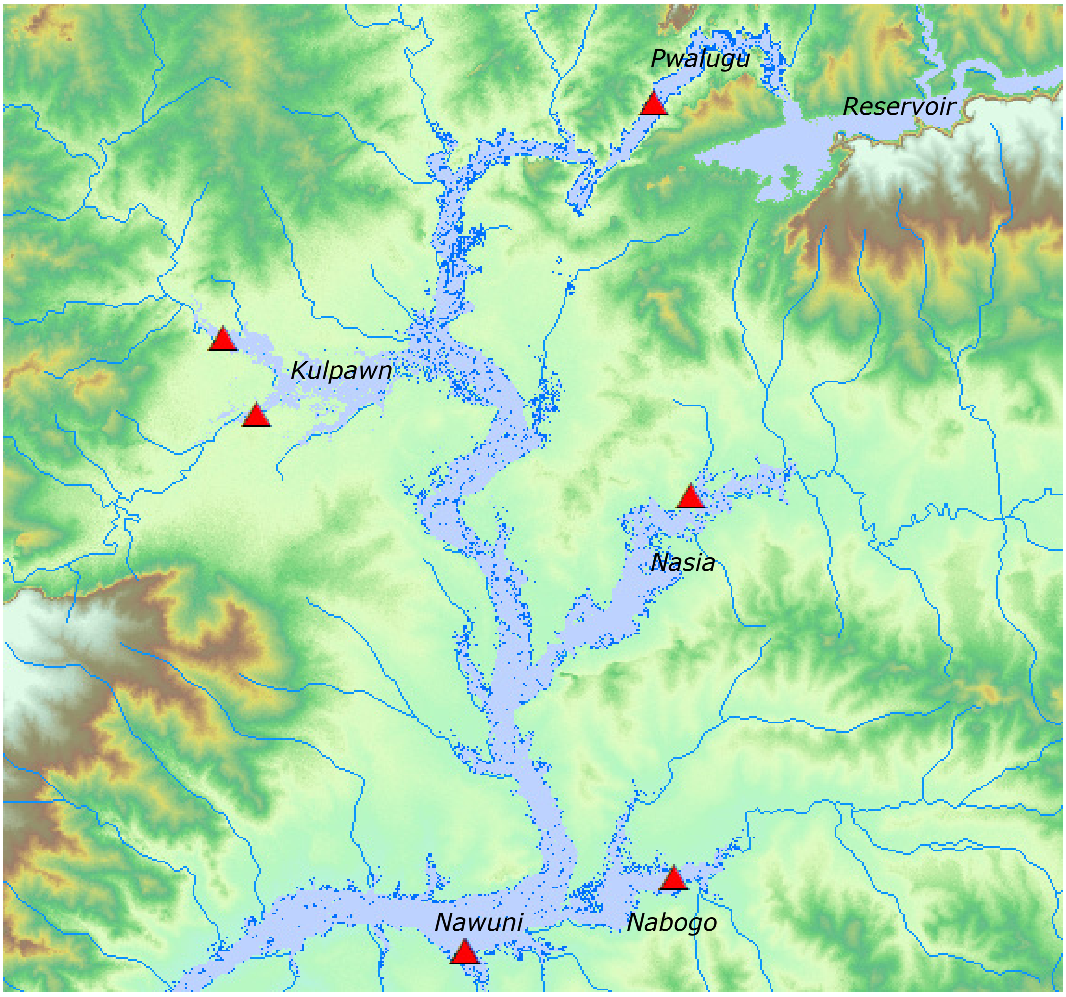


Figure 7-10 flood extent 2007 with and without Pwalugu-West reservoir

7.3.3 Conclusions

Variants

- Both reservoir locations mitigate the flood of 2003 with a non-operated fixed spillway.
- Both reservoir locations do not mitigate the flood of 2007 with a non-operated fixed spillway.
- Both reservoir locations mitigate the flood of 2003 with an operated outflow structure (like gates).
- The West Variant decreases the water level directly downstream of the reservoir with 3 m, the East Variant mitigates the flood level over 2 m when using the operated variant.

General

- From a flood protection point of view the Pwalugu dam can only have a positive effect when it is operated properly.
- The reservoir can decrease the flood extent of medium floods (up to 10 years return period) with around 50%. The flood extent of extreme floods as 2007 can be reduced with 10%.
- A controlled release structure (like gates as used for the Bagre dam in Burkina Faso) would improve flood mitigation downstream of the.

In order to properly manage the reservoir operation it is recommended to use a forecasting system, including the Bagre outflow. Other important flows to Pwalugu reservoir are Nouhao river, a tributary just upstream of the border with Burkina and the Red Volta, located just upstream of Pwalugu East.

7.4 By-pass near Nawuni

The White Volta River is a natural dynamic river consisting of a network of old river channels. During flood these old channels inundate, retain or even transport water. Also see Annex 1 and 2 deliverable 3 [HKV 2012] for a detailed description. The topography of old river channels can be used to transport more water in areas at risk, resulting in lower water levels during flood periods. Around gauging station Nawuni, the White Volta floodplains are very wide, while the river meanders heavily as shown in Figure 7-11.
Two flood mitigation measures were defined where the transport capacity of several old river channels was restored. Figure 7-11 shows measure 1, where only one river channel is restored (shown in yellow) and measure 2, where an additional number of 4 old channels are restored (shown in red).

Figure 7-12 shows the results. Measure 1 has a maximum effect of the maximum water levels in 2007 of 0.08 m. Measure 2 reduces the maximum water levels with 0.66 m. From this we conclude that by-passes have a significant flood mitigation effect when old river channels are restored over a considerable river length, not over short distances.

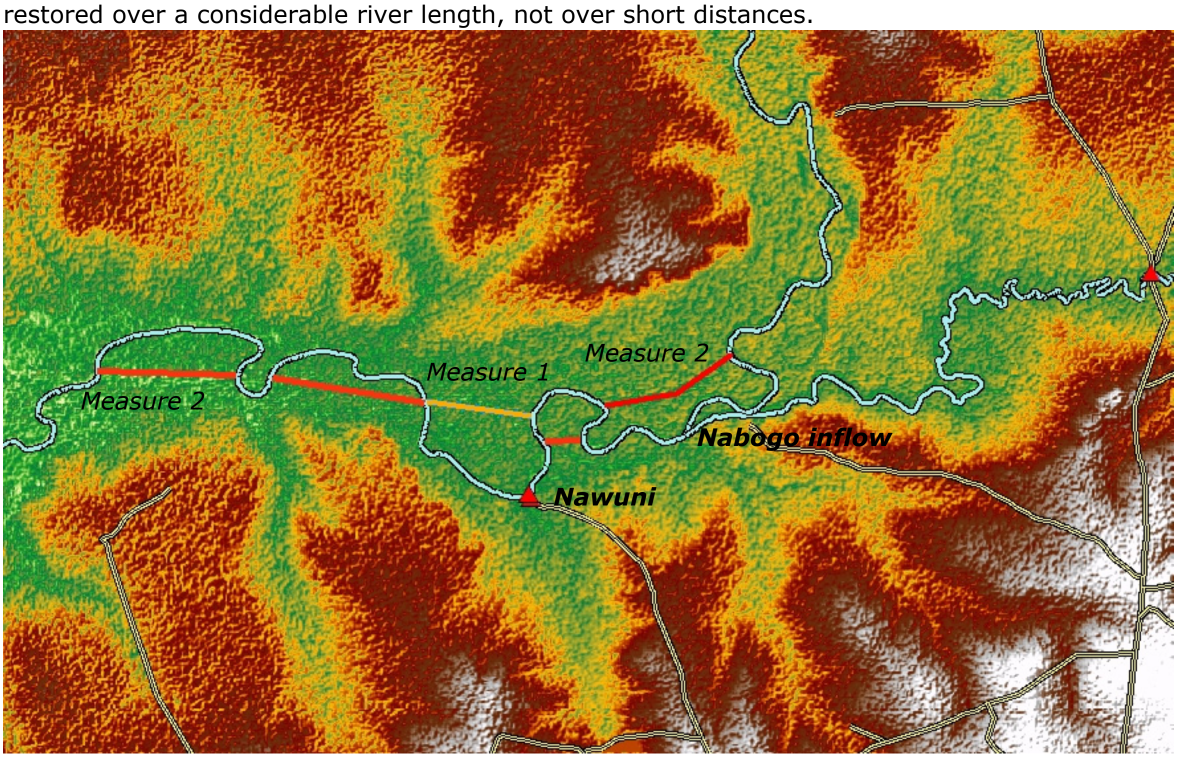


Figure 7-11 Location of restored old river channels near Nawuni

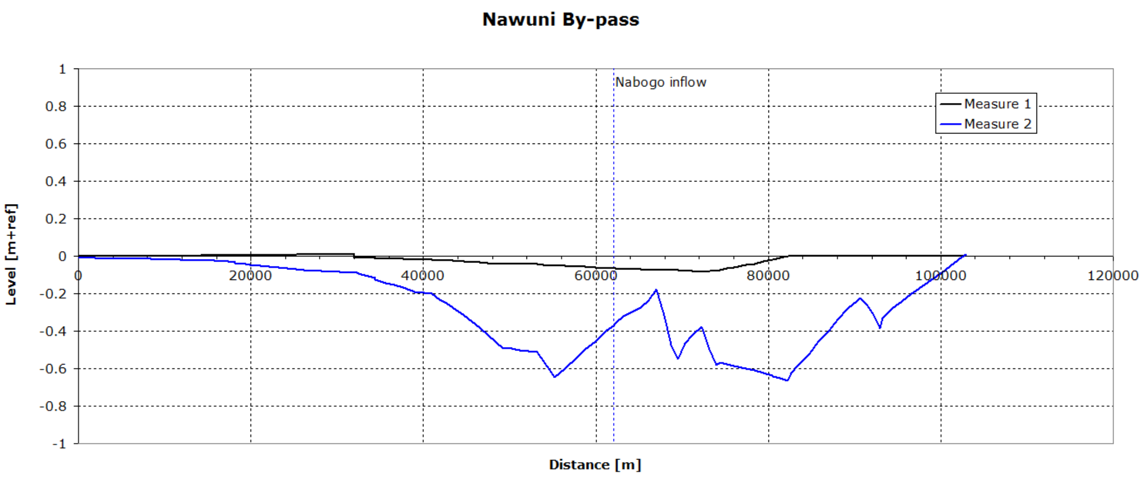


Figure 7-12 Effect on maximum water due to restoring old river channels on White Volta River

7.5 Morphological effects

When constructing reservoir or reopening old river branches, the river morphology will be affected. Reservoirs block sediment transport resulting in sedimentation of the reservoir lakes and erosion of the river downstream of the reservoir.
Figure 7-13 shows the sedimentation principles of a reservoir: the flow velocity drops as soon as the river widens when entering the lake. This causes suspended sediment to deposit mainly near the entrance of a reservoir. More coarse and heavy sediment deposits faster than finer material. This leads to more coarse material in the upper part of the reservoir and finer deposits in the lower part of the reservoir. The sedimentation of the Pwalugu reservoir and Sisili-Kulpawn reservoirs were analysed in van der Zwet (May 2012) and HKV (October 2012), from which it was concluded that the sedimentation rates are limited: the reservoir capacity of Pwalugu was reduced with 3% after 100 years and the Sisili Kulpawn reservoirs 4% after 50 years.

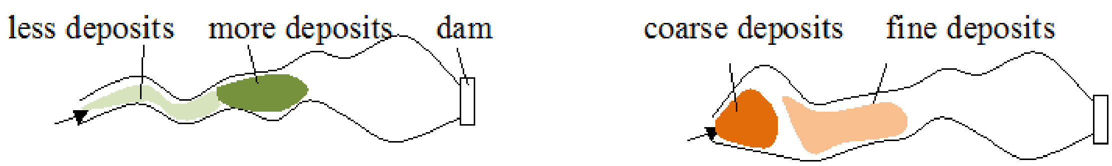


Figure 7-13 Principles of reservoir sedimentation

Erosion can have more potentially negative effects. Directly downstream of the reservoir erosion holes can develop. In time the holes deepen and move in downstream direction. In case of the Pwalugu reservoir, this might affect the Pwalugu bridge. A reservoir in the Sisili river might affect the bridge near Wiasi.

Sedimentation and erosion effects are typically long term. A more immediate effect is that reservoir construction causes the groundwater levels to reduce. Combined with riverbed deepening this results in relative high riverbanks leading to the collapse of riverbanks relatively soon after construction of the reservoir.

The morphological effects of by-passes have less impact and is probably more localised compared to reservoir construction. As the river bed capacity is increased, flow velocities decrease and more sediment is deposited locally. This disturbance will affect the morphology downstream as well. Horizontal river bed changes can also occur: when the water follows a different course, new river branches might develop and while old branches might close. The morphological effect caused by by-passes at Nawuni are difficult to assess, especially horizontal changes. Such an assessment requires additional information and more time.

7.6 Conclusion

Analysis of the flood genesis showed us that the areas between Yarugu and Kulpawn confluence are dominated by the inflow from Burkina and the Red Volta. When Pwalugu reservoir is constructed and operated it should be able to prevent future floods in this area. For instance a non-operated reservoir at Pwalugu could mitigate the 2003 flood (return period once in 2-5 years) and an operated reservoir at Pwalugu could even mitigate the 2007 flood (return period once in 10-100 yeasr). However large flood prone areas are located mainly downstream of the Kulpawn confluence, where the mitigating effect of Pwalugu is almost damped out.

Water retention from individual tributaries has no effect on the flood level in the White Volta River. Around flood prone areas the river capacity can be increased locally. Old river arms can be restored to create a bypass, decreasing the water levels during a flood in the area. Besides the Pwalugu dam it is not recommended to construct large structural measures to reduce the flood impact in the White Volta, because the effect is limited. It is better to assess and mitigate the flood impact locally where needed using tailor made solutions.

Structural measures in the tributaries *are* effective. Reservoirs or retention areas mitigate flood waves, as presented for Nasia and Kulpawn Rivers. In order to be effective a reservoir should be operated. Reservoir operation can be seen as a non-structural measure. Flood risk maps and flood early warning systems are also non-structural measures that help to reduce the flood risk in the area with relatively little investment. For proper operation of a reservoir the incoming flood wave should be forecasted. Especially for Pwalugu dam intense contact should be made with the Bagre dam management in order to react on flows coming from Burkina Faso. It would be optimal when Bagre and Pwalugu dam are considered as a cascade, meaning they are operated in cooperation to optimise flood mitigation. In this case it is recommended to extent the hydrodynamic model into Burkina including Bagre reservoir and the White Volta more upstream.

This paragraph also shows that the hydrological and hydrodynamic modelling system developed in this project can be used to assess different types of flood mitigation measures. Other usages are:

- In combination with the hydro-meteorological database more detailed models can be set-up to answer water related questions in any area in the White Volta catchment and to support policies or assess projects.
- HSD can use the models to assess their rating curves and in general use it to check their data.
- The flood hazard maps can help to plan the development of towns and villages as well as agricultural areas.

8 Input Emergency Preparedness Plan

FEWS-Volta

NADMO (Natural Disaster Management Organization) is an important stakeholder in the White Volta flood hazard assessment project. NADMO has indicated to be specifically interested in the flood early warning system. A NADMO employee has participated in the training sessions, during which the project outputs were presented, submitted and trained, including FEWS-Volta. NADMO should help in fine tuning the alert levels as defined at this moment. They have people in the field especially during the wet season that can provide valuable information about flood impact and alert levels.

Flood maps

NADMO is lead partner in a UN funded project that aims to develop flood hazard maps for all of Ghana. NADMO suggested to use the experience gained in the White Volta flood hazard assessment for their hazard-mapping project. NADMO can use the flood risk and hazard maps developed in this project as a start and improve and develop the maps by conducting field inspections, which are planned. For now the maps clearly show the villages at risk and possible escape routes. Appendix I also summarises the communities, areas and constructions at risk. In the future more detail should be made available and vulnerable objects should be identified. NADMO has indicated that they will conduct a large-scale field survey during which they will do exactly that.

Reaction time

The flood propagation in the White Volta can assist NADMO in prioritising their help to local people, depending on the source of the flood. The figure and table below show these propagation times. The values are indicative, meaning that during different floods the propagation times can differ as well.

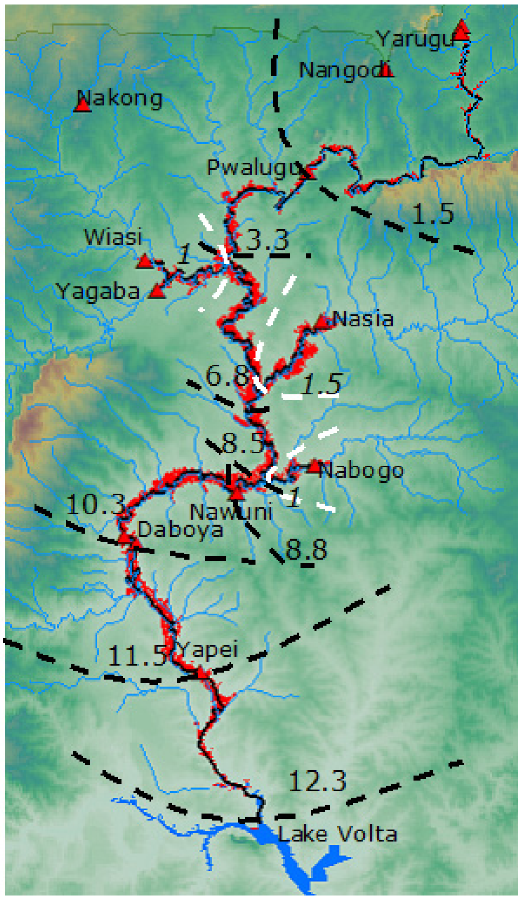


Figure 8-1 Propagation times in the White Volta

Location	Propagation time [days]	
	From Yarugu	**From previous**
Yarugu	0	0
Pwalugu	1.5	1.5
Kulpawn mouth	3.3	1.8
Nasia mouth	6.8	3.3
Nabogo mouth	8.5	1.7
Nawuni	8.8	0.3
Daboya	10.3	1.5
Yapei	11.5	1.2
Lake Volta	12.3	0.8
Wiasi - Kulpawn mouth	1	1
Yagaba - Kulpawn mouth	1	1
Nasia - Nasia mouth	1.5	1.5
Nabogo - Nabogo mouth	1	1

Table 8-1 Propagation times

9 Workshop and trainings

The following workshops and training sessions were organised until May 2012:

1. Hydrological data monitoring, data validation and correction;
2. Sobek 1D modelling;
3. Meteorological data monitoring, data validation and correction, Sobek Rainfall Runoff modelling;
4. Sobek 2D modelling;
5. Sobek 1D and 2D model calibration and application;
6. Flood forecasting and working with WIS-Volta and FEWS-Volta;
7. Flood forecasting and working with WIS-Volta and FEWS-Volta continued;

The programs of the 7 training sessions are summarized in appendix J.

The following stakeholders participated in the training sessions: HSD, WRC, WRI, NADMO, VRA, GMET and GIDA. The total number of participants varied between 9 and 14 and is listed in appendix J. In September and October 2012 training continued in the form of on-the-job training and working on day-to-day basis with FEWS-Volta in order to get used to the system and evaluate its possibilities and accuracy. The evaluation is reported separately in the FEWS-Volta evaluation report (HKV, November 2012).

Impression of the Sobek training session

10 Summary, conclusions and recommendations

10.1 Introduction

An adequate flood hazard assessment is generally a challenge for data poor areas like White Volta catchment. Smart, state-of-the-art, efficient and pragmatic methods and solutions, including a thorough validation of the available data, were needed to carry out the project and meet the objectives. In this chapter we describe in retrospective the most important challenges and results regarding the main objectives of White Volta Flood Hazard Assessment project.

10.2 Data and models

For data poor areas, which means that the area of interest is large compared to the available data, it is of the outmost importance that the data that is available is validated thoroughly. This appeared to be one of the most time consuming activities of the project. Not only did we validate i) the rainfall and ii) the evapotranspiration data, also iii) the water level gauge zero's (by re-levelling them in the field), iv) the water level data and v) the rating curves, that translate the measured water levels into discharges, were validated thoroughly. Much effort was put in the analyses of the available flow measurements and the resulting rating curves. After a thorough inspection of the available data, we decided that the best estimate of the rating curves would be the ones that were to be generated by the physically based hydrodynamic model that we were going to develop. To be able to construct this model, we executed a bathymetric survey of White Volta and the downstream parts of the main tributaries during the flood season of 2011. It took 3 months to complete this survey that had to be carried out in difficult circumstances (e.g. navigability problems occurred due to heavy vegetation on banks, fish nets in the water, rapids, etc. which forced the survey team to leave the zodiac and to continue with a small pirogue with all the equipment on and beneath it.). Moreover, a DTM was developed for the flood prone area based on SPOT Satellite Imaginary and ground control points that were surveyed in the field. The accuracy of this DTM is listed below.

Source Satellite Data	5m stereo satellite images (SPOT HRS)
Image Date(s)	Post 2002
Time of Collection	Approximately 10:30am local sun time
Cloud Cover	0%

Deliverable Parameter	Specification
DEM Type	Digital Surface Model – large land cover features will affect elevation values and cannot be filtered.
Posting	20 metre
Vertical Accuracy	3 metre r.m.s. (with high quality ground control)
Horizontal Accuracy	15 metre r.m.s. (with high quality ground control)
Contour Interval	5 metre
Projection / Datum	WGS84 / UTM Zone 31

Finally, we processed data of Landsat Satellite which gave us extend of the floods since the year 2000. This later on appeared to be a crucial factor for proving the quality of our models. An example of the flood extend on basis of Landsat data is shown in the figure below.

Figure 10-1 Example of the flood extent calculated from Landsat data: Number of years areas near Nawuni were flooded in the period 2000-2009.

The figures and table below show some typical examples of the calibration and validation result of the rainfall-runoff models of the tributaries and the hydrodynamic model of White Volta:

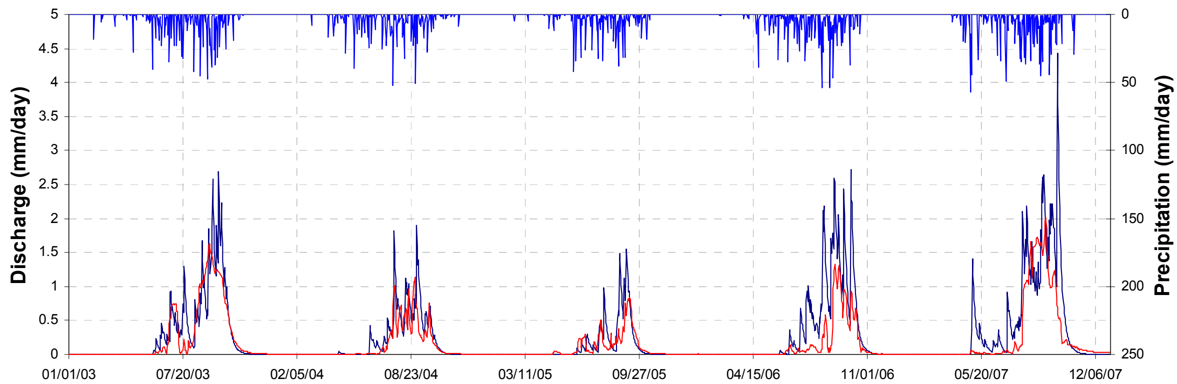


Figure 10-2 Calculated (blue) and discharges on basis of the measured water levels and the rating curves generated with the hydrodynamic model (red) of Sisili River. The areal precipitation follows from data of three available gauging stations.

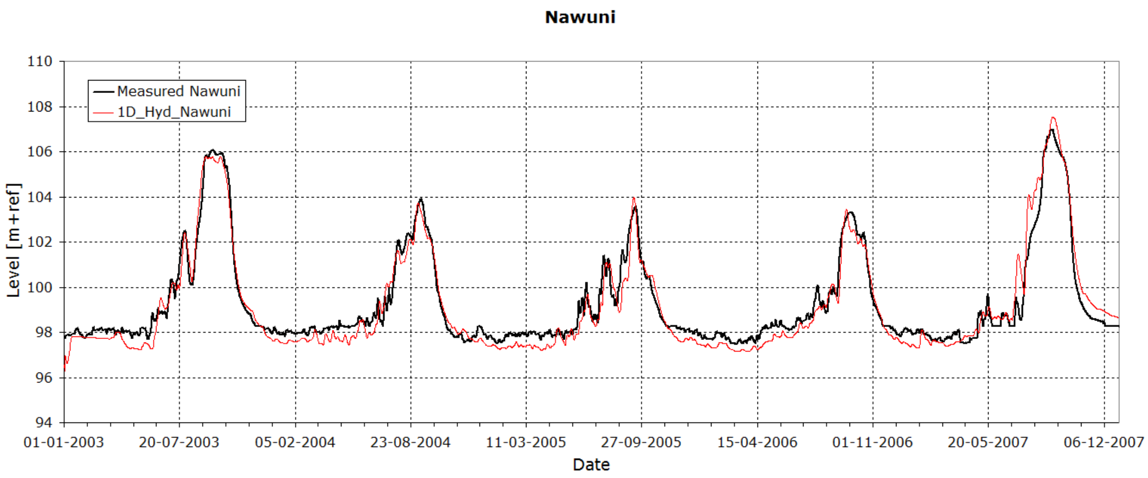


Figure 10-3 Measured and calculated water levels, Nawuni, 2003-2007.

Station	2003	2004	2005	2006	2007	Average station
Yarugu	-0.26	-0.10	-0.23	-0.20	0.05	-0.15
Pwalugu	0.47	1.80	0.30	0.02		0.65
Nawuni	0.28	0.17	-0.43	-0.12	-0.53	-0.13
Daboya	0.21	0.00	-0.23	0.14	0.06	0.04
Yapei	-0.23					-0.23
Wiasi	0.02	0.04	0.12	0.02	0.08	0.06
Yagaba		0.06	0.01	-0.03	-0.05	0.00
Nasia	0.35	0.20	0.02	0.23	0.02	0.20
Nabogo	0.21	0.42	0.06	0.13	-0.22	0.12
Average total	-0.02	-0.03	-0.29	-0.20	-0.03	-0.11

Table 10-1 Calibration and validation results 2003-2007, measured – calculated water levels, the grey cells indicating that unreliable data could not be filled in, leaving it as missing data.

10.3 Flood Risk Mapping

The major floods since the year 2000 have return periods ranging from 5 to 100 years, with only very little variation in the peak discharges, as illustrated in the figure below. We therefore decided to construct two flood risk map that are applicable for floods with returns periods of 2-5 years and 10-100 years.

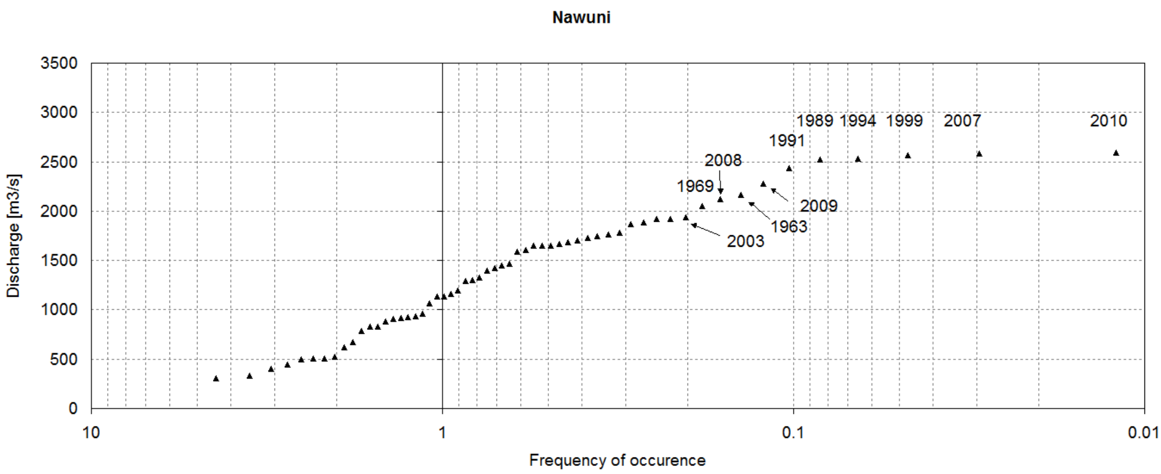


Figure 10-4 Return periods annual maximum discharges at Nawuni

We calculated the flood prone areas applying the developed models and compared it to the flood prone areas we calculated from Landsat data. The comparison between these two fully independent calculations is striking, see the figure below.

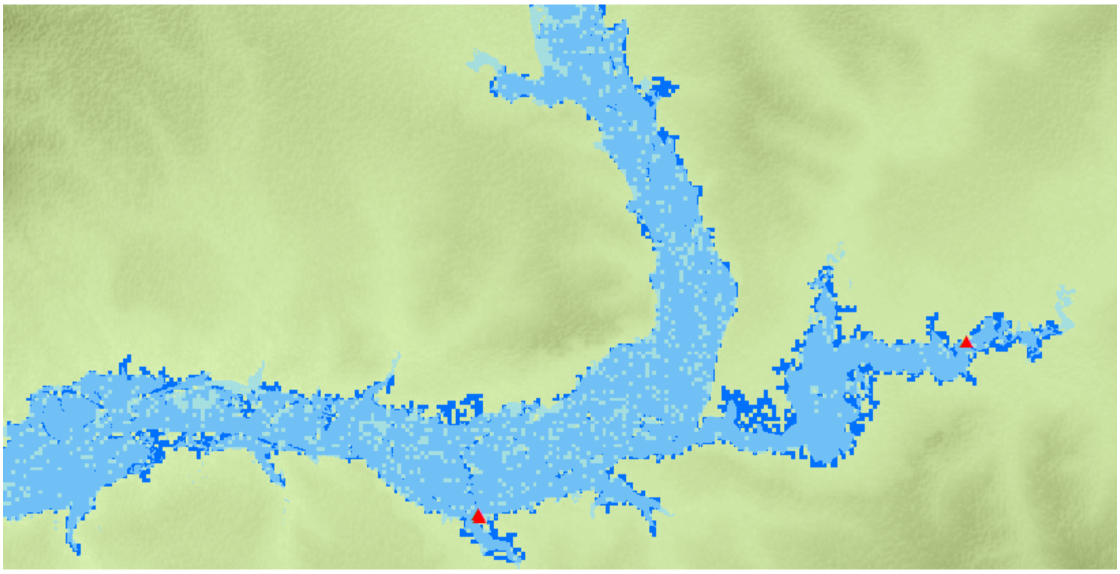


Figure 10-5 Landsat image 2003 (light blue) and 2D model results (dark blue) Nawuni - Nabogo

This proves that the data (after validation and a field survey) and the resulting models are accurate enough to determine the flood prone areas. One of the issues of the project before hand was whether the DTM on basis of SPOT Satellite data would be accurate enough for the flood hazard assessment. We showed that this is the case and no investment in a more detailed DTM (e.g. on basis of Lidar measurements or terrestrial measurements) is necessary for accurately calculating the flood extent.

10.4 Genesis of floods

One of the issues that can be analysed with the developed models is to what extend the spill from Bagré reservoir and the discharges of the various tributaries contribute to the floods on White Volta. The result of model calculations is shown in the figure below. From this figure it can be concluded that if there would be no spill from Bagré reservoir, the maximum flood levels of White Volta would decrease approximately 75 cm upstream of Pwalugu, reducing to approximately 20 cm downstream of the inflow of Sisili-Kulpawn. The figure also shows that the back water effect of Lake Volta reaches until Yapei.

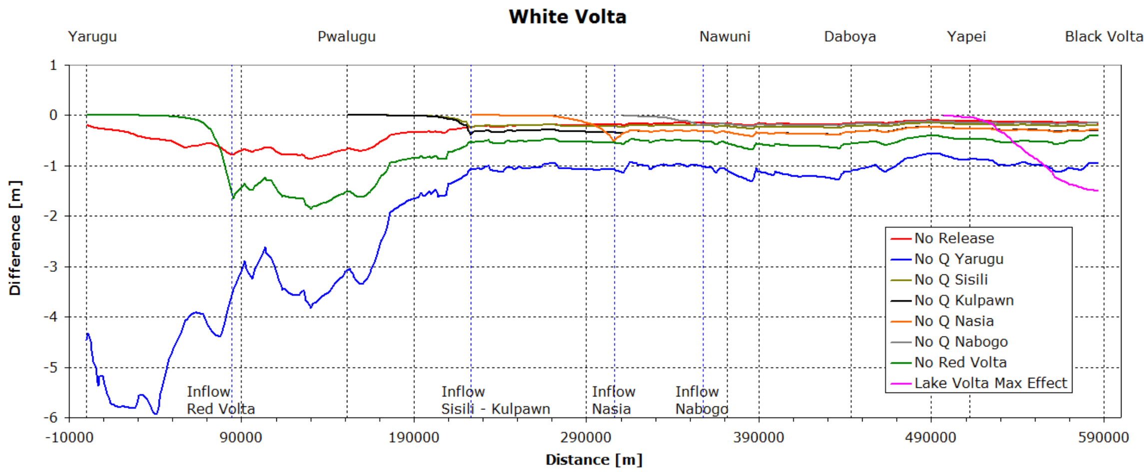


Figure 10-6 Contribution of Bagré spills and the various tributaries on floods on White Volta.

10.5 Flood Early Warning System (FEWS)

The rainfall runoff and hydrodynamic models of White Volta and its tributaries form the basis of FEWS-Volta. These models need forecasts or readings of rainfall, evapotranspiration and water levels to make calculations. The user interface completes the system for operational (real time) flood forecasting.

Rainfall or water level data is not available in real time for flood forecasting of White Volta River. We decided to use a real time meteorological forecast instead. The system is set-up in such a way that it uses real time meteo forecast [IMK-IFU] provided an internet connection is available. If this is not the case the system provides for manual offline imports as well. Once the system is back online it automatically downloads all missing meteo forecasts and calculates a forecast.

All stakeholders were provided with the system and are trained to make forecasts. WRC is the institute that formally produces the forecasts and that provides forecast information to NADMO.

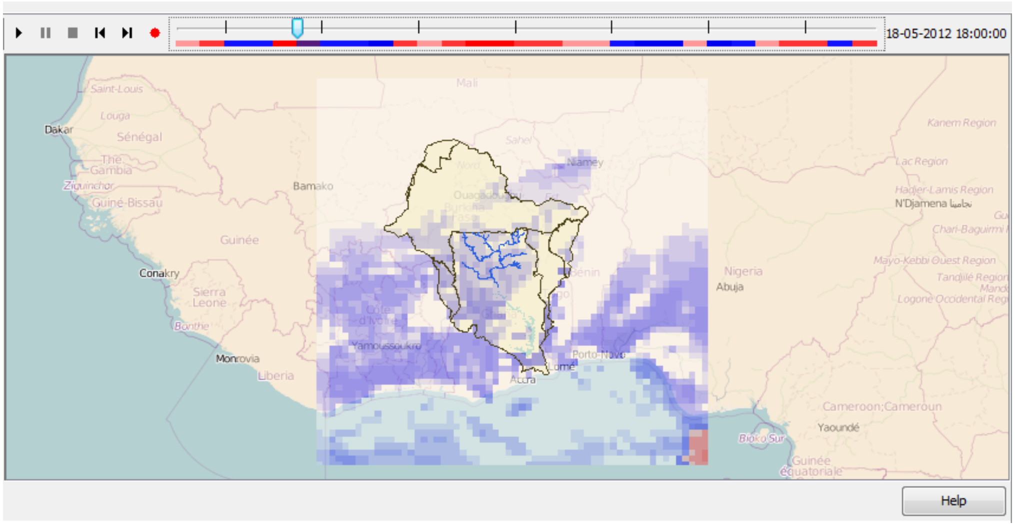


Figure 10-7 Meteo forecast visualised in FEWS-Volta

The accuracy and lead time of FEWS-Volta is assessed after the 2012 wet season and described in FEWS-Volta evaluation report included as annex in this report (HKV, November 2012). Based on the results so far we have confidence in accurate forecasting especially in the White Volta flood prone areas downstream of the Kulpawn inflow. The tributaries and the upstream part of White Volta are more sensitive to rainfall and inflow inaccuracies than the downstream (flood prone) part. The figure below illustrates this; Where the mismatch of the rainfall runoff model of Kulpawn Sisili does have a considerable effect on the accuracy of the calculated water level at Yagaba (as shown in the left part of the figure), the calculated water levels at Daboya are still quite good (as the right part of the figure shows).

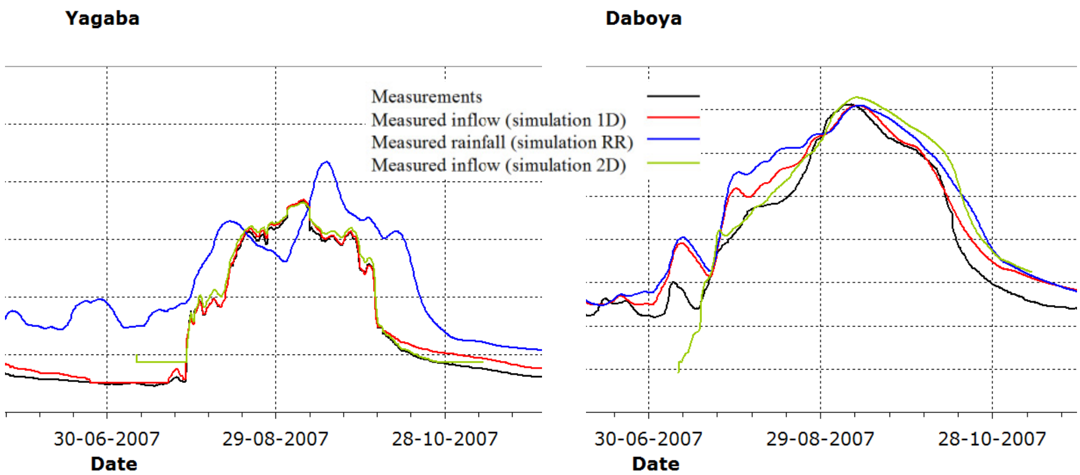


Figure 10-8 Simulated results at Yagaba and Daboya

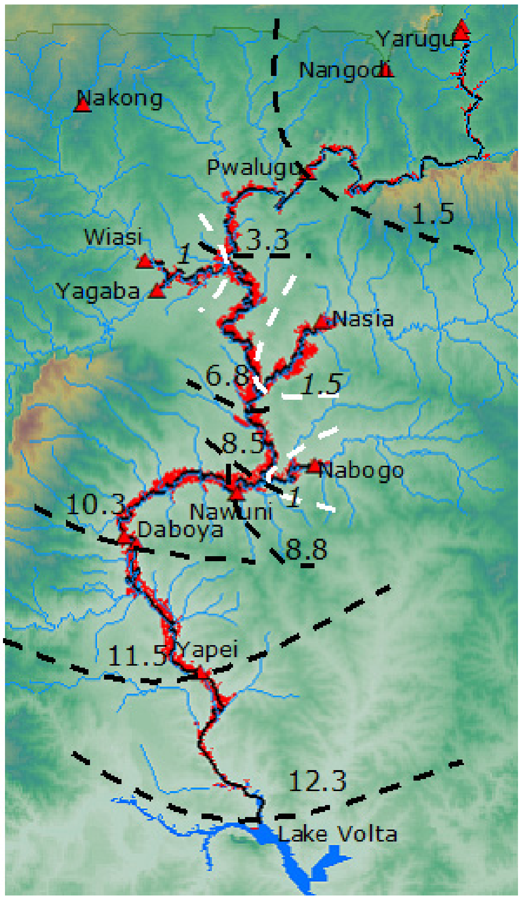


Figure 10-9 Propagation times in the White Volta

	Propagation time [days]	
Location	**From Yarugu**	**From previous**
Yarugu	0	0
Pwalugu	1.5	1.5
Kulpawn mouth	3.3	1.8
Nasia mouth	6.8	3.3
Nabogo mouth	8.5	1.7
Nawuni	8.8	0.3
Daboya	10.3	1.5
Yapei	11.5	1.2
Lake Volta	12.3	0.8
Wiasi - Kulpawn mouth	1	1
Yagaba - Kulpawn mouth	1	1
Nasia - Nasia mouth	1.5	1.5
Nabogo - Nabogo mouth	1	1

Table 10-2 Propagation times

The map and table above shows approximate flood wave propagation times in days in the White Volta river and its main tributaries. It also shows the flood prone areas marked in red, the largest being between the confluence with the Kulpawn and gauging station Daboya. For this area a warning lead time of 3.3 days assured is with the current FEWS-Volta system.

The lead time in the tributaries is at least 5 days because the meteo forecast is provided for 5 days. The quality of the forecast is not yet known.

The lead time between Yarugu and Kulpawn confluence is less than 3 days, because the system depends on the boundary condition at Yarugu. To increase the lead time and accuracy in this section a proper discharge forecast or measurement from Bagre is needed in combination with the discharge from the catchment between Bagre and Yarugu, including the tributary Nouhao in Burkina Faso.

10.6 Recommendations

10.6.1 Meteorological monitoring system

Real time measured rainfall data will improve the forecast accuracy of the FEWS and still provide a lead time of at least 3 days. Real time rainfall measurements will become available in Ghana in the future via rainfall radar and telemetered ground stations. Near real time rainfall data from satellite imaginary is already available and included in FEWS-Volta (TRMM data, see http://trmm.gsfc.nasa.gov/) as described in the FEWS-Volta evaluation report (HKV, November 2012). With these additional data flows implemented, FEWS-Volta is not solely available on the meteo forecast implemented in this study. Although the FEWS greatly takes advantage of this meteo forecast, its continuity in the future is uncertain. We therefore strongly recommend upgrading the availability of real time rainfall data in the FEWS in the near future, first on basis of satellite data (TRMM) and later on basis of rainfall radar and telemetered ground stations, once available. As stated, during finalisation of this report and as commissioned by the World Bank, TRMM has been included in FEWS-Volta.

At least 3 new ground stations should be located in the mid and south-west part of the project area, with a minimum of one synoptic station. Figure 10-10 illustrates this by showing the coverage of the meteorological ground stations used in this project and relating it to the coverage according to WMO standards (WMO 1994). When following the WMO standards in a more strict way at least 8 new precipitation stations should installed (see Figure 10-11).

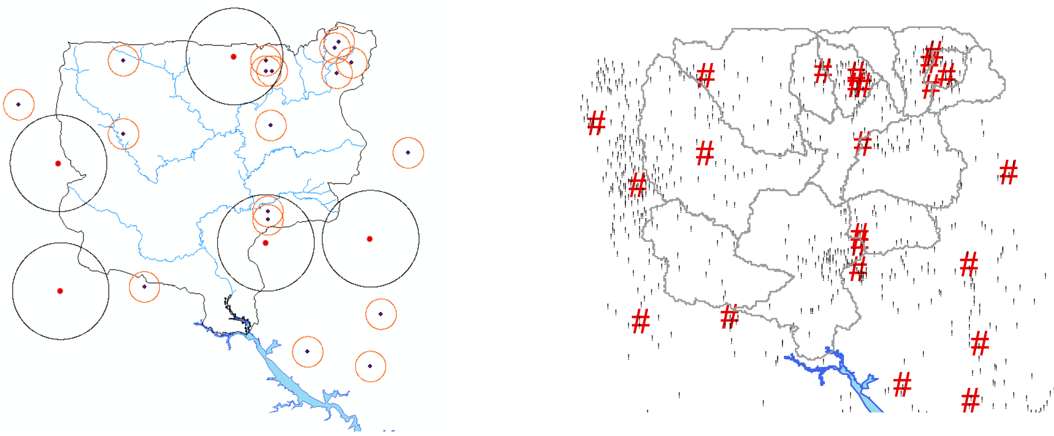


Figure 10-10 ***Left:*** *Coverage meteo-network according to WMO standards* ***Right:*** *Location meteo-stations (red triangles) in relation to village density (black dots)*

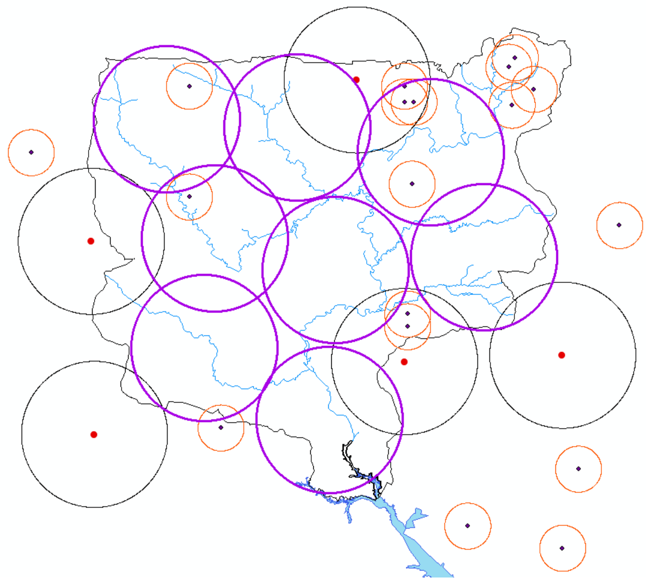


Figure 10-11 Possible extension (purple circles) of the current precipitation network coverage to fulfil WMO standards.

Report Hydrological database, deliverable 3 [HKV 2012] and appendix 3 of deliverable 3 describe the assessment and recommendations on the meteorological monitoring network in more detail.

10.6.2 Hydrological monitoring system

Telemetered water level gauging stations will not improve the lead-time of FEWs-Volta, but will improve the accuracy. When the hydrological data at Yarugu becomes available in real-time, the system does not depend on uncertainties from Burkina Faso. We recommend to rehabilitate the existing but not operational telemetered Hydro Argos water level gauging stations, or to put another system in place for obtaining real time water level data. A simple but adequate way could be to provide the gauge readers of HSD with cell phones, to enable them to text the water levels to the headquarters in Accra every 6 hours. This would also enable HSD to monitor the availability and quality of the 6 hourly readings of the gauges.

To reduce the uncertainty in the rating curves of the gauging stations in White Volta River, we recommend carrying out field flow measurements on regular basis with proper material. These flow measurements have not been performed for many years, leaving the official rating curves in a deplorable state. Flow measurements and rating curves should be defined for locations where the flood is confined. This is not the case at Nawuni and Daboya, where the river bypasses the gauging stations. The stations are suitable for water level measurements. Nawuni was installed to monitor the water intake just upstream of the station. It was not installed to measure flows, especially not during floods.

We recommend to install new stations or update the stations at:

- Gauging station Nangodi should be rehabilitated and reinforced. This is an important flow measurement station as the Red Volta is the largest Ghanaian tributary of the White Volta.
- Another location in the Nawuni-Daboya reach should be found to carry out flow measurements, in a section that conveys all the water.
- We also recommend to assess gauging station Kpasenkpe, downstream Pwalugu, similar to the other hydrological gauging stations analysed in this study. Kpasenkpe is operational since 2004, but only recently known to us.
- We recommend to install a water level station upstream Nasia, where historical flood images show a large flood extent.
- We recommend to install a gauging station directly downstream of the confluence with the Black Volta.
- A gauging station on Mole river should be installed to measure the inflow to the White Volta.

Figure 10-12 illustrates these stations and the historical flood extent.

Report Hydrological database, deliverable 3 [HKV 2012] describes the assessment and recommendations on the hydrological monitoring network in more detail.

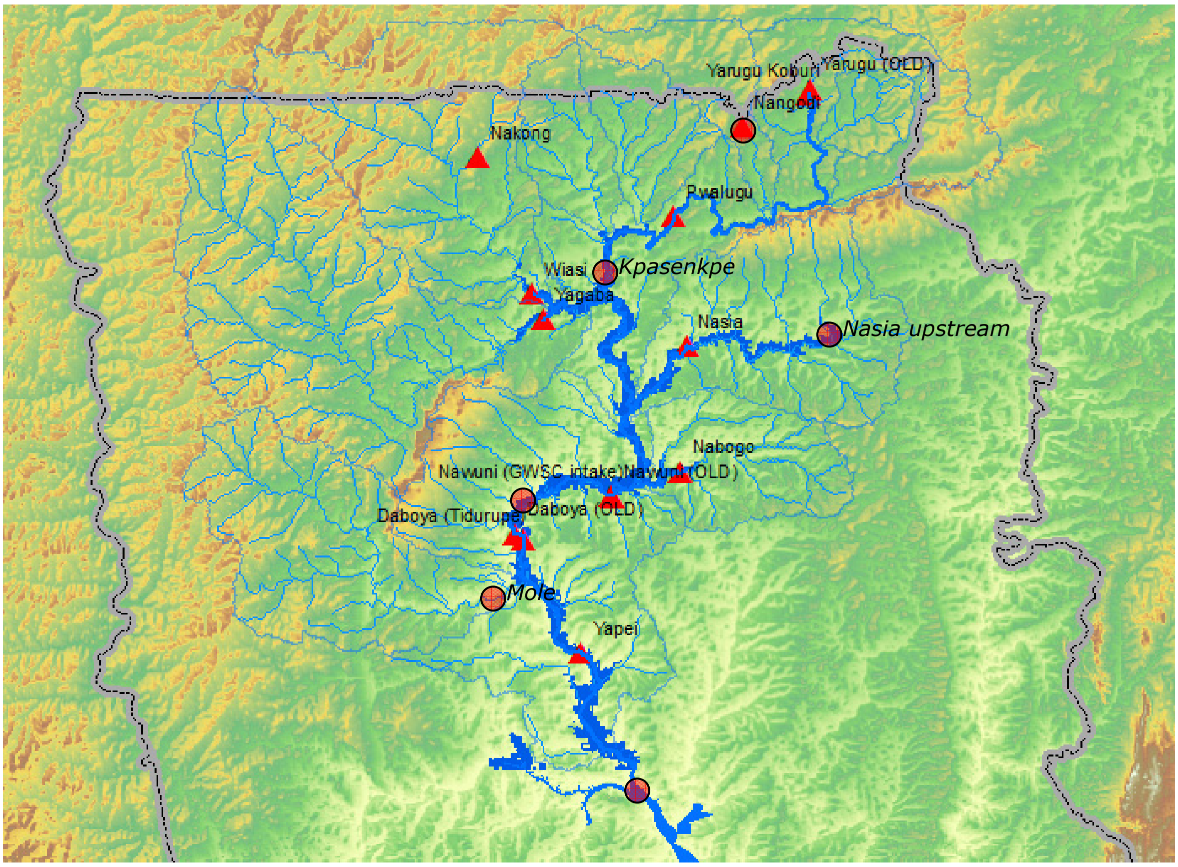


Figure 10-12 Coverage hydrological monitoring network related to the historical flood extent

10.6.3 Application and improvement of models and maps

As described in chapter 3.2 the hydrological models do not perform well. Based on a project commissioned by Wienco Ghana Ltd. and an addendum to the World Bank contract, the hydrological models were improved as described in HKV Deliverable 9 report (December 2012) and implemented in FEWS-Volta. This report is added as appendix K to the final report.

The project showed that the hydrological and hydrodynamic modelling system can be used to assess different types of flood mitigation measures. We recommend using the models for other assessments and projects as well:

- In combination with the hydro-meteorological database more detailed models can be set-up to answer water related questions in any area in the White Volta catchment and to support policies or assess projects. Examples are: dam assessment studies, local flood assessment, water availability studies and so on.
- HSD can use the models to assess new flow measurements, rating curves and in general use it to check their data.
- The flood hazard maps and 2-dimensional hydraulic models can help to plan the development of towns and villages as well as agricultural areas.

The flood hazard and risk maps that were developed show potentially flooded areas in terms of water depth as well as how often areas were flooded in the last 10 years. Both maps show similar flood extents and clearly delineate the flood prone areas.
The vulnerable areas at the moment are defined as towns, villages and infrastructure. During the data collection phase we found out that little information is available about vulnerable areas: the land-use maps are questionable and the locations of vulnerable objects like hospitals

or schools are generally not known. Large-scale field operations before and after floods should be organised to better define and assess vulnerable areas and especially objects and incorporate them in the risk maps.

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Appendices

Appendix A: Abbreviations

ABBREVIATIONS USED

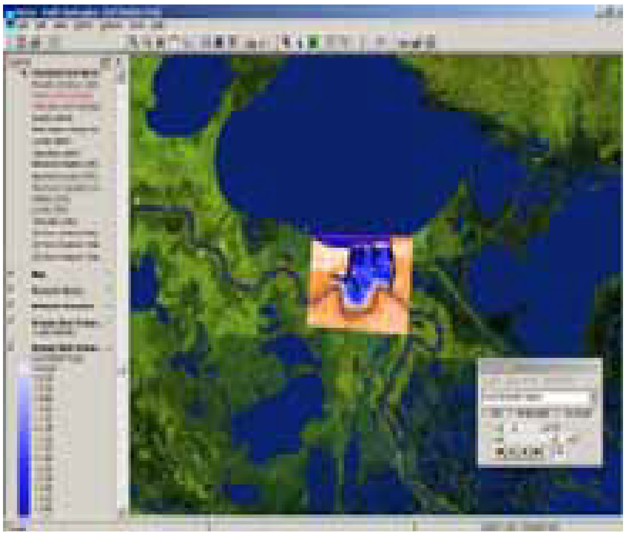
BFMA Burkina Faso Meteorological Agency
BPA Bui Power Authority
DFR Department of Feeder Roads
DISEC District Security Council
DMC Disaster Management Committee
DVG Disaster Volunteer Group
EMO Emergency Management Organization
EOC Emergency Operation Centre
EPA Environmental Protection Agency
EPP Emergency Preparedness Plan
FEWS Flood Early Warning System
GIDA Ghana Irrigation Development Agency
GHA Ghana Highway Authority
GMET Ghana Meteorological Agency
HSD Hydrological Services Department
ICOLD International Commission on Large Dams
masl meters above sea level
NADMO Natural Disaster Management Organization
NDSU National Dam Safety Unit
PAP Potentially Affected People
PR Public Relations
SADA Savannah Accelerated Development Agency
VBA Volta Basin Authority
VRA Volta River Authority
WIS Water Information System
WRC Water Resources Commission
WRI Water Research Institute

UNIT CONVERSIONS

1 inch 25.4 mm
1 ft (= 12 inch) 0.3048 m
1 mile (statute) 1609.344 m
1 sqm 2.59 km2
1 acre 0.4046856422 ha
1 MAF 1233.482 Mm3
1 cfs 0.02831685 m3/s

Appendix B: Sobek

SOBEK is a practical modelling framework, supporting the work of engineers in the design or rehabilitation of water systems. SOBEK simulates the complex flows and the water related processes in almost any system. SOBEK is the ideal tool for guiding the designer in making optimum use of his limited financial resources.



Simulation Katrina 2005

Integrated approach

SOBEK offers one software environment for the simulation of all management problems in the areas of river and estuarine systems, drainage and irrigation systems and wastewater and storm water systems. This allows for combinations of flow in closed conduits, open channels, rivers overland flows, as well as a variety of hydraulic, hydrological and environmental processes. Three product lines, SOBEK-River, SOBEK-rural and SOBEK-Urban, have been developed with specific user interfaces enabling our clients to competently and efficiently deal with all water related problems.

A powerful hydrodynamic 1D/2D/3D simulation engine.

The hydrodynamic 1D/2D/3D simulation engine is the computational core of the SOBEK product lines. This engine is used in all 1DFLOW modules and Overland Flow modules (2DFLOW) within the SOBEK framework. Thus allowing the combined simulation of pipe channel-and overland flow through an implicit coupling of 1D and 2D flow equations. SOBEK is the ideal tool for studying the effects of dam breaks, river floods, dike breaches, urban flooding etc.

Open system

The wide range of additional modules within the SOBEK framework makes it possible to model almost any aspect of a water system. However, for those who prefer to add new processes to proven knowledge, SOBEK offers two easy open system approaches:

• Open Process Library approach

An Open Process Library for water related processes. Since people are not writing their own word processor before writing a word document SOBEK offers now a kind of word processor for water related processes, such as water quality processes. A powerful user interface allows the possibility to describe new substances/organisms, processes and coefficients and based on this description to generate a personalised water quality computer code, which can be interlinked with the other SOBEK modules.

• OpenMI (www.openmi.org) approach

Most of the modules of SOBEK are OpenMI compliant. Therefore, these modules are open to the connection of user-made modules through the widely accepted unified method to link models.

GIS environment

As our clients all have different requirements relating to GIS, SOBEK offers two GIS solutions:

• The Delft-TOOLS OpenGIS environment NETTER. This environment is free of charge. It allows for the import and export of a range of GIS formats. The NETTER layers provide an extremely fast data access while performing map based input data editing and post processing of results.

• A Map Front End approach to plug in SOBEK components into GIS environments such as ArcGIS.

Robustness of numerical operations

The hydrodynamic 1D/2D/3D simulation engine is equipped with a very robust scheme for numerical computation. It also guarantees mass conservation, even in case of transitions through suddenly varying cross section shapes. The engine combines computations of sub critical and supercritical flow, at scales selected by the user. It handles flooding and drying of channels without the use of artificial methods such as the Preissmann slot.

Numerical efficiency

The hydrodynamic 1D/2D/3D simulation engine has a very efficient numerical solution algorithm; this is based upon the optimum combination of a minimum connection search direct solver and the conjugate gradient method. It also applies a variable time step selector, which suppresses the waste of computational time wherever this is feasible.

Size of models

The size of the model is only limited by the size of the internal memory of the computer used.

Powerful water quality facilities

SOBEK is supplied with a water quality processes editor, which contains in excess of 600 processes. It allows the user to combine their own sets of processes or to select from predefined sets. One of SOBEK's powerful water quality functionalities is the determination of the source of water at any time of the year and at any location of the modelled area.

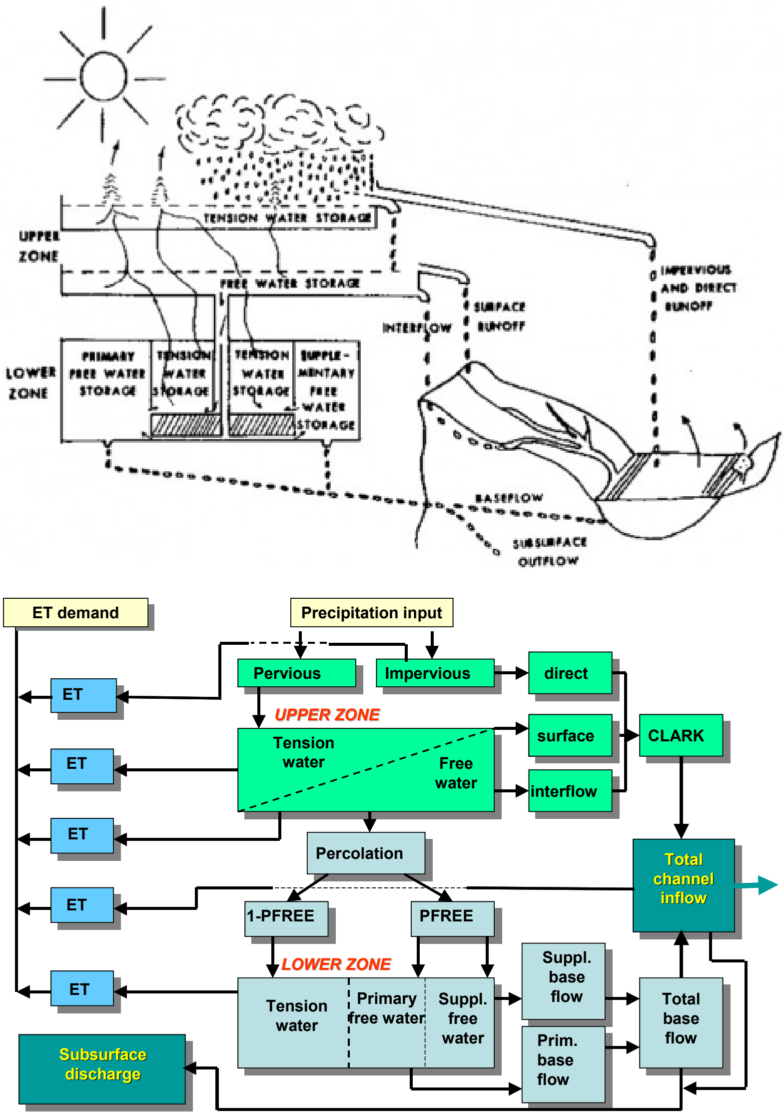
Development

SOBEK is the product of the joint effort of Delft Hydraulics, the Ministry of Public Works of the Netherlands and a number of widely respected consulting firms. As a result SOBEK software combines state-of-the-art knowledge with a practical approach making this software invaluable for engineering and water management studies.

	Rural	Urban	River
Hydrodynamics			
1DFLOW	●	●	●
Overland Flow module (2D)	●	●	
Hydrology			
RR	●	●	
Morphology			
1DMOR (incl Sediment Transport)			●
Water Quality			
1DWAQ	●		●
Real Time Control			
RTC simulation module	●	●	

Appendix C: Sacramento

To model the rainfall-runoff process SOBEK software was used. The SOBEK software contains several model concepts to simulate the rainfall-runoff process. For this study the physically based, conceptual lumped Sacramento rainfall-runoff model was used. The Sacramento model concept was developed by the National Weather Service located in Sacramento, California.
The most important input parameters of the model are time series with precipitation and Evapotranspiration (ET_{ref}) data. The basin is divided into different reservoirs representing the upper zone and the lower zone of the soil matrix. These reservoirs are divided into the tension water content and the free water content. The Sacramento model only describes the land phase. However some basic routing, to incorporate the flow through the modelled catchment, a Unit Hydrograph can be used.
An extensive description of the model can be found in NOAA, 1976. A visual and schematic representation of the Sacramento model is displayed below.



Visual and schematic representation of Sacramento and the incorporated processes (Sobek help files, 2012)

Appendix D: Manning roughness

Manning's n for Channels (Chow, 1959).			
Type of Channel and Description	Minimum	Normal	Maximum
Natural streams - minor streams (top width at flood stage < 100 ft)			
1. Main Channels			
a. clean, straight, full stage, no rifts or deep pools	0.025	0.03	0.033
b. same as above, but more stones and weeds	0.03	0.035	0.04
c. clean, winding, some pools and shoals	0.033	0.04	0.045
d. same as above, but some weeds and stones	0.035	0.045	0.05
e. same as above, lower stages, more ineffective slopes and sections	0.04	0.048	0.055
f. same as "d" with more stones	0.045	0.05	0.06
g. sluggish reaches, weedy, deep pools	0.05	0.07	0.08
h. very weedy reaches, deep pools, or flood ways with heavy stand of timber and underbrush	0.075	0.1	0.15
2. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages			
a. bottom: gravels, cobbles, and few boulders	0.03	0.04	0.05
b. bottom: cobbles with large boulders	0.04	0.05	0.07
3. Floodplains			
a. Pasture, no brush			
1.short grass	0.025	0.03	0.035
2. high grass	0.03	0.035	0.05
b. Cultivated areas			
1. no crop	0.02	0.03	0.04
2. mature row crops	0.025	0.035	0.045
3. mature field crops	0.03	0.04	0.05
c. Brush			
1. scattered brush, heavy weeds	0.035	0.05	0.07
2. light brush and trees, in winter	0.035	0.05	0.06
3. light brush and trees, in summer	0.04	0.06	0.08
4. medium to dense brush, in winter	0.045	0.07	0.11
5. medium to dense brush, in summer	0.07	0.1	0.16
d. Trees			
1. dense willows, summer, straight	0.11	0.15	0.2
2. cleared land with tree stumps, no sprouts	0.03	0.04	0.05
3. same as above, but with heavy growth of sprouts	0.05	0.06	0.08
4. heavy stand of timber, a few down trees, little undergrowth, flood stage below branches	0.08	0.1	0.12
5. same as 4. with flood stage reaching branches	0.1	0.12	0.16

Table D- 1 Manning's n Roughness values (Chow, 1959)

Land use	Manning roughness ($m^{1/3}/s$)
Grass and herb with or without scattered trees	0.06
Open Cultivated Savanna Woodland	0.045
Closed Savanna Woodland	0.1
Widely Open Cultivated Savanna Woodland	0.04
Settlement	0.2
Open Savanna Woodland	0.06
Closed Cultivated Savanna Woodland	0.1
Riverine Savanna Vegetation	0.12
Grassland with or without scattered trees and shrubs	0.045
Unclassified/Bushfire	0.04
Reservoir	0.03
Unclassified/Cloud	x
Rock	0.03
Closed Forest	0.05
Moderately Dense Herb and Bush with Scattered Tre	0.09
Moderately Closed Tree Canopy with Herb and Bush	0.13
Riverine Forest Vegetation	0.15
Open Forest	0.08
Planted Cover	0.04

Table D- 2 Manning roughness estimation based on land use and Chow [1959]

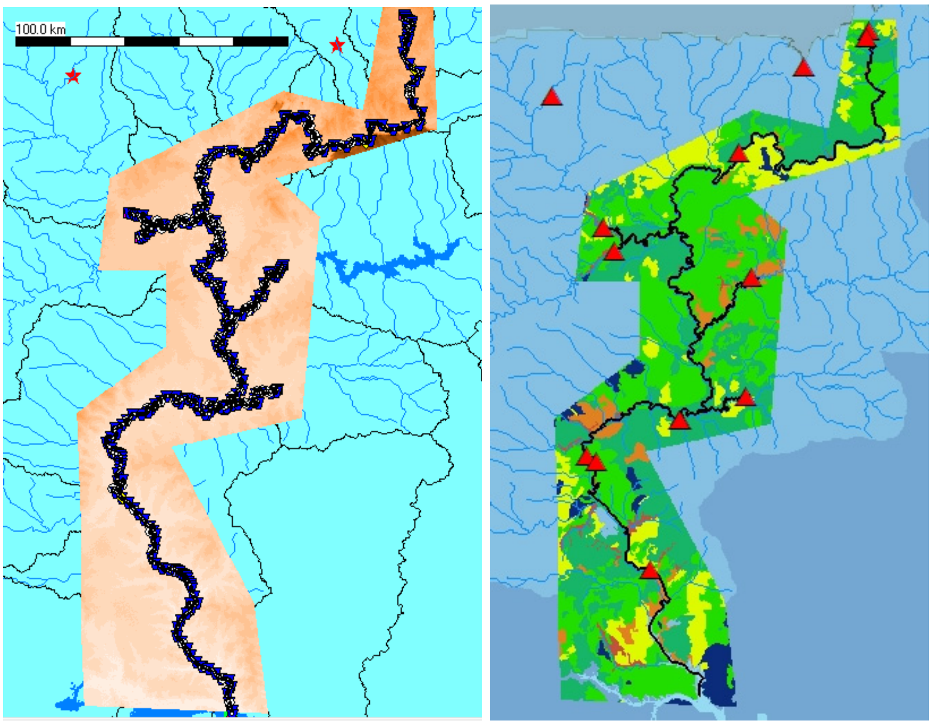


Figure D- 1 DEM used in Sobek-1D2D and roughness grid

Appendix E: Calibration and validation results hydrodynamic model

Results 2003

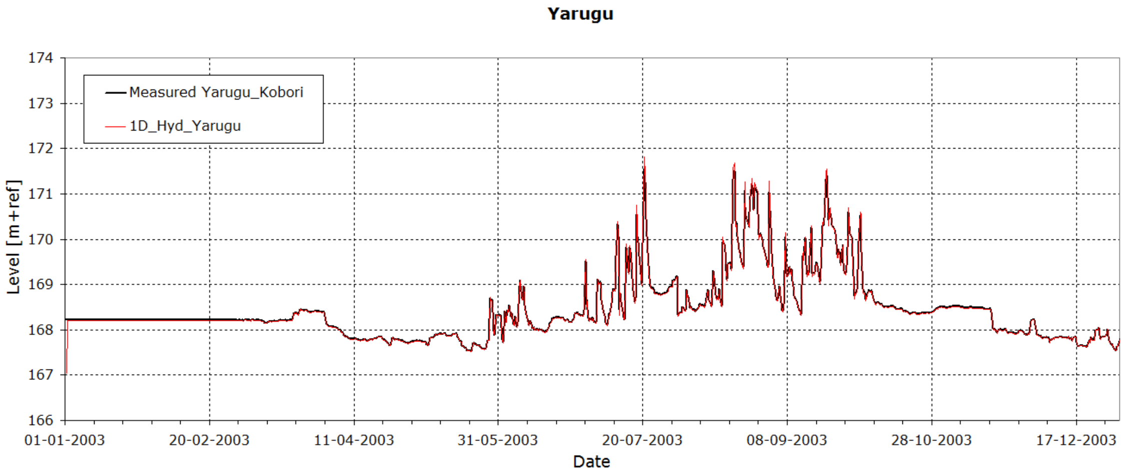


Figure E- 1 Measured and calculated water levels 2003 Yarugu Kobori

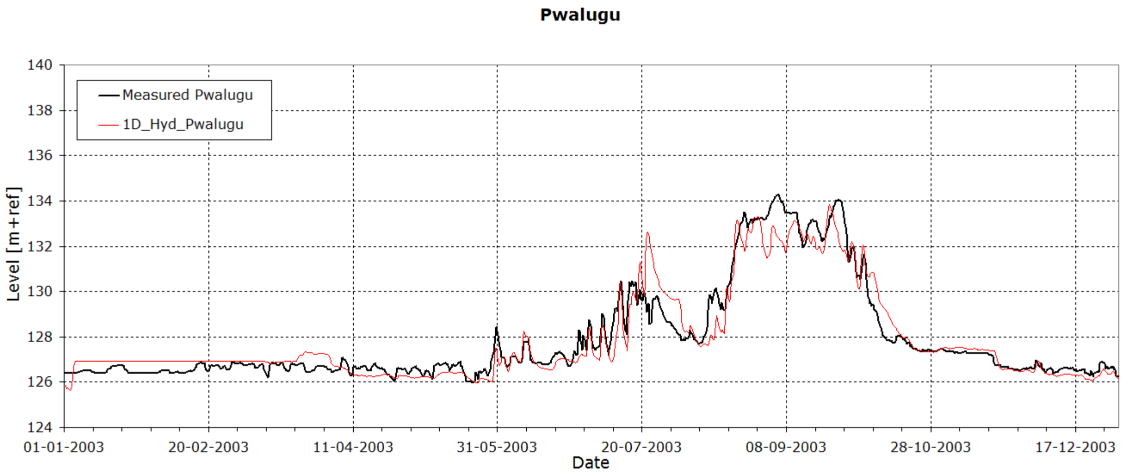


Figure E- 2 Measured and calculated water levels 2003 Pwalugu

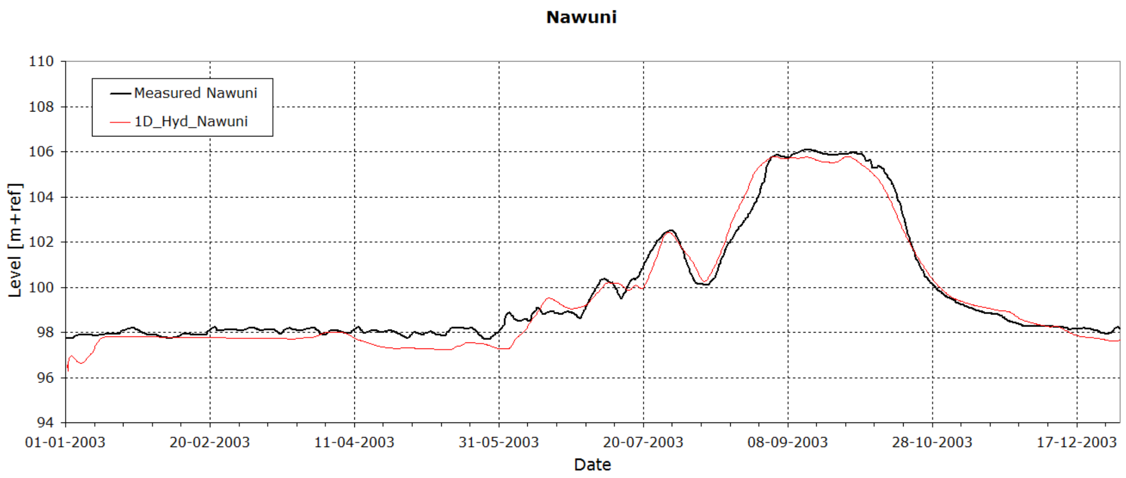


Figure E- 3 Measured and calculated water levels 2003 Nawuni

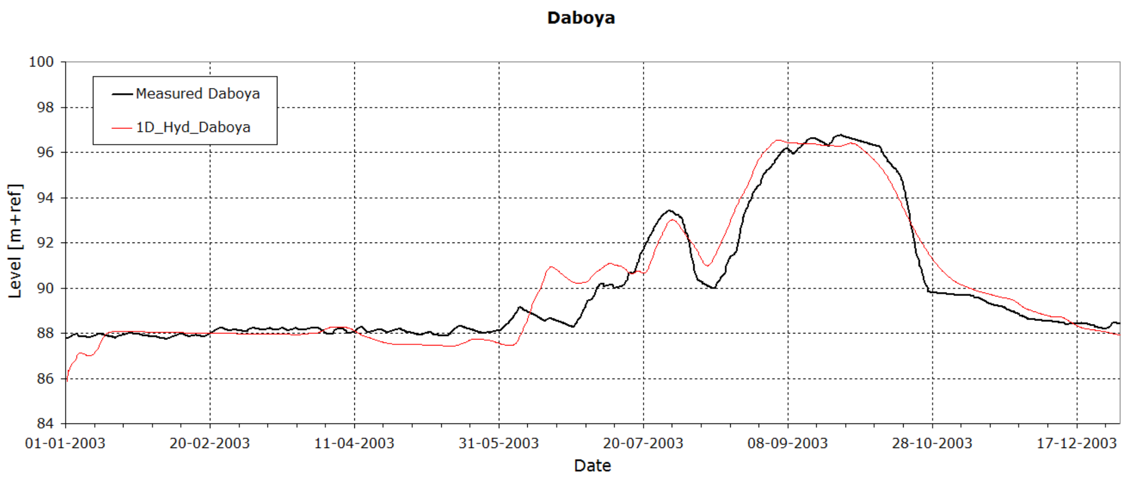


Figure E- 4 Measured and calculated water levels 2003 Daboya

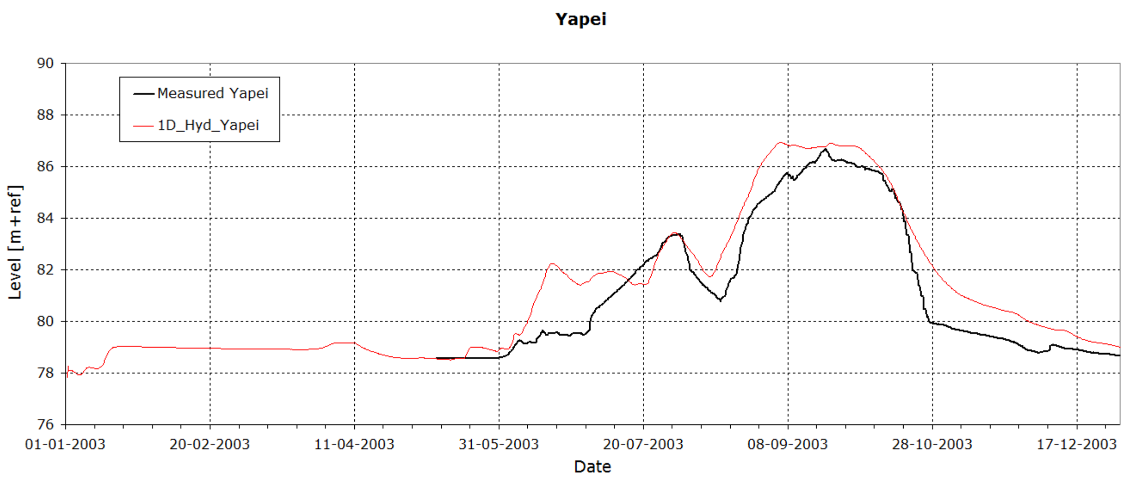


Figure E- 5 Measured and calculated water levels 2003 Yapei

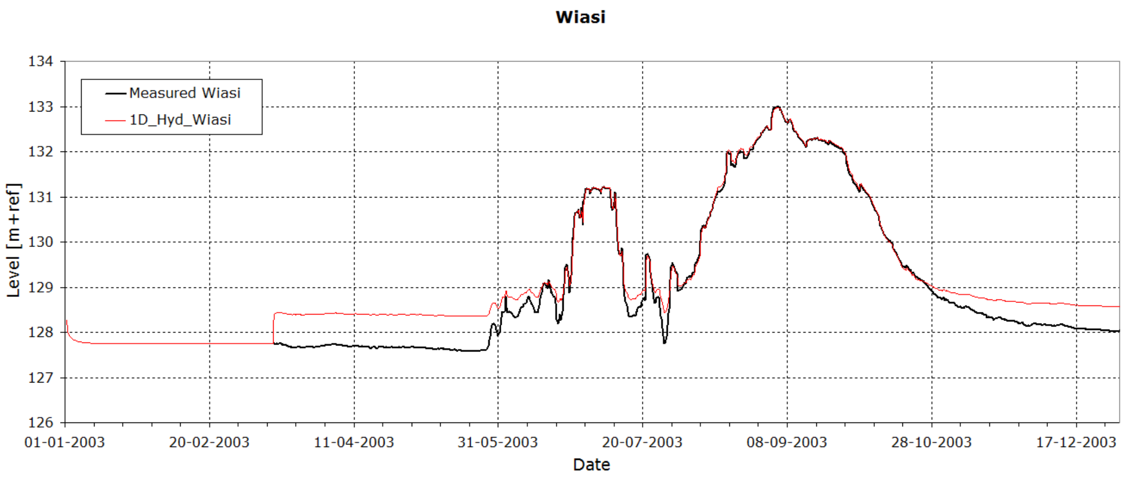


Figure E- 6 Measured and calculated water levels 2003 Wiasi

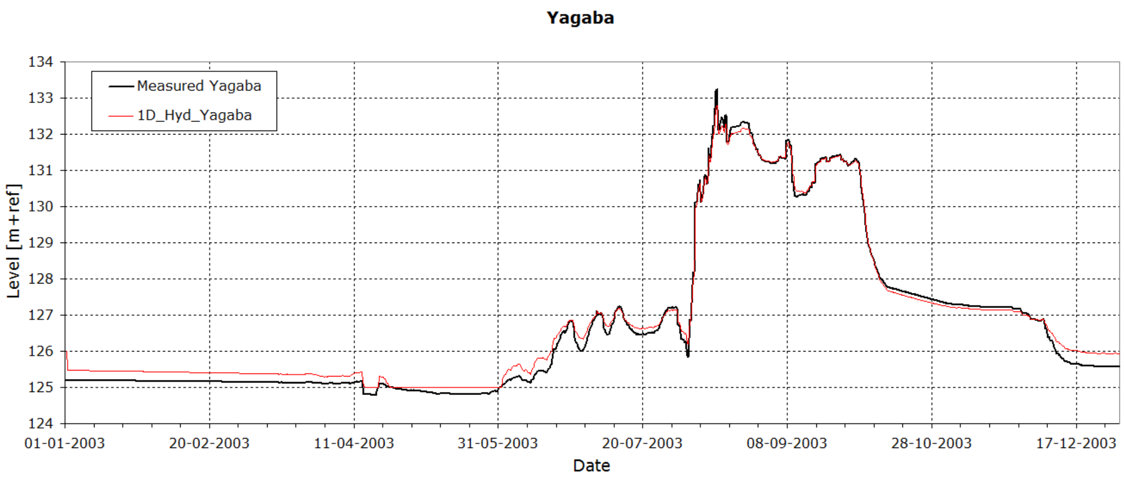


Figure E- 7 Measured and calculated water levels 2003 Yagaba

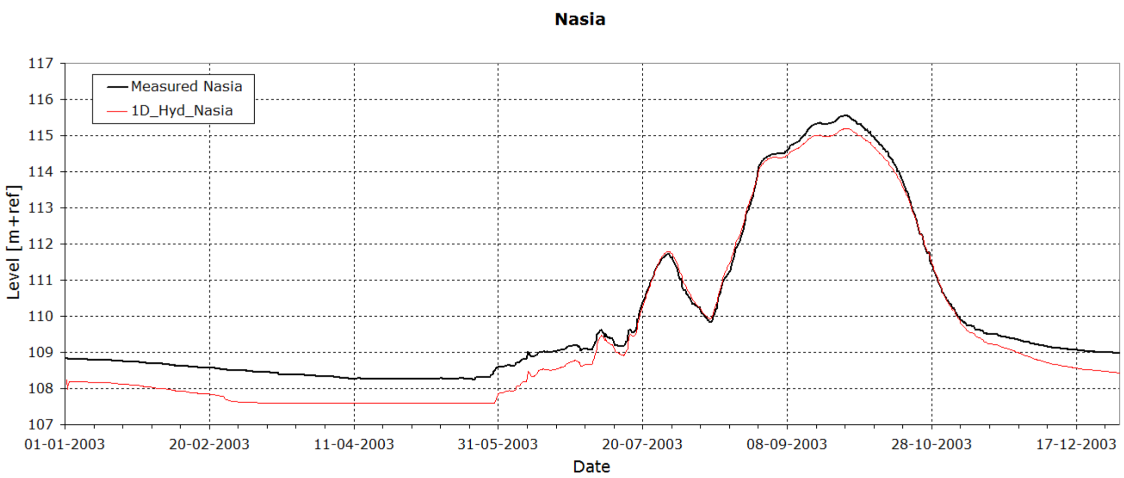


Figure E- 8 Measured and calculated water levels 2003 Nasia

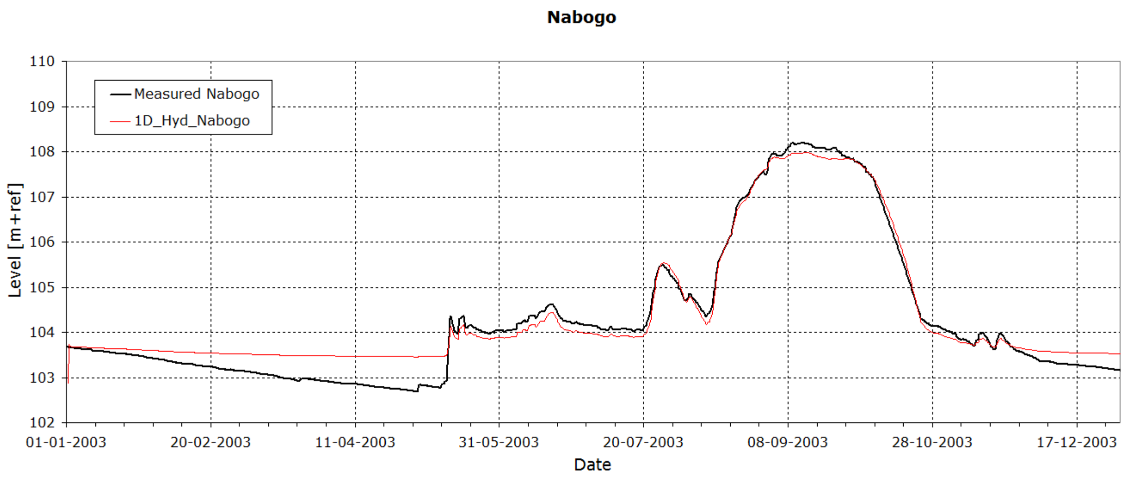


Figure E- 9 Measured and calculated water levels 2003 Nabogo

Results 2007

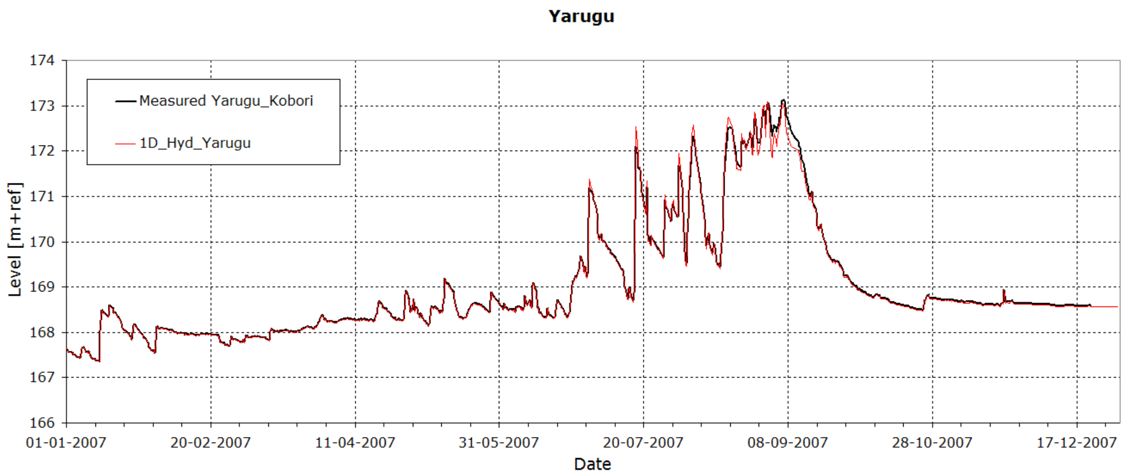


Figure E- 10 Measured and calculated water levels 2007 Yarugu Kobori

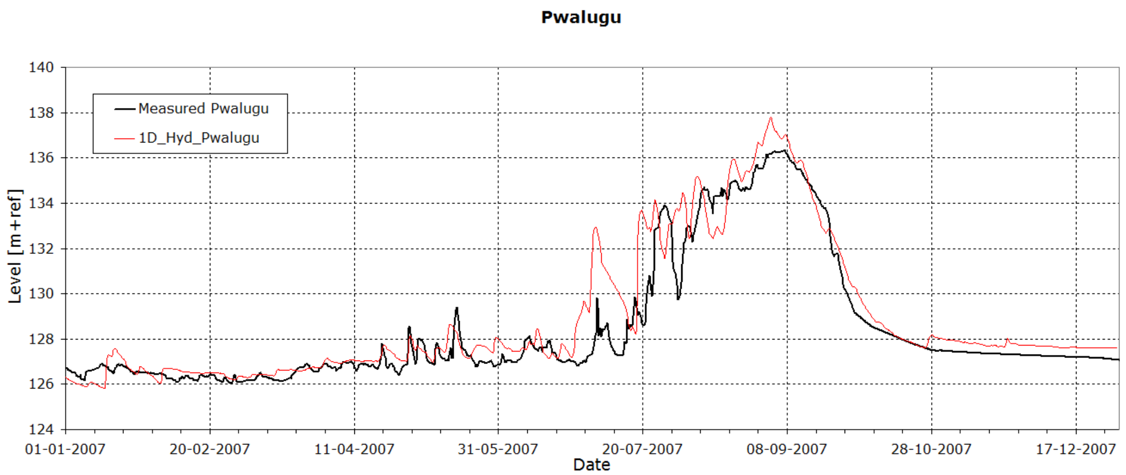


Figure E- 11 Measured and calculated water levels 2007 Pwalugu

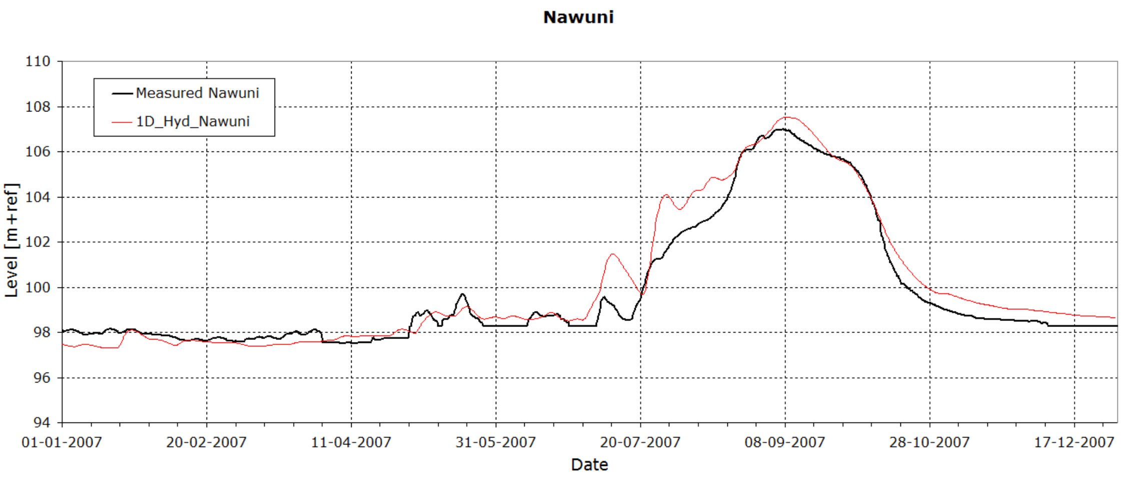


Figure E- 12 Measured and calculated water levels 2007 Nawuni

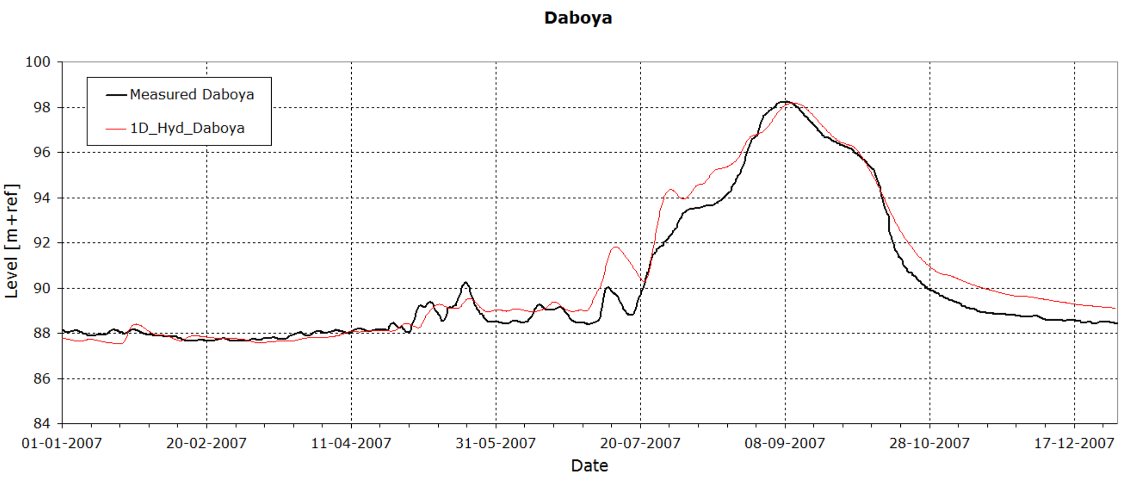


Figure E- 13 Measured and calculated water levels 2007 Daboya

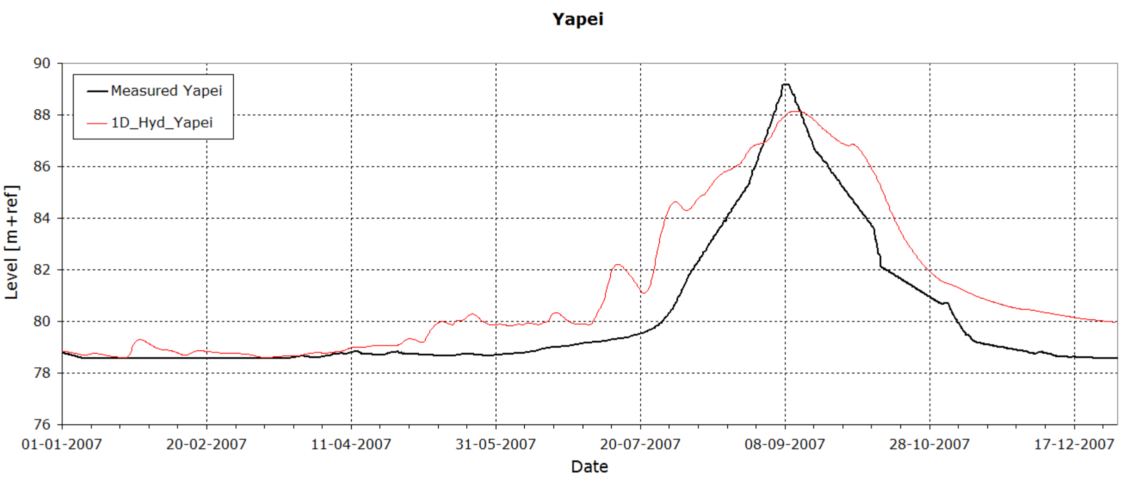


Figure E- 14 Measured and calculated water levels 2007 Yapei

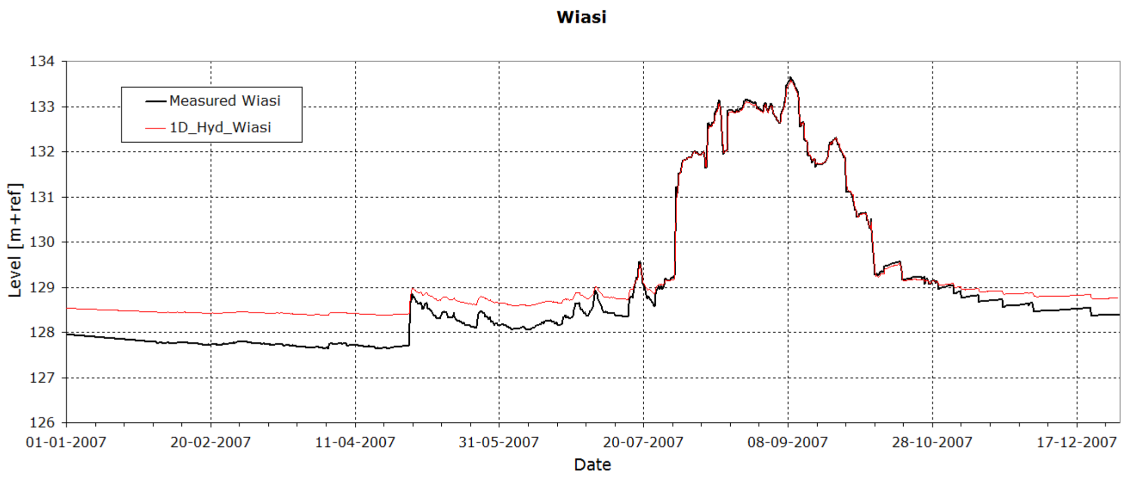


Figure E- 15 Measured and calculated water levels 2007 Wiasi

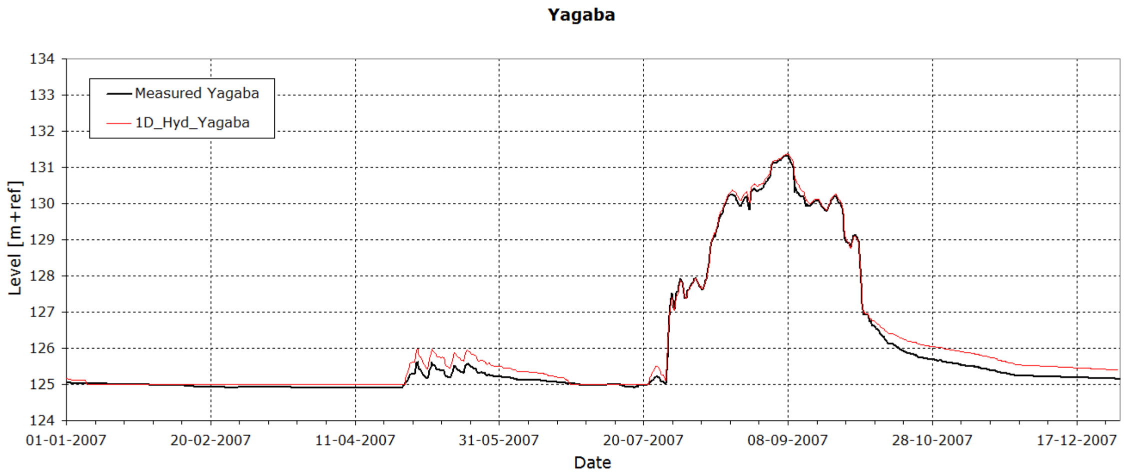


Figure E- 16 Measured and calculated water levels 2007 Yagaba

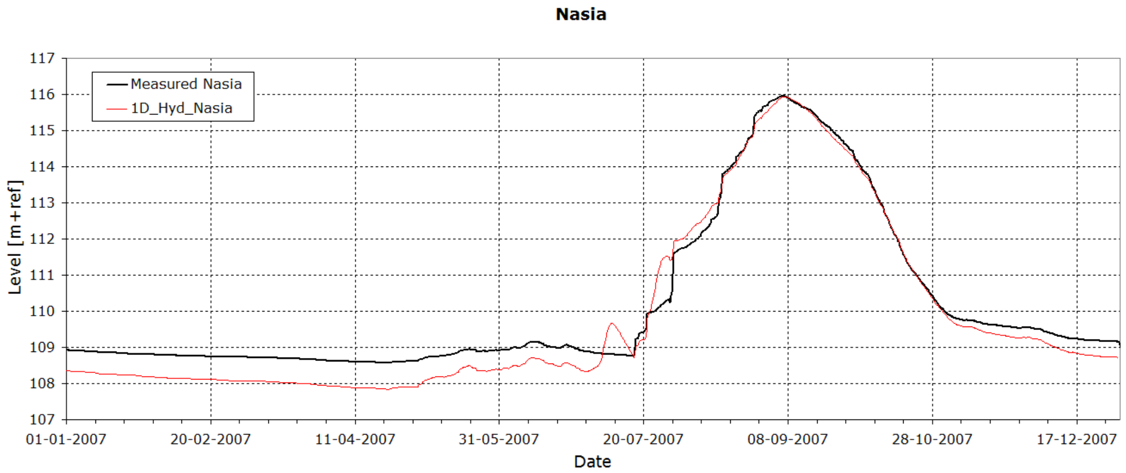


Figure E- 17 Measured and calculated water levels 2007 Nasia

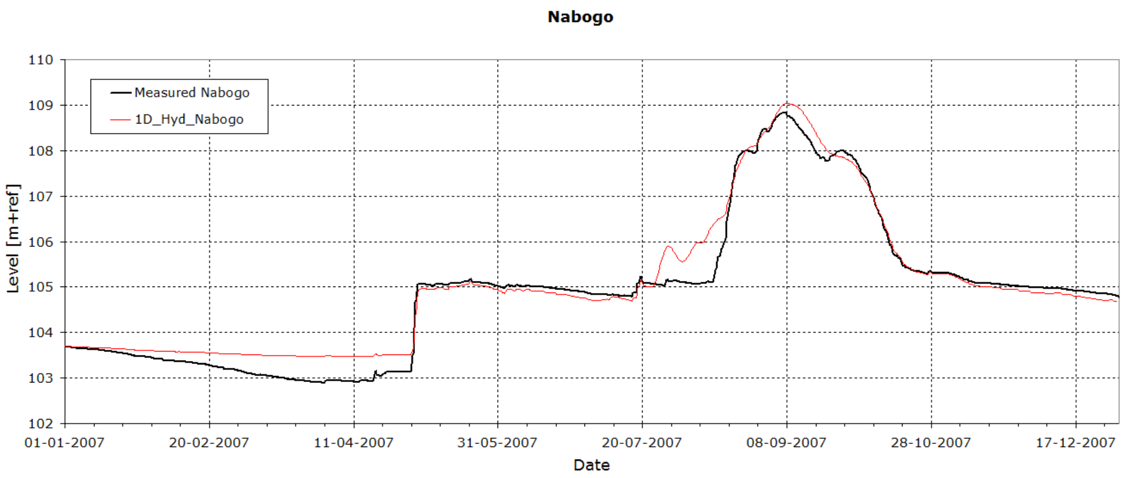


Figure E- 18 Measured and calculated water levels 2007 Nabogo

Results 2003-2007

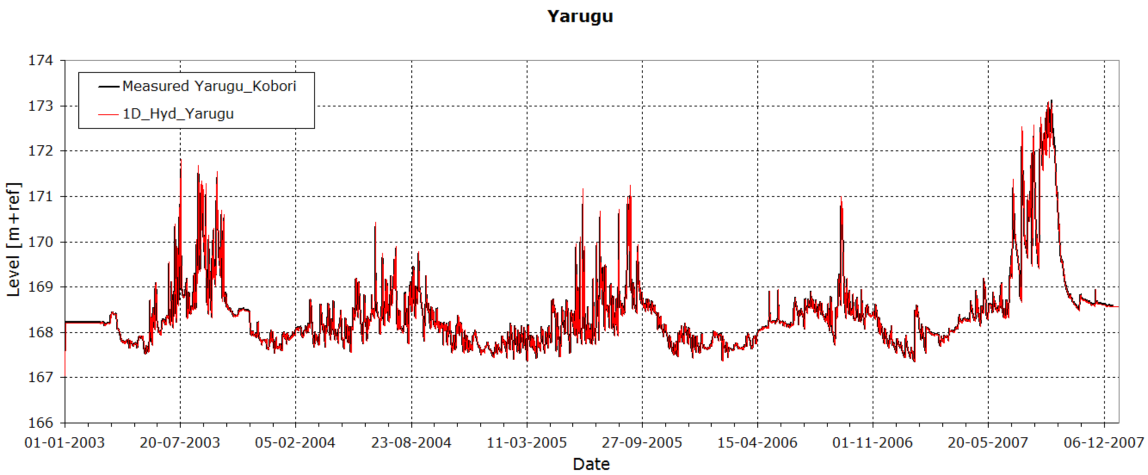


Figure E- 19 Measured and calculated water levels 2003-2007 Yarugu Kobori

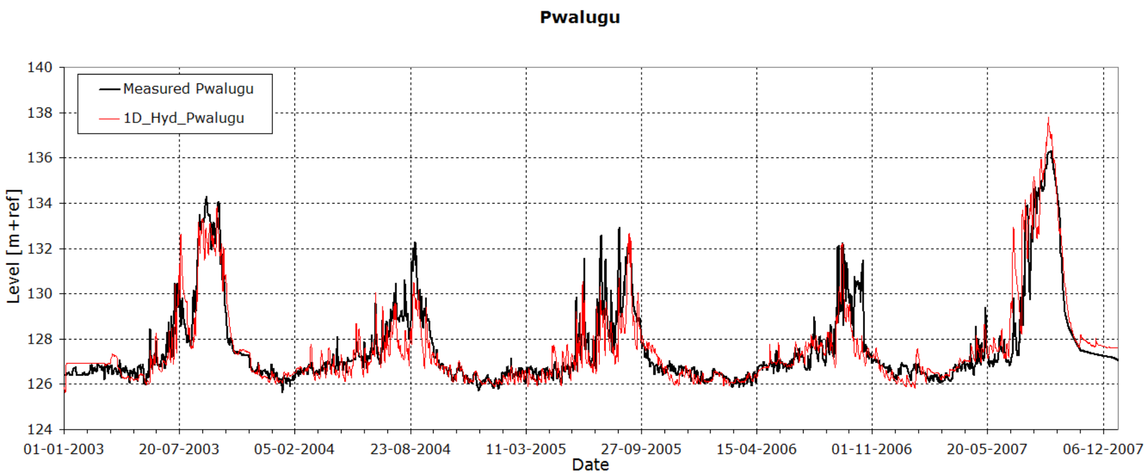


Figure E- 20 Measured and calculated water levels 2003-2007 Pwalugu

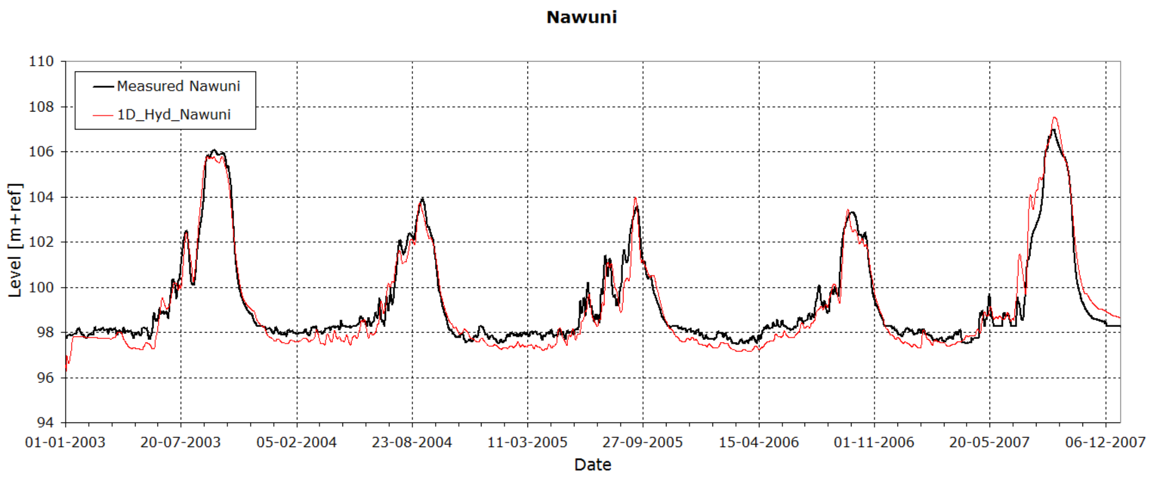


Figure E- 21 Measured and calculated water levels 2003-2007 Nawuni

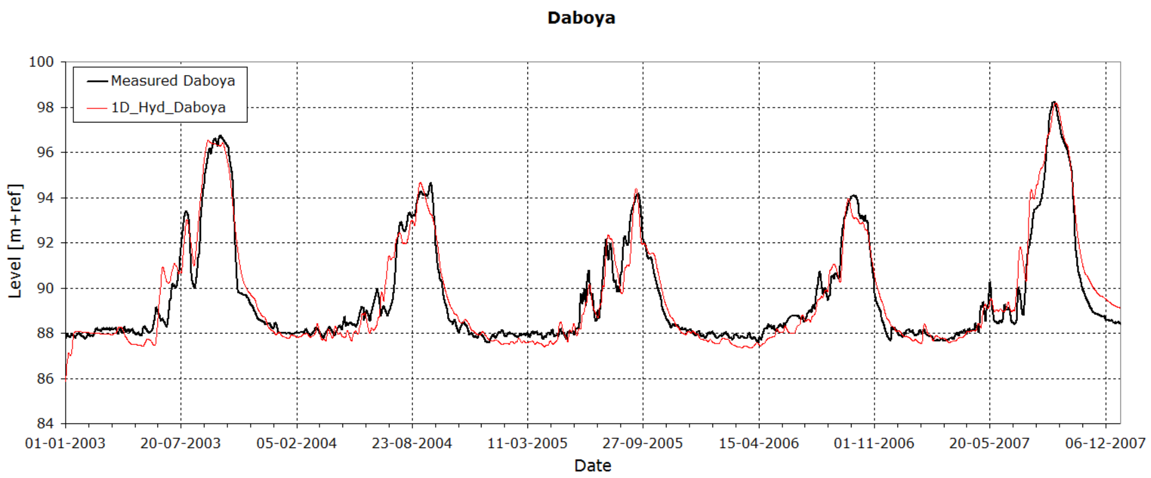


Figure E- 22 Measured and calculated water levels 2003-2007 Daboya

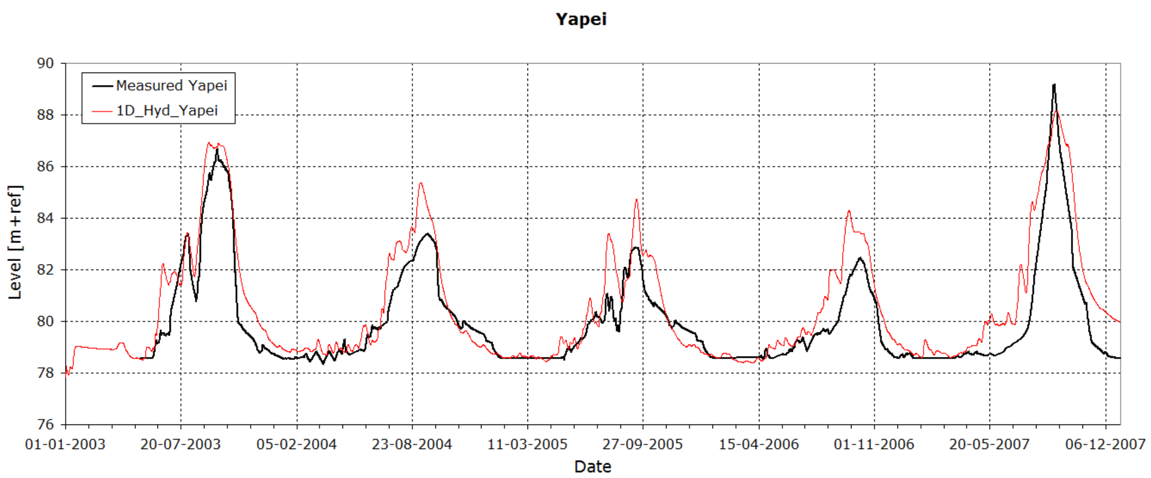


Figure E- 23 Measured and calculated water levels 2003-2007 Yapei

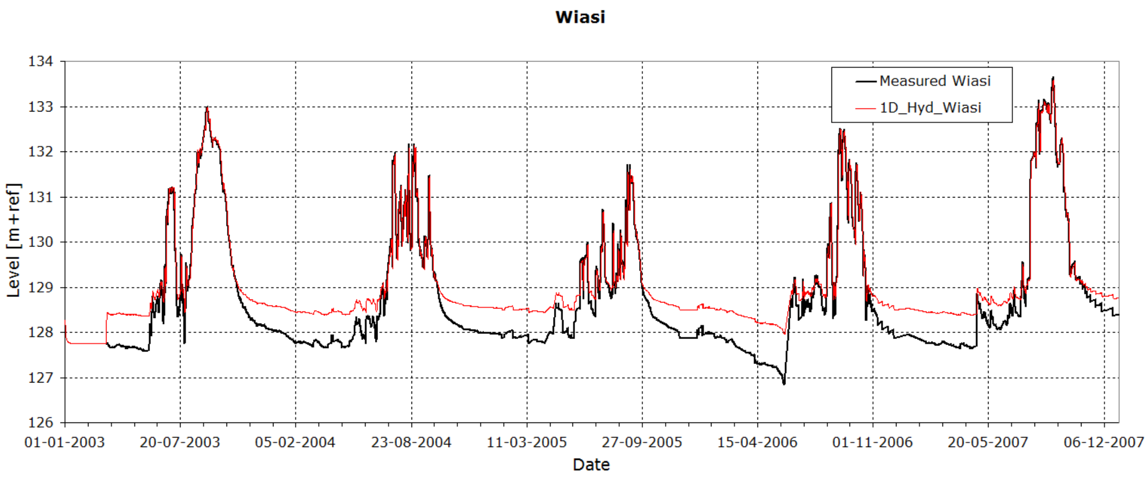


Figure E- 24 Measured and calculated water levels 2003-2007 Wiasi

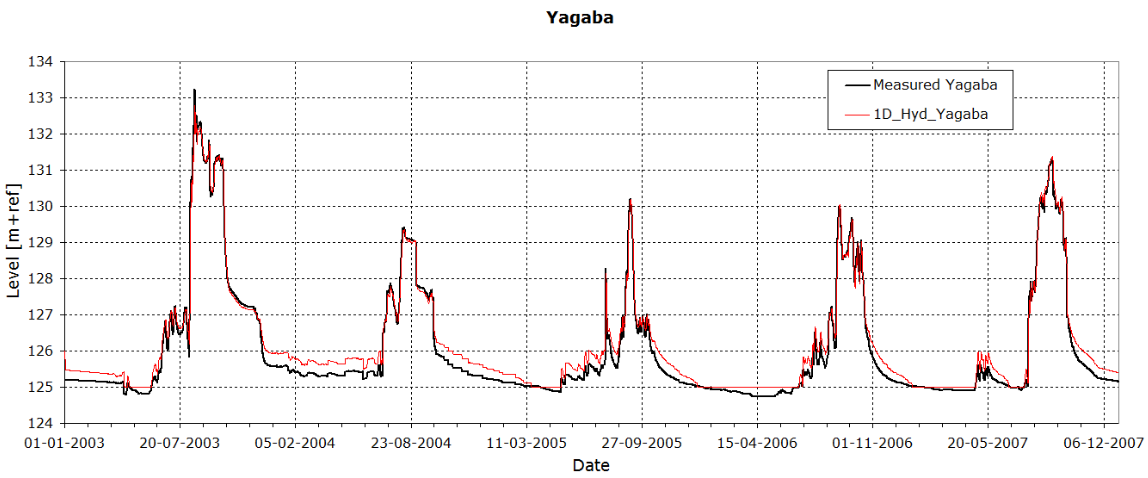


Figure E- 25 Measured and calculated water levels 2003-2007 Yagaba

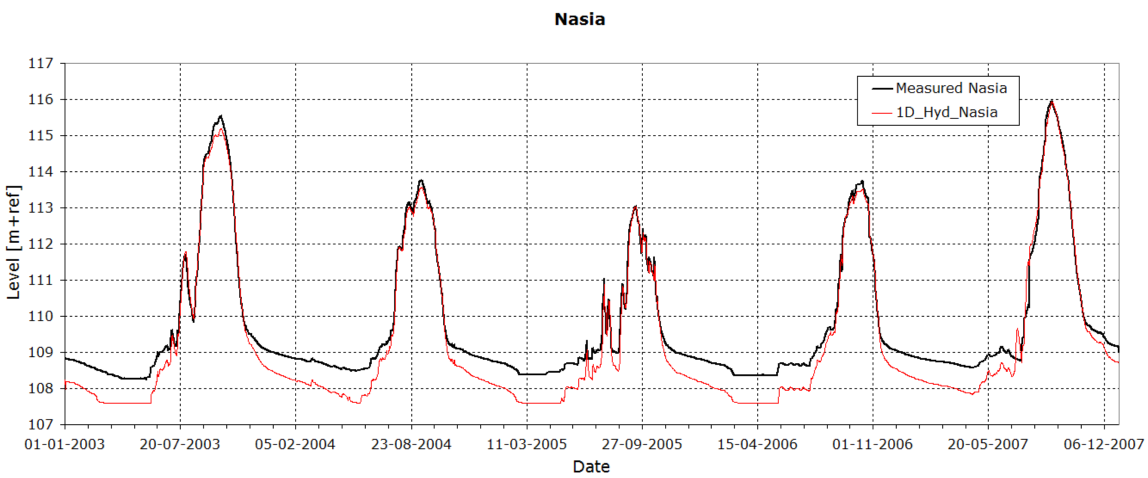


Figure E- 26 Measured and calculated water levels 2003-2007 Nasia

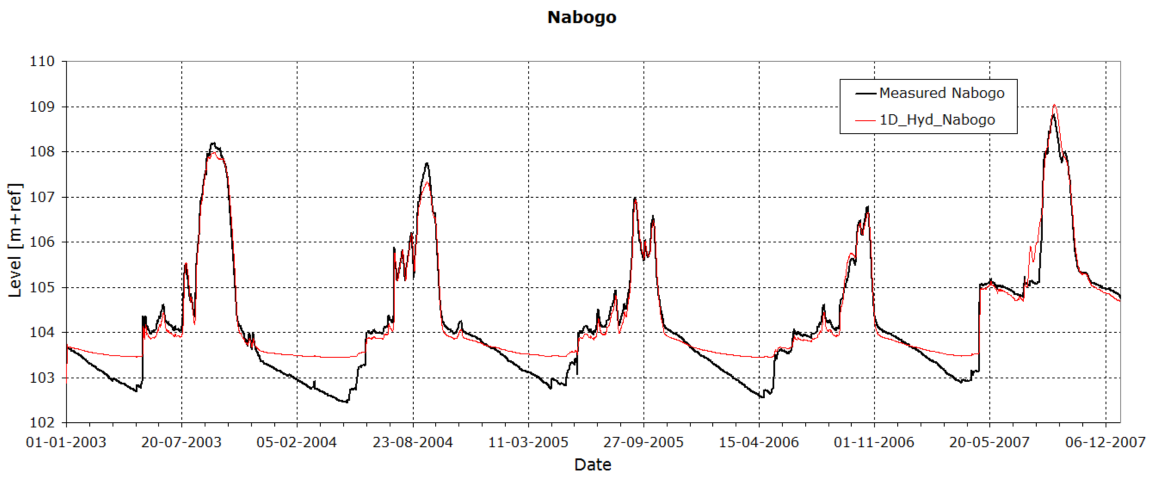


Figure E- 27 Measured and calculated water levels 2003-2007 Nabogo

Appendix F: Meteo forecast description

MM5 version 3.6 is run for two domains with 61 x 61 horizontal grids of 81 km and 27 km resolution, respectively, and 25 orographically adopted vertical levels extending between 20 m above ground and 30 hPa. To couple these domains, two-way nesting technique is applied.
As input we use the 6-hourly global analysis and forecast 1-degree resolution fields provided by Global Forecast System (GFS) from NCEP:
http://www.nco.ncep.noaa.gov/pmb/products/gfs/
The fallowing physical model setup is being used (detail descriptions cited from MM5 User Guide):

- Noah Land-Surface Model
  The land-surface model is capable of predicting soil moisture and temperature in four layers (10, 30, 60 and 100 cm thick), as well as canopy moisture and water-equivalent snow depth. It also outputs surface and underground run-off accumulations.
- MRF planetary boundary layer scheme
  Efficient scheme based on Troen-Mahrt representation of countergradient term and K profile in the well mixed PBL, as implemented in the NCEP MRF model. See Hong and Pan (1996) for details. Vertical diffusion uses an implicit scheme to allow longer time steps.
- Grell cumulus scheme
  Based on rate of destabilization or quasi-equilibrium, simple single-cloud scheme with updraft and downdraft fluxes and compensating motion determining heating/moistening profile. Useful for smaller grid sizes 10-30 km, tends to allow a balance between resolved scale rainfall and convective rainfall. Shear effects on precipitation efficiency are considered. See Grell et al. (1994).
- Shallow convection switched on
- Cloud-radiation scheme
  Sophisticated enough to account for longwave and shortwave interactions with explicit cloud and clear-air. As well as atmospheric temperature tendencies, this provides surface radiation fluxes.
- Explicit Moisture Scheme: Reisner graupel
  Based on mixed-phase scheme (supercooled water added to above and allowing for slow melting of snow, see Reisner et al. (1998) for details) and adding graupel and ice number concentration prediction equations.

Basic tests on the validation of this model setup had been published at *Kunstmann and Jung (2003):*
Investigation on feedback mechanisms between soil moisture, land use and precipitation in West Africa; IAHS publications No. 280; Water Resources Systems – Water availability and Global Change.
and further applied as cited in the PhD-work by *G. Jung (2006): "Regional Climate Change and Impact on Hydrology in the Volta Basin of West Africa"* .

Appendix G: Forecast procedure

version 1.01 October 2012

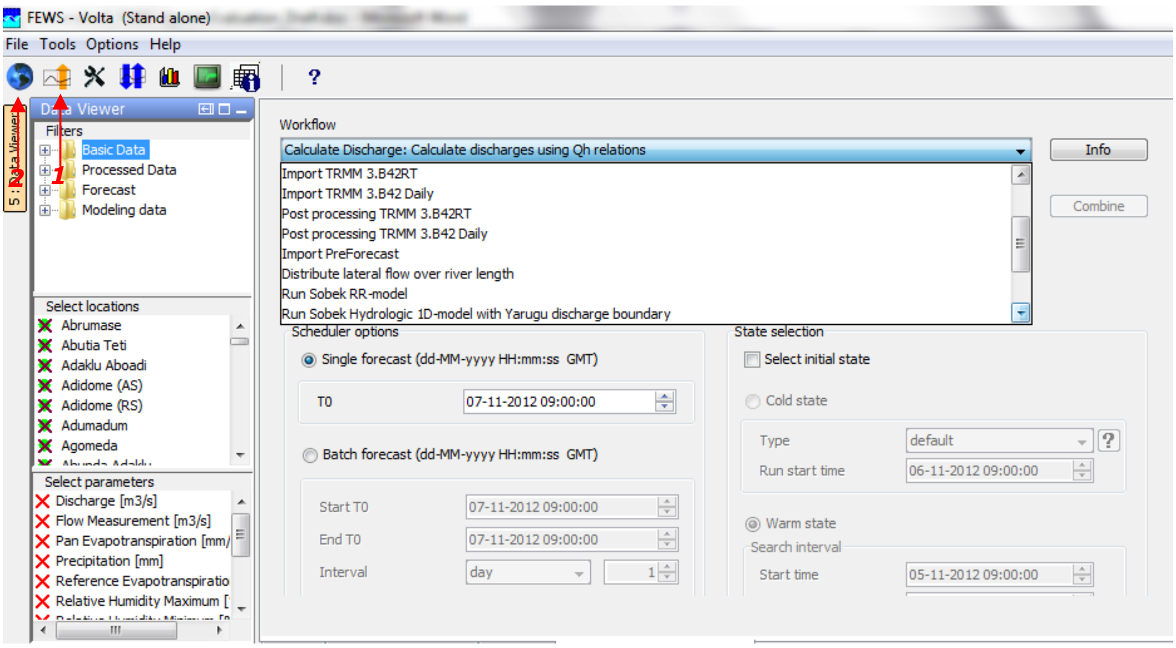
The following steps describe the standard forecasting procedure for FEWS-Volta used by the forecaster on duty.

Download meteorological data

1. Run the download script *Download.pl* manually or automatically (scheduling a task in windows scheduler). \FEWS_VOLTA\Software\Perl\FTP\TRMM\PerlFTPDownload\
   The script downloads both the meteorological forecast (also called preforecast) as well as the TRMM-RT data.
2. TRMM daily data is updated only every 2-3 months. A separate download script is available for this download (*Download_Daily.pl* in \FEWS_VOLTA\Software\Perl\FTP\TRMM\PerlFTPDownload\) that should be run every week.
3. Check if the download of was successful in
   \FEWS_VOLTA\Import\PreForecast_tgz for meteo forecast
   \FEWS_VOLTA\Import\TRMM\3B42RT\asc for TRMM RT
   \FEWS_VOLTA\Import\TRMM\3B42Daily for TRMM daily
   a. yes: proceed
   b. no: download manually when internet is available (also see manual download under How to) **mind:** the cause that TRMM daily was not downloaded is probably that it was not updated yet. Data can also be checked on the ftp-site (see manual download under How to).

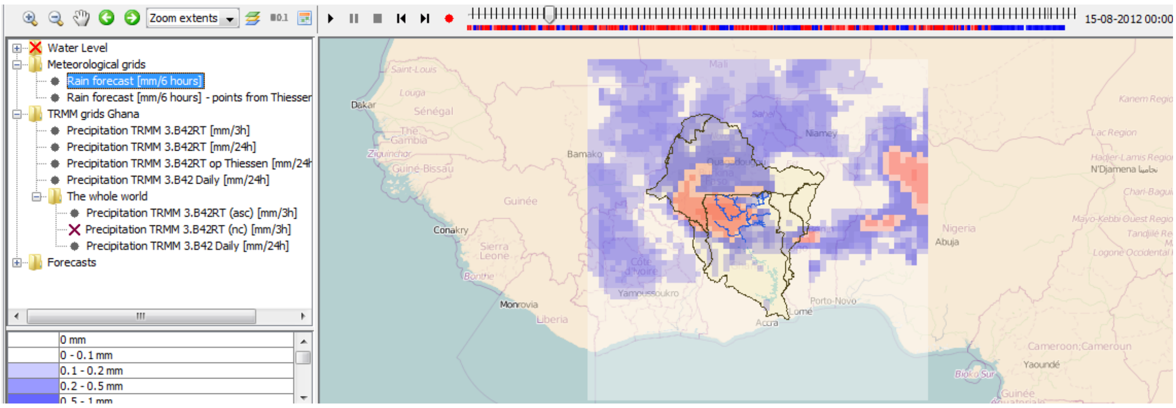
Import data in FEWS-Volta

The meteo data is imported using the manual forecast button (1 in figure below). A list of workflows appear. The workflows are set for the daily forecast runs.



4. Run *Import PreForecast* in FEWS-Volta.
   Check the grid display whether the forecast was imported in FEWS-Volta successfully. Use (2) in the figure above to activate the grid display.

5. Run *Import TRMM 3.B42RT* in FEWS-Volta.
   This workflow imports TRMM data for the whole world.
6. Run *Postprocessing TRMM 3.B42RT* in FEWS-Volta.
   This workflow cuts out TRMM RT data for the White Volta catchment. The world wide TRMM data is removed automatically from FEWS to save memory.
   Check the grid display whether the forecast was imported in FEWS-Volta successfully.



Filters showing meteo forecast (meteorological grids), TRMM grids Ghana (RT and Daily), TRMM grids world (RT and daily)

7. If TRMM daily is available 5 and 6 should be performed for TRMM daily data as well (*Import TRMM 3.B42Daily* and *Post processing TRMM 3.B42Daily*).

Run forecasts

8. Run *Run Sobek RR-model* in FEWS-Volta. You can check in the filter *Modelling data\Sobek-RR\Input* and *Output* if the results are satisfactory. This filter also shows the merge of the different meteo sources in *Sobek RR precipitation merge*. It presents ground station data, TRMM RT, TRMM daily and meteo forecast. It also shows that the merge hierarchy is:
   a. Ground station data, if not available;
   b. TRMM daily data, if not available;
   c. TRMM RT data, if not available;
   d. Meteo forecast data.
9. Add using *edit mode* in the filter *Processed data\Hydrology* the following data for the relevant forecast period:
   a. *Yarugu* discharge or;
   b. *Yarugu* water level;
   Water level data is available at:
   http://platform.novacom-services.com/novaserv/jsp/novacom/login.jsp
   User: HSD-GHANA
   Password: GLOWA
   c. *Akosombo* water level.
   Available at VRA (Philip or Afua)
   Make sure to save the added data!
10. Run *Sobek Hydrologic 1-D model with Yarugu discharge boundary* when calculating with Yarugu discharge or *Sobek Hydrologic 1-D model with Yarugu water level boundary* when calculating with Yarugu water level.
    Check the filter *Modelling data\Sobek-1D\Input* and *Output* if the results are satisfactory.
11. Check the final forecast results and warning levels in the filter *Forecast* and decide whether to:

a. do nothing;
b. rerun the forecast with different settings or data;
c. forward the forecast to relevant institutes.

How to?

Download data manually
You can also download the trmm and meteo forecast data manually (with an ftp-programme for instance). After downloading it place it in the import directories listed below. Next run the updated Download.pl or DownloadDaily.pl.

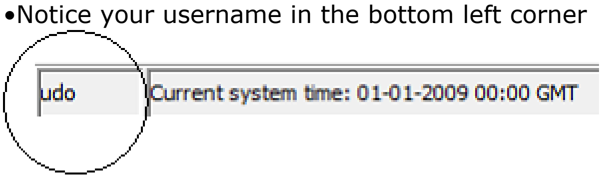
TRMM-RT
ftp://trmmopen.gsfc.nasa.gov/pub/merged/calibratedIR/
User: ftp
Password: helpdesk_fews@hkv.nl
\FEWS_VOLTA\Import\TRMM\3B42RT\asc

TRMM-Daily
ftp://disc2.nascom.nasa.gov/data/TRMM/Gridded/Derived_Products/3B42_V7/Daily/2012/
User: ftp
Password: helpdesk_fews@hkv.nl
FEWS_VOLTA\Import\TRMM\3B42Daily

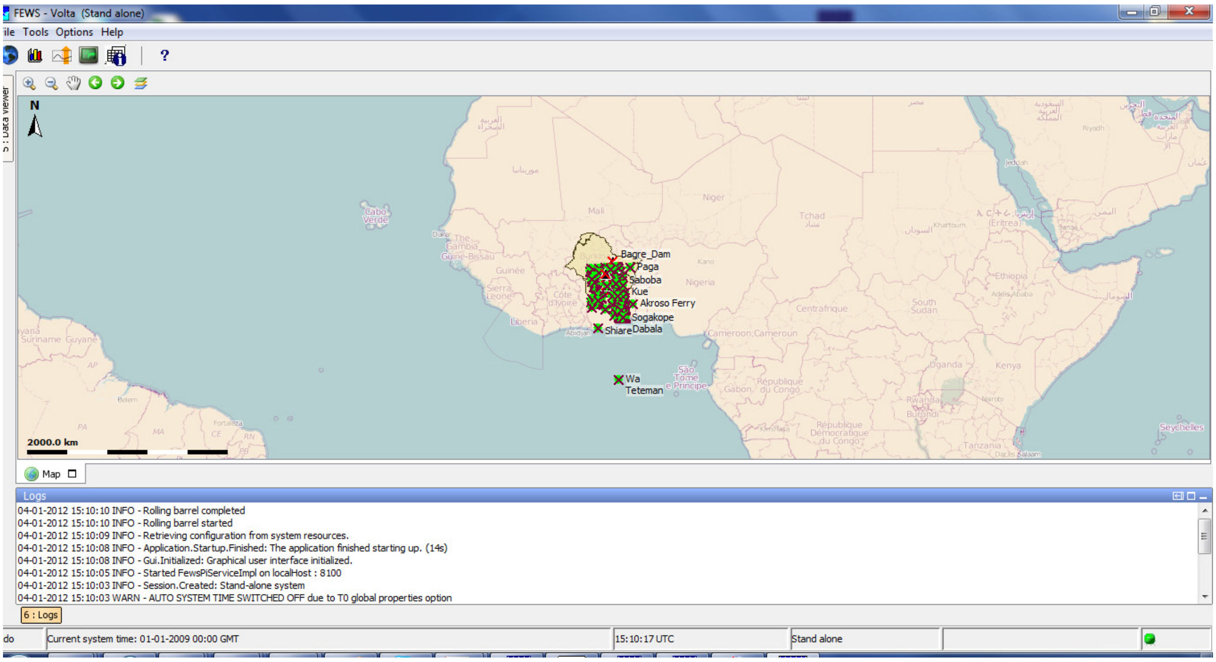
Meteoforecast:
ftp://ftp.imk-ifu.kit.edu/projects/wetter/Westafrica/
User: wetterget
Password: ?Wteg-8
\FEWS_VOLTA\Import\PreForecast_tgz

Install the system

•Copy \FEWS_VOLTA\ to your computer
•Make sure you have java installed or install it: \FEWS_VOLTA\Java
•Find and open with notepad \\FEWS_VOLTA\bin\FEWS_VOLTA.jpif
•Make sure it refers to where java is installed on your computer, for example: C:\Program Files (x86)\Java\jre6
•Find and double click \FEWS_VOLTA\bin\FEWS_VOLTA.exe
•Notice your username in the bottom left corner



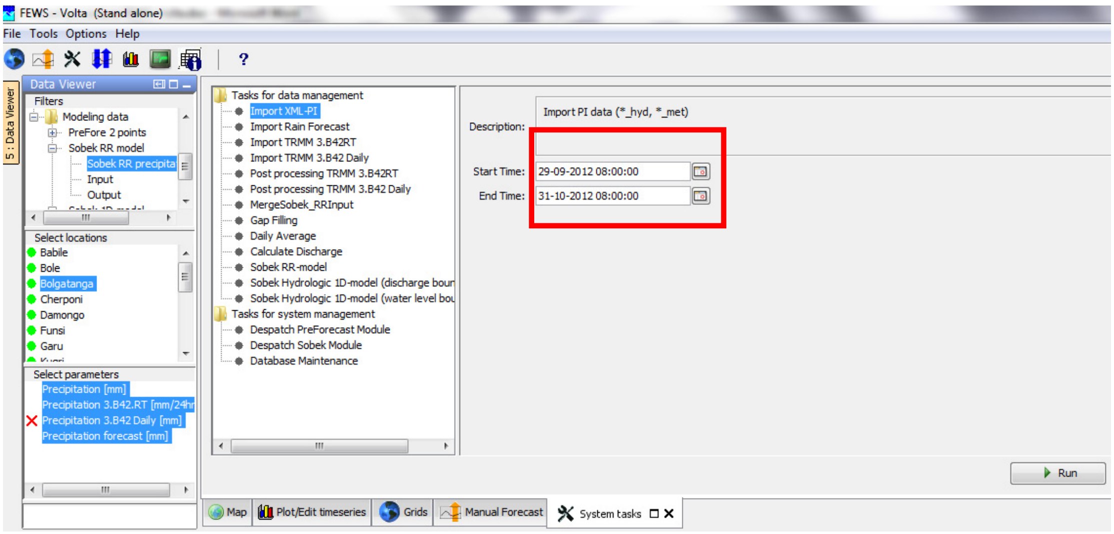
•Notice you can't see any stations
•Find and open with notepad \FEWS_VOLTA\Config\SystemConfigFiles\UserGroups.xml
•Add your name to
<userGroup id="configuratoren">
Similar to the other names
•Find and double click \FEWS_VOLTA\bin\FEWS_VOLTA.exe



Extent calculation period

Click on the system tasks button 

Any workflow can be defined for a user defined period as indicated in red. Mind, when running a 1D calculation the used needs to ensure that all boundary conditions are available in the system, otherwise the calculation will crash. This means: Sobek-RR model results, Aksomobo dam and Yarugu boundary (Q or h).



Appendix H: Annual precipitation anomaly

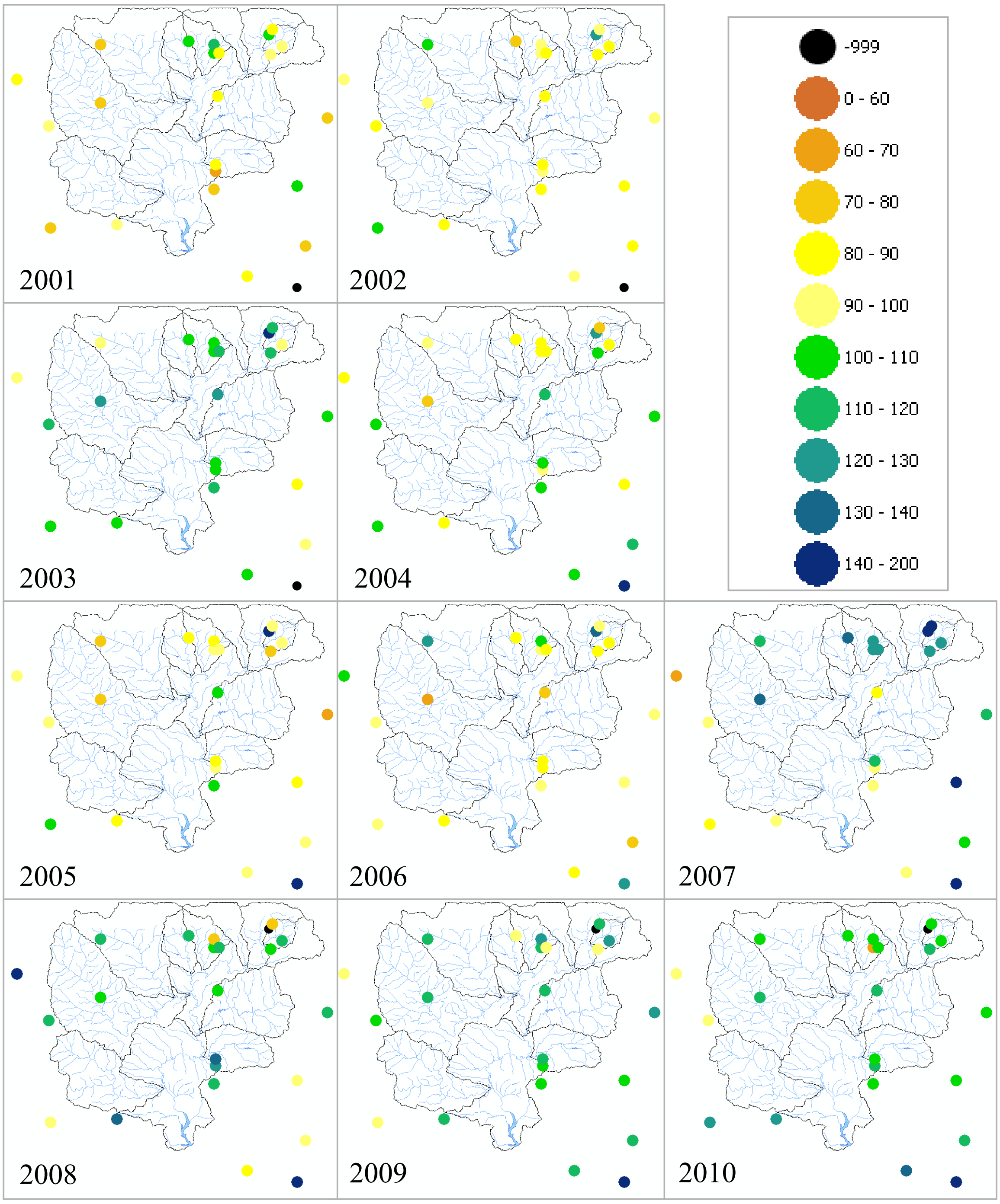


Figure H- 1 Percentage difference between the annual average precipitation (over the period 2000 to 2010) for each year per meteorological station

Appendix I: Flood risk map examples

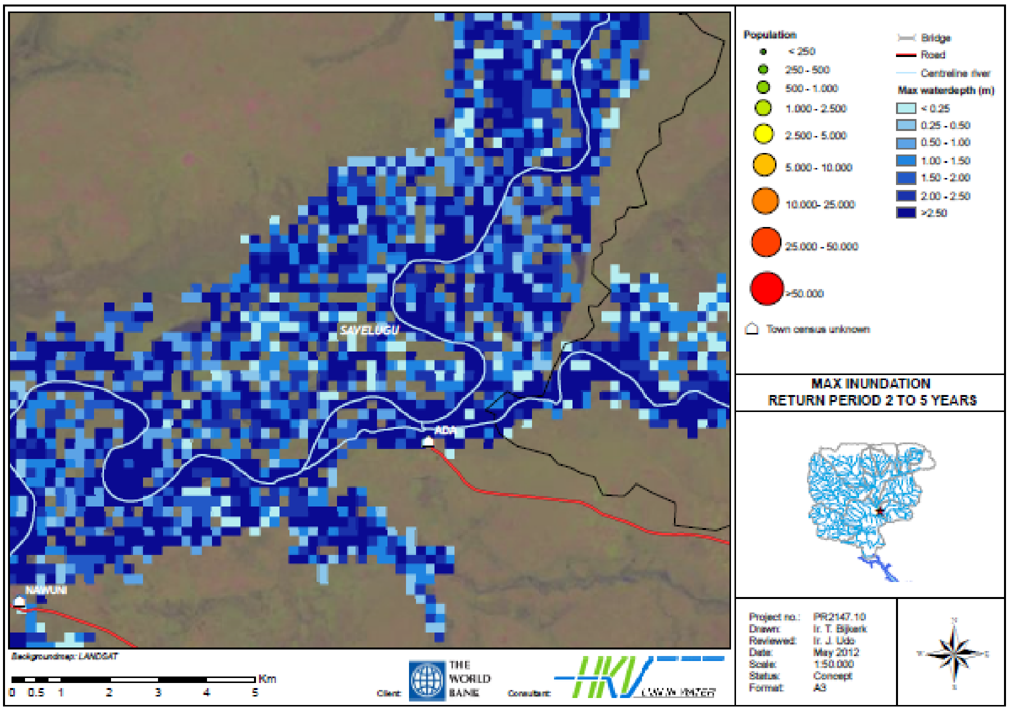


Figure I- 1 Flood risk map 1:10, 1:25, 1:50 1:100 in 1:50000 scale, Nawuni area

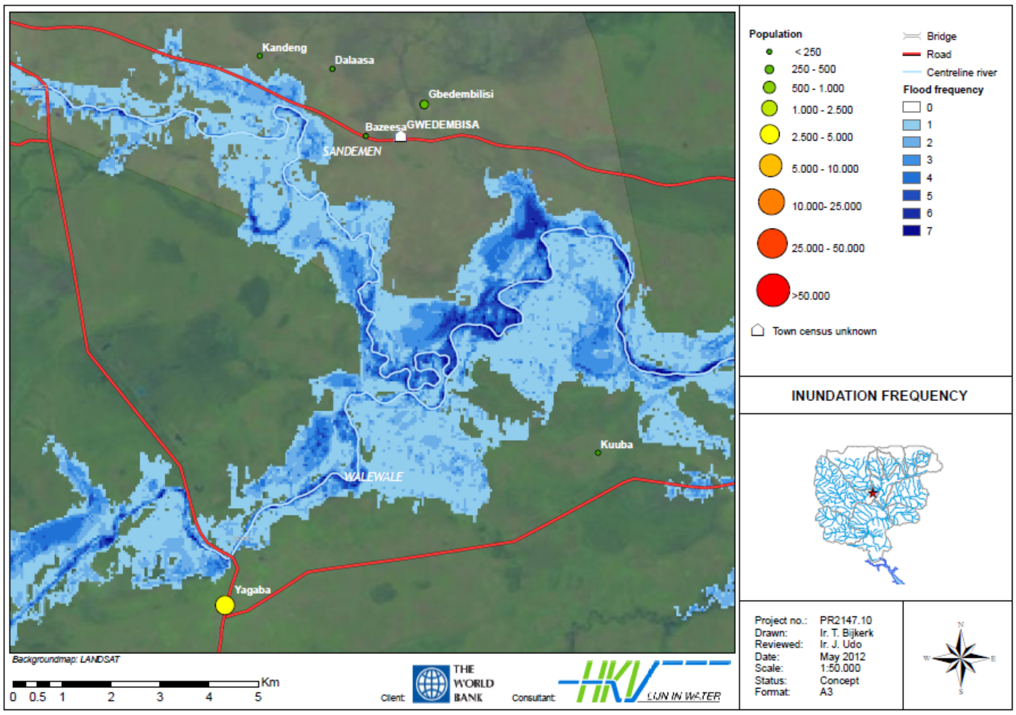


Figure I- 2 Flood event frequency map in 1:50000 scale, Yagaba area. Showing areas that were flooded between 1-7 times based on 7 flood images available between 2000-2010.

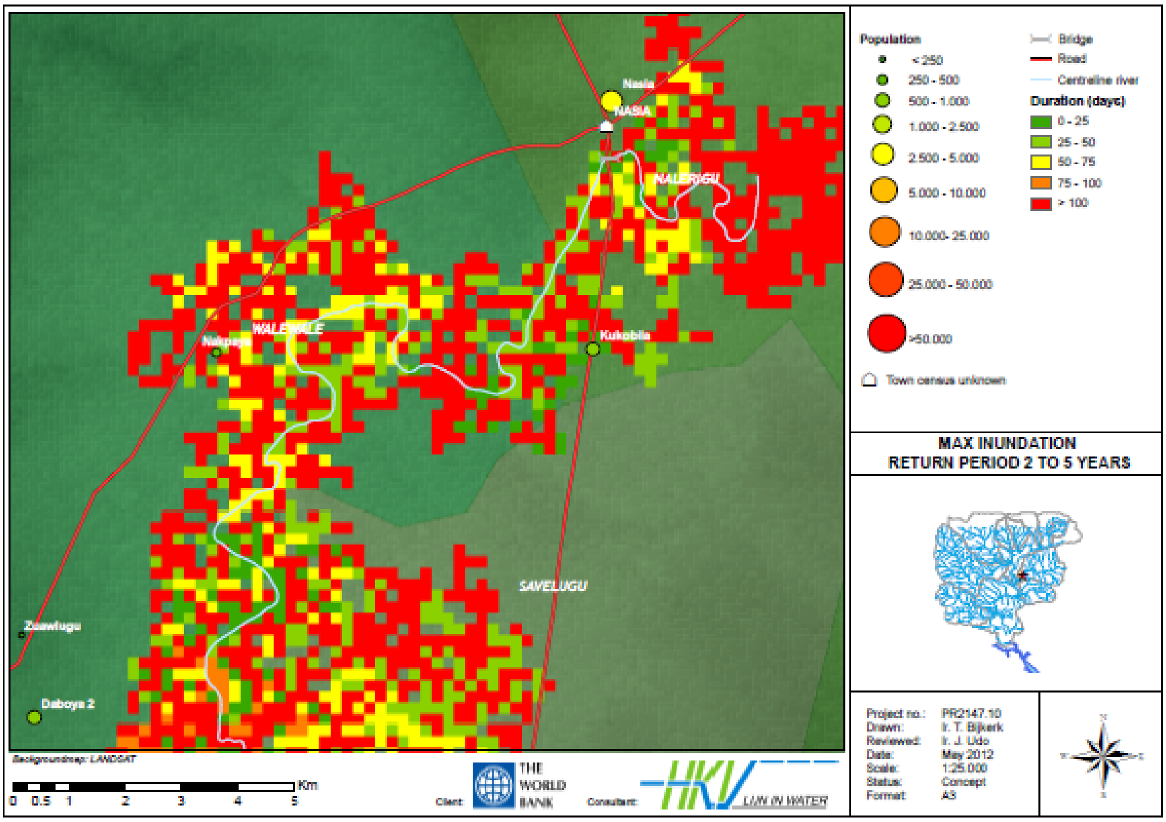


Figure I- 3 Flood duration map 1:2 and 1:5 years in 1:50000 scale, Nasia area

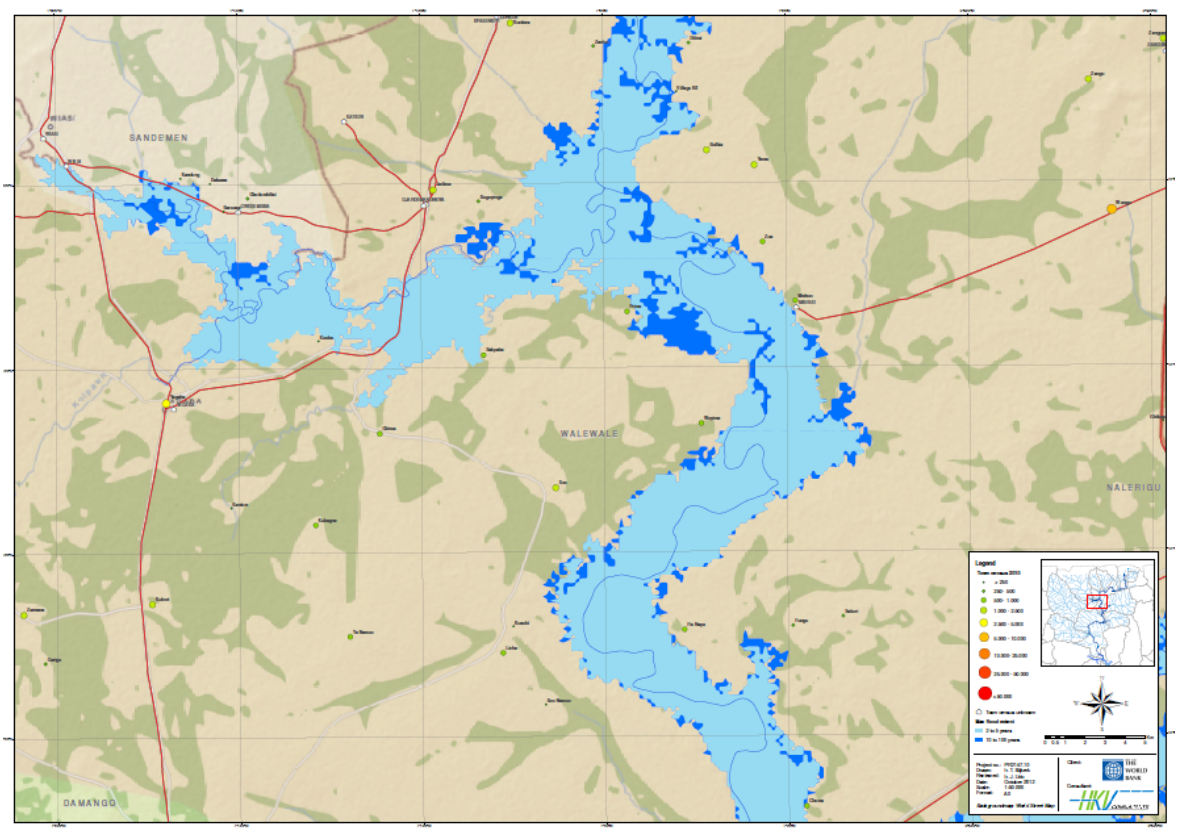


Figure I- 4 Flood extent map 2-100 years return period Kulpawn – White Volta area, A0

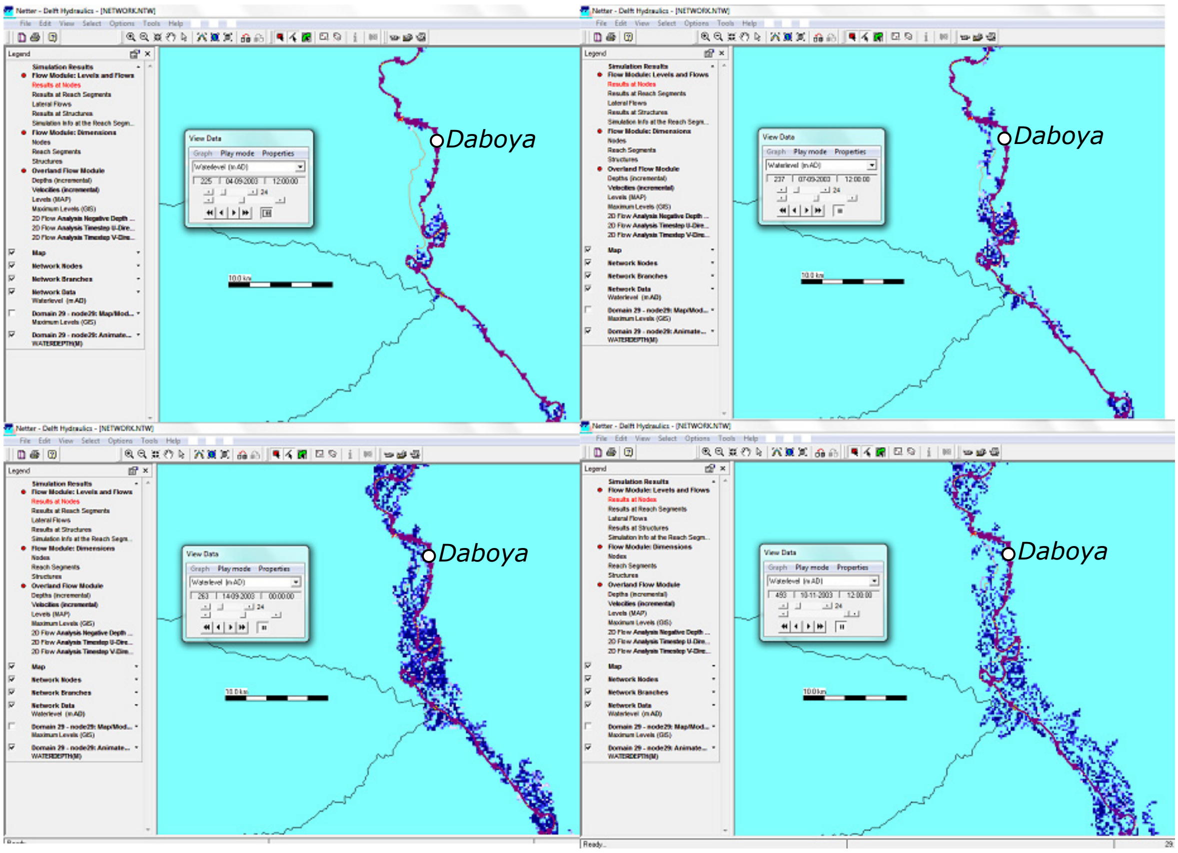


Figure I- 5 Snapshots of flood 2003 animation near Daboya illustrating that the water is transported through an old river channel

The maps below indicate communities at risk, preferred evacuation routes if relevant, roads that might be flooded, or bridges that might be affected. Specific areas at risk that might be difficult to reach during extreme flood events are indicated in red. Besides the communities presented in the maps, Google earth was used to identity additional vulnerable structures, areas and communities.

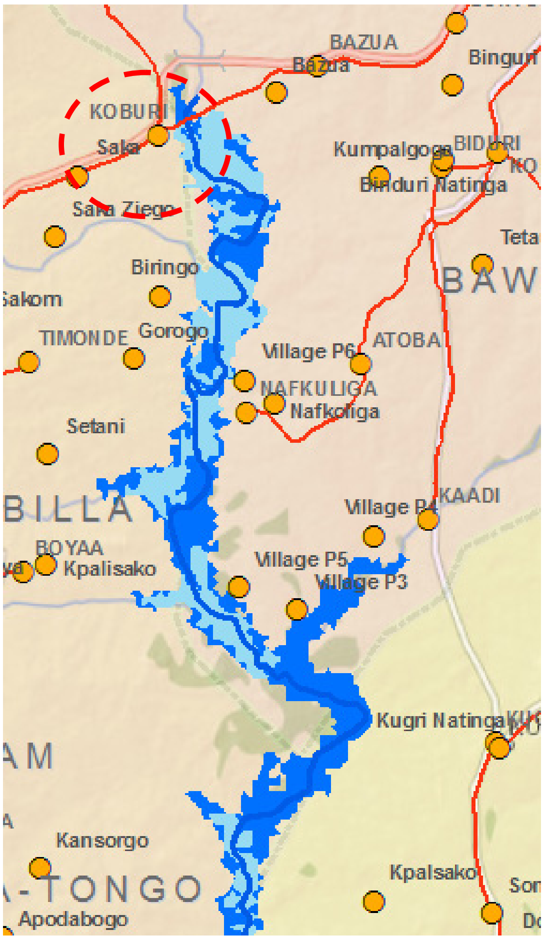


Figure I- 6 Flood extent Yarugu -Pwalugu

Section Yarugu – Pwalugu

The bridge and road near Yarugu and Kobori can be affected by floods, marked red in the figure. In 2012 the road was flooded from the west side due to extreme releases from the Bagre dam.

Remark: the road near Kobori follows a northern direction as indicated in the background map. The straight river crossing does not exist any more.

Communities at risk are:

- Kobori
- Village P6
- Village P3

Section Pwalugu – Kpasenkpe

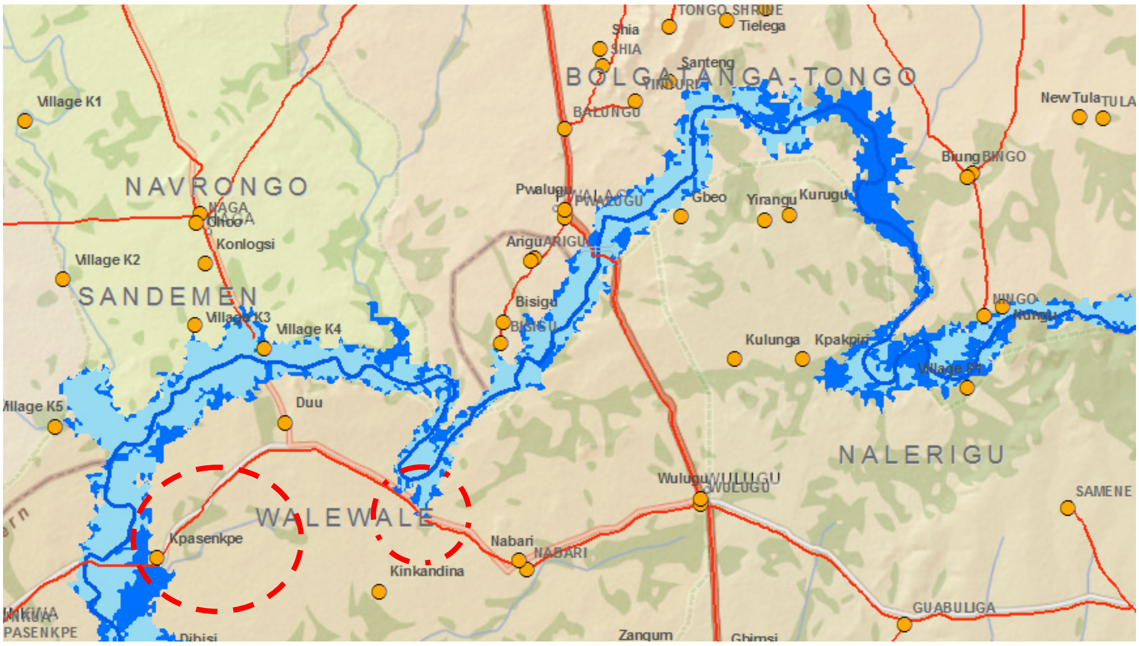


Figure I- 7 Flood extent Pwalugu - Kpasenkpe

The road from Wulugu to Kpasenkpe might be flooded from the north as marked in the maps above. This means that the community of Kpasenkpe might be difficult to reach in an extreme flood event. Field inspection shows that the bridge near Kpasenkpe is high enough to sustain extreme floods. The road to and from the bridge is prone to floods.
The following communities and structures shown on the map might be at risk as well:

- Kpasenkpe
- Ningo
- Village P1
- Pwalugu, bridge and road
- Gbeo
- Bisigu
- Arigu
- Balure
- Village K3
- Village K4
- Village K2
- Village K5

Section Kpasenkpe – Kulpawn

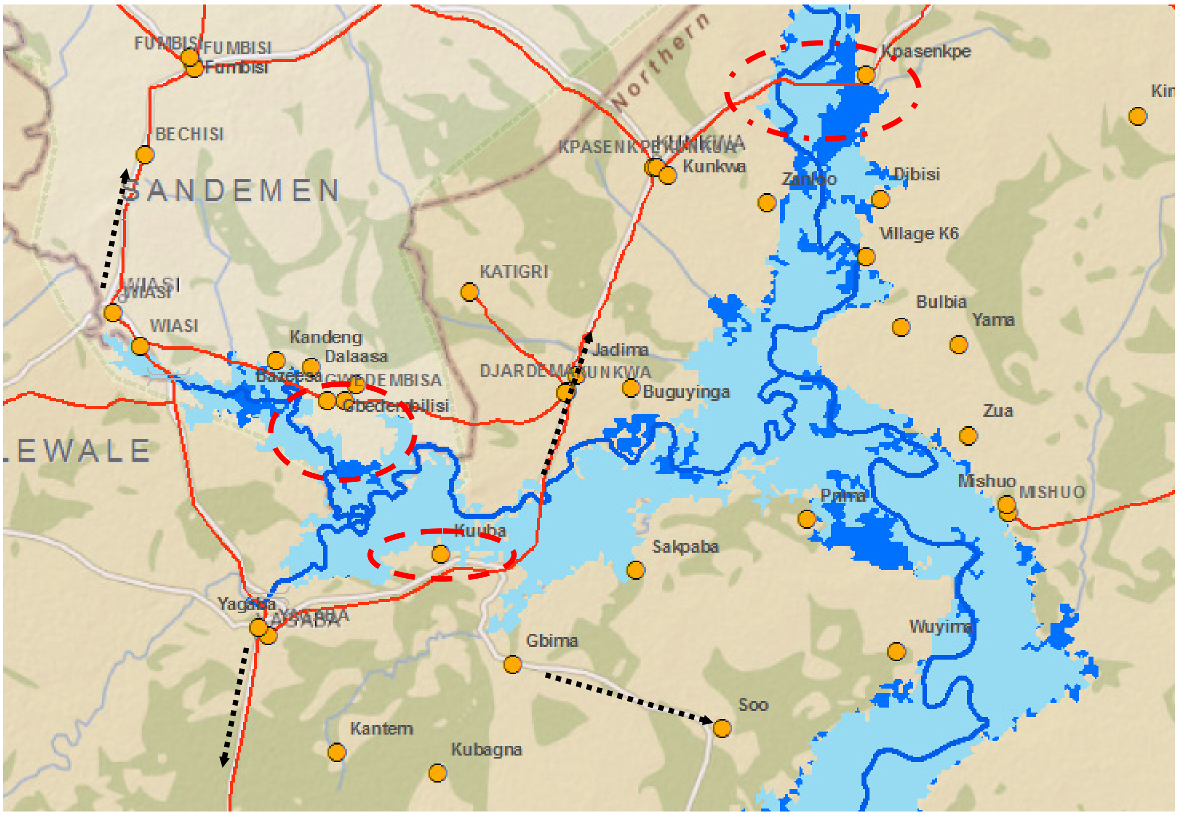


Figure I- 8 Flood extent Kpasenkpe - Kulpawn

Communities along the White Volta that might be at risk are:

- Zanloo
- Dibisi
- Village K6
- Bulbia
- Kunkwa

Communities along the Sisili - Kulpawn River that might be at risk are:

- Sakpaba
- Buguyinga
- Jadima/Djardema, use the road in north east direction for evacuation
- Gbima, use the road in south east direction for evacuation
- Kuba, might be enclosed by extreme floods.
- Yagaba (bridge and road), evacuate in southern direction
- Wiasi (bridge and road), evacuate in northern direction
- Kandeng, Dalaasa, Gwedembisa, Bazeesa: area might be enclosed by flood.

Section Kulpawn – Nasia

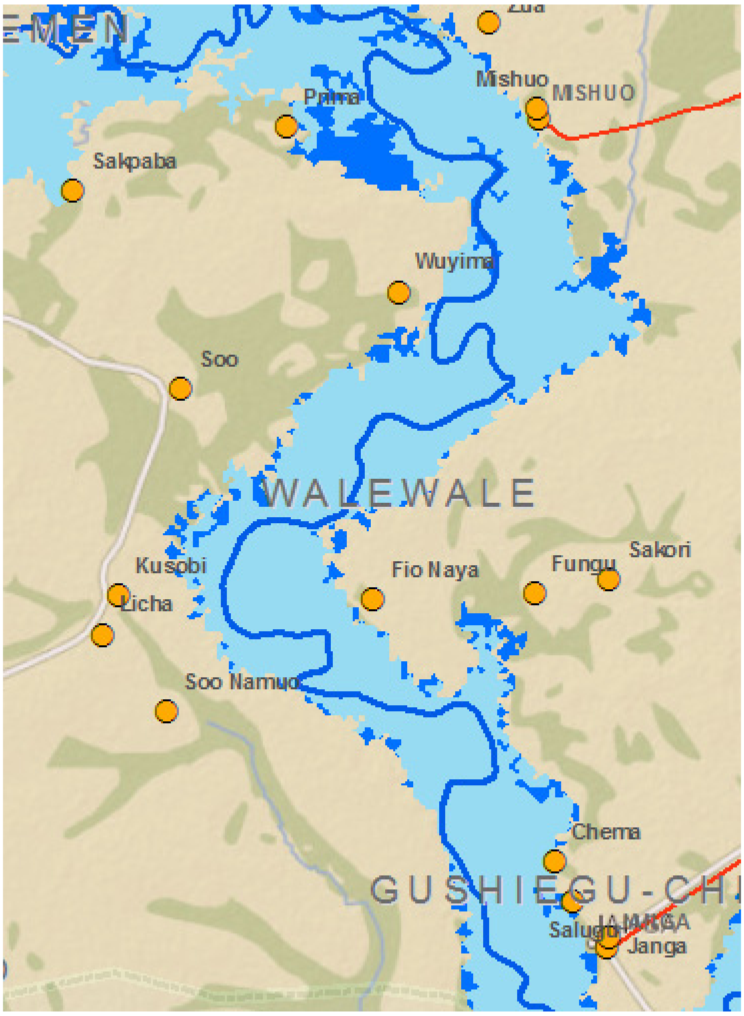


Figure I- 9 Flood extent Kulpawn - Nasia

Communities along the White Volta that might be at risk are:

- Prima
- Zua
- Mishuo (road to and from the community might be flooded as well)
- Wuyima
- Fio Naya
- Fungu
- Chema
- Salugu
- Janga

Section Nasia

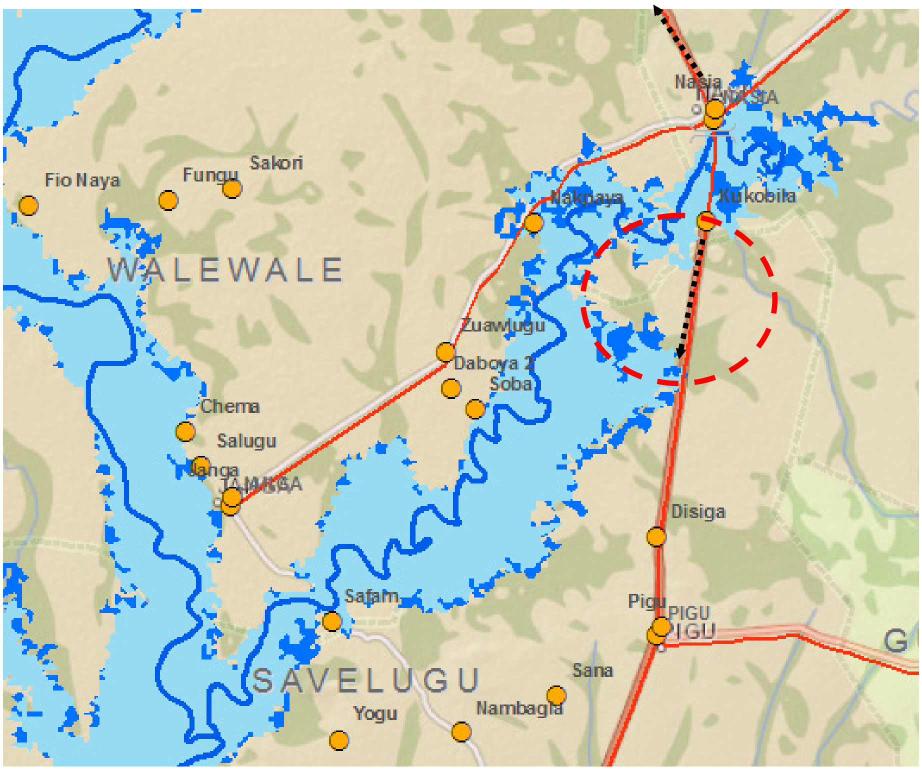


Figure I- 10 Flood extent Nasia

Communities along the Nasia River that might be at risk are:

- Nasia (also road and bridge), evacuate in northern direction.
- Disiga
- Kukubila, evacuate south, although road might be flooded from south side as well
- Nakpaya
- Soba
- Safam

Section Nasia – Nabogo

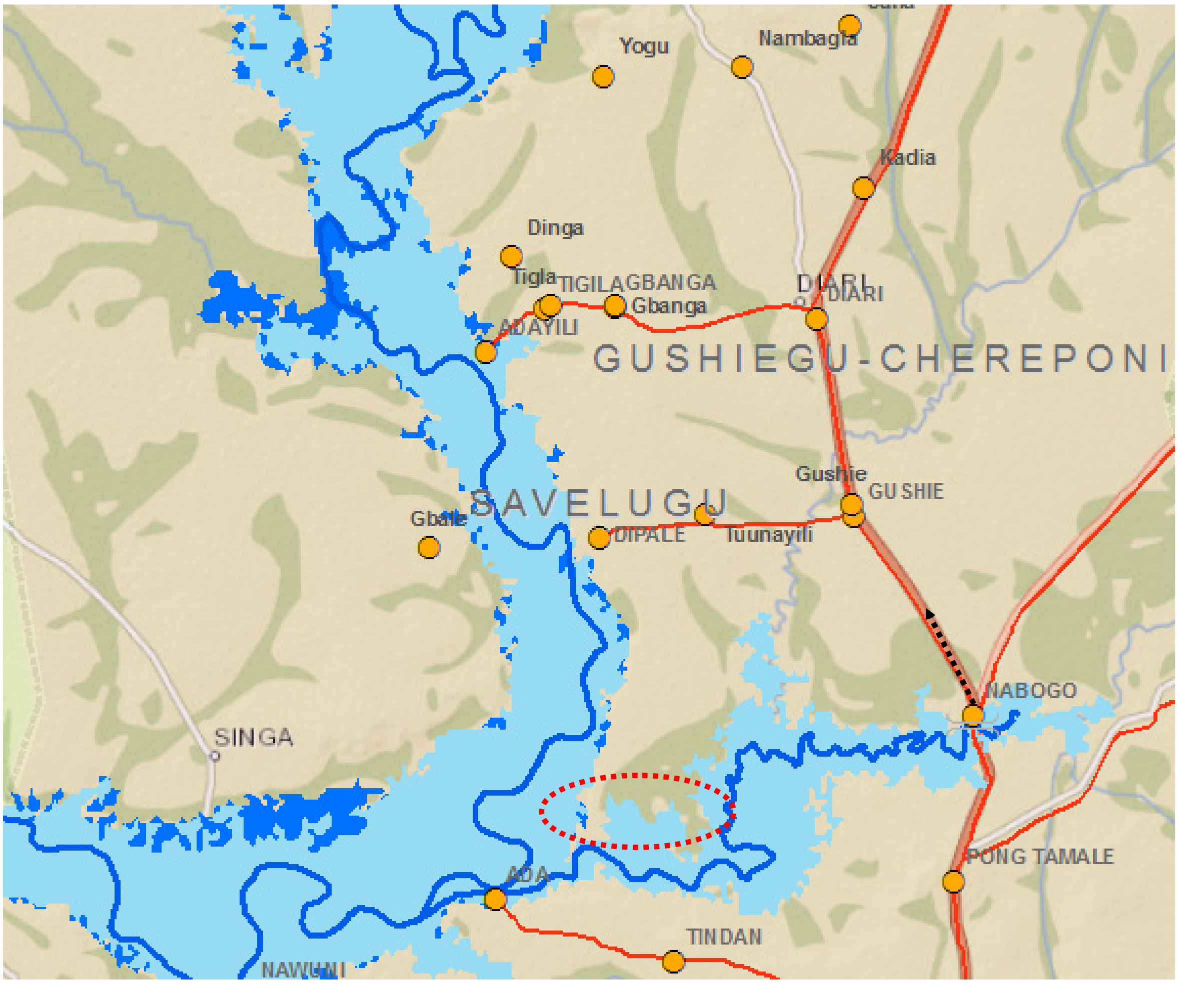


Figure I- 11 Flood extent Nasia - Nabogo

The following communities and areas are at risk along the White Volta River:

- West of Dinga, agricultural lands and roads
- South west of Dinga, agricultural lands and roads
- Adayili
- Duni
- Gbale
- Dipale

Along the Nabogo River the following communities are at risk:

- Nabogo, road and bridge, evacuate in northern direction
- A number of unnamed communities on the north banks of Nabogo and east bank of White Volta are at risk.

Section Nabogo – Nawuni – Daboya

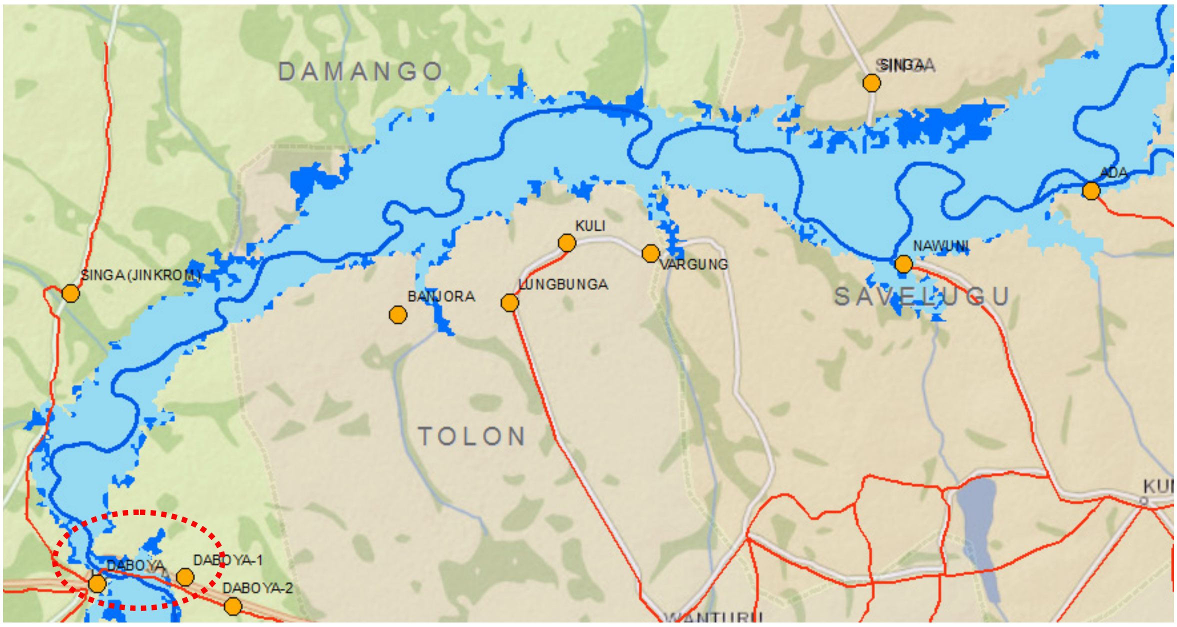


Figure I- 12 Flood extent Nawuni - Daboya

The following communities are at risk:

- Ada
- Singa
- Nawuni, the water intake for the city of Tamale is located here as well
- Vargung
- Kuli
- Villages north west of Lungbunga
- Banjora
- Communities west and north west of Banjora
- North of Daboya, the road parallel to the river is under flood threat as well
- Daboya
- Communities east of Daboya

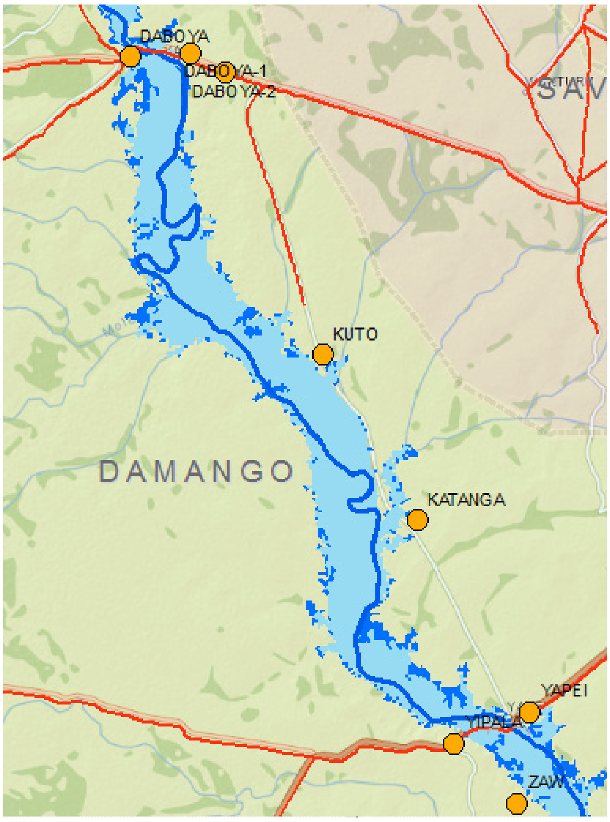


Figure I- 13 Flood extent Daboya - Yapei

Section Daboya - Yapei

The following communities are at risk:

- Kuto
- Katanga
- Road between Kuto and Katanga parallel to the White Volta River
- Communities between Katanga and east river bank

Community west of Katanga on west river bank, road from there with some structures parallel with river in southern direction.

Section Yapei – Lake Volta

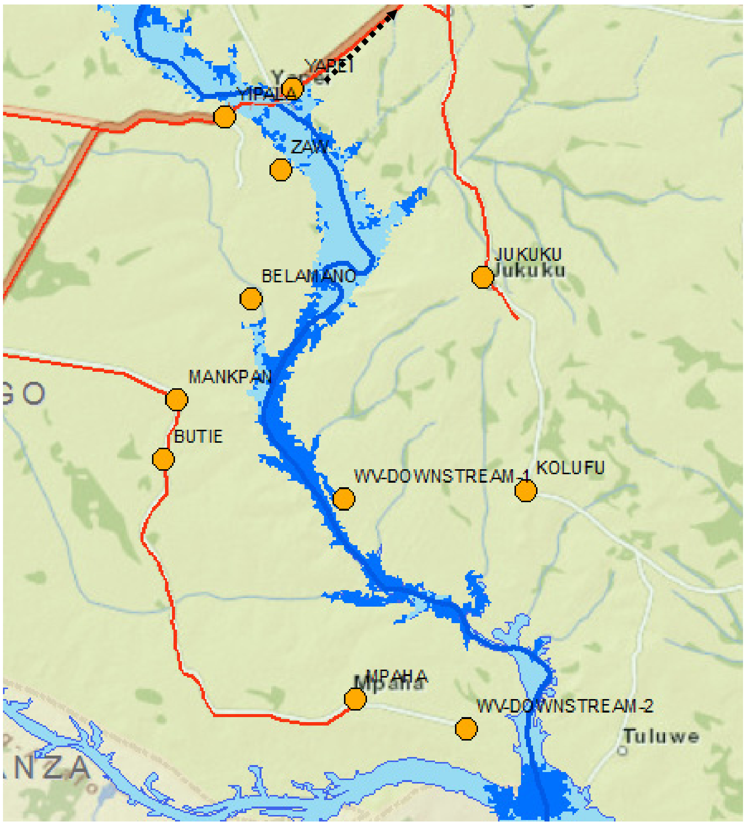


Figure I- 14 Flood extent Yapei – Lake Volta

The following communities are at risk:

- Yapei, road and bridge, evacuate in eastern direction
- Yipala
- Zaw
- Roads, buildings, farmlands, unnamed villages on both sides of the river south of Yapei until the confluence with the Black Volta.
- Belamano, backwater effect in the tributary from the White Volta River can affect this community

Appendix J: Participants training sessions

Name	Institute
Lumor Mawuli	WRC
Enoch Asare	WRC
Bob Alfa	WRC
Sylvester Darko	HSD
Jakpa Abdul-Ganiu Adamu	HSD
Barnabas Amisigo	WRI
Frederick Logah	WRI
Philip Tetteh Padi	VRA
Afua Adwubi	VRA
Juati Ayilari-Naa	GMET
Ronand W. Essilfie	NADMO
Maxwell Boateng-Gyanh	WRC
Ebenezer Alllotey	HSD
Ebod Aman Kwah Mikah	HSD

Table J- 1 Participants training session

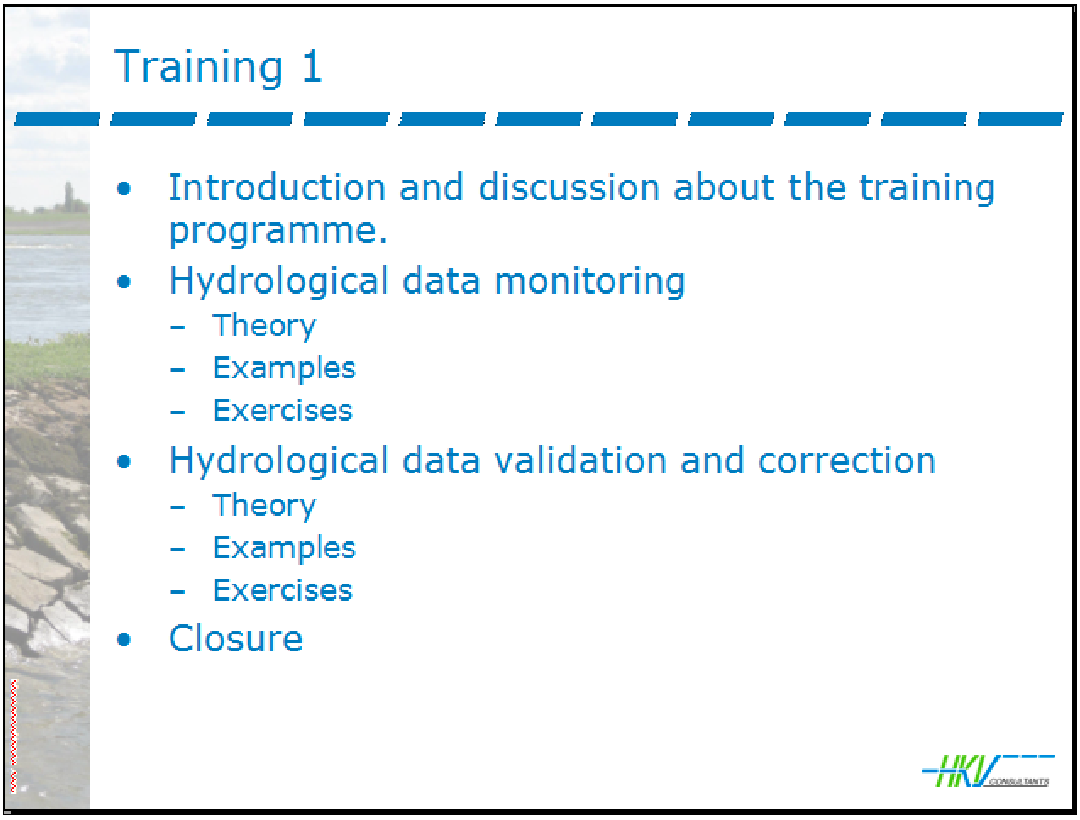


Figure J- 1 Programme training 1

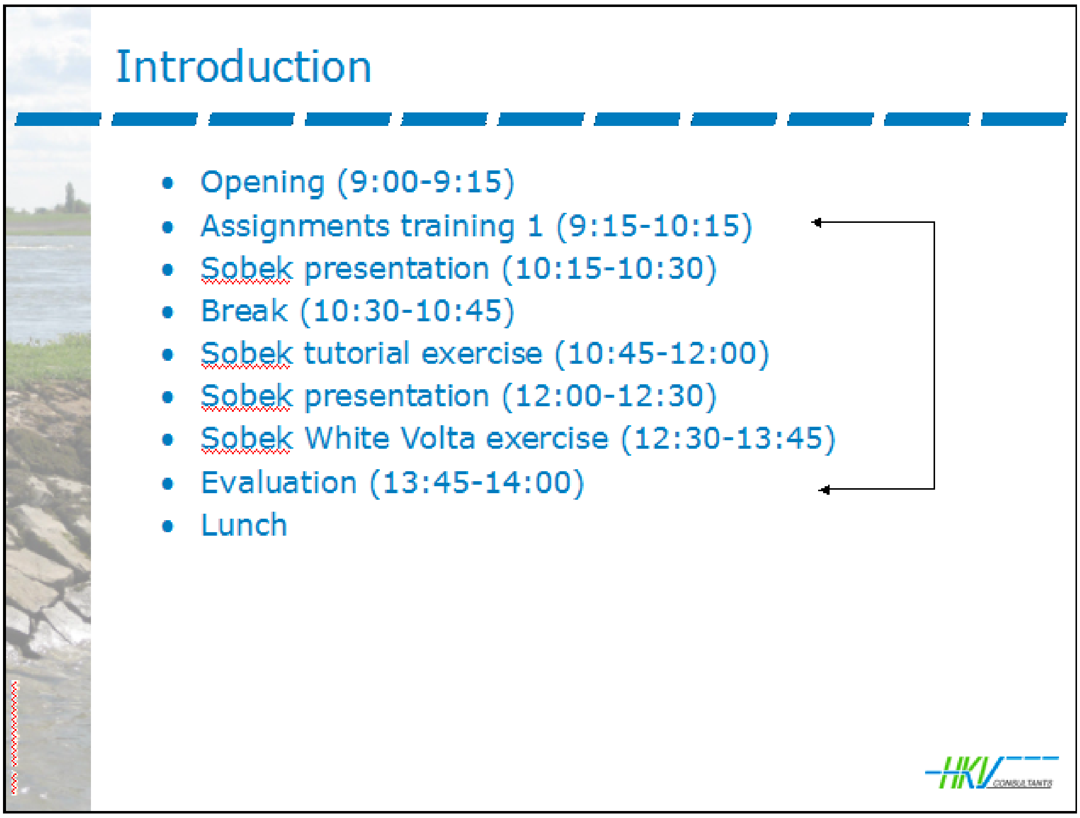


Figure J- 2 Programme training 2

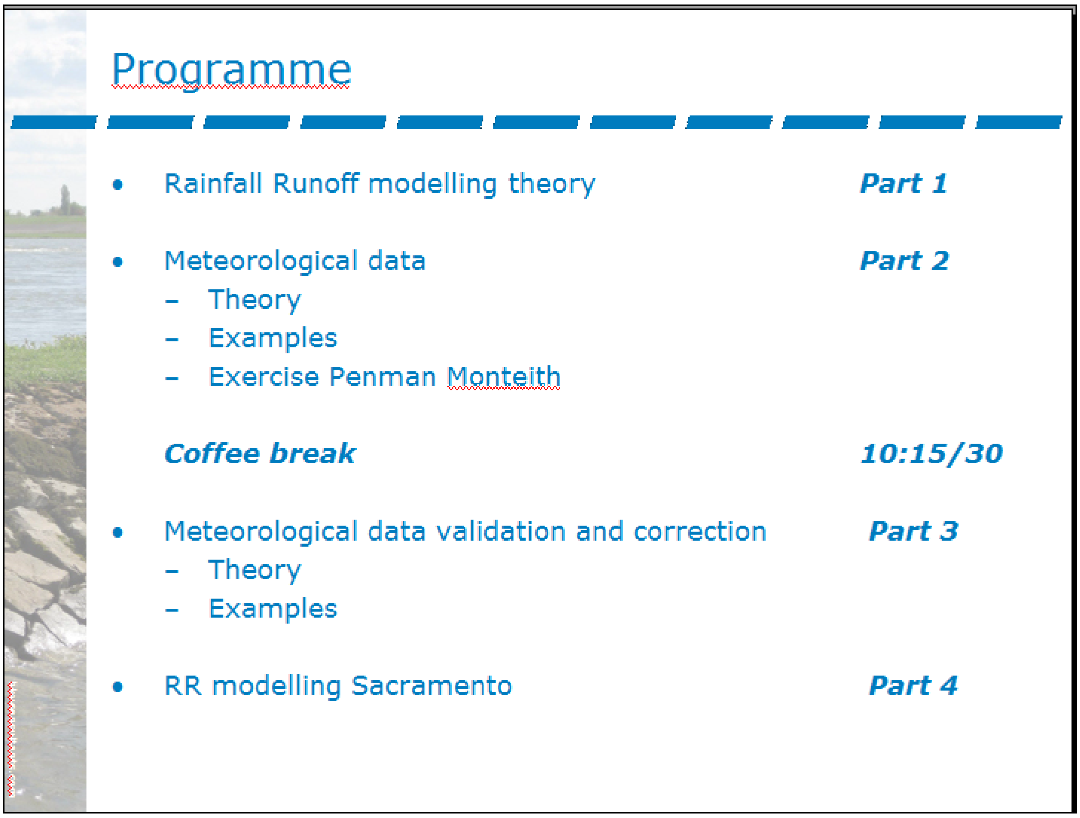


Figure J- 3 Programme training 3

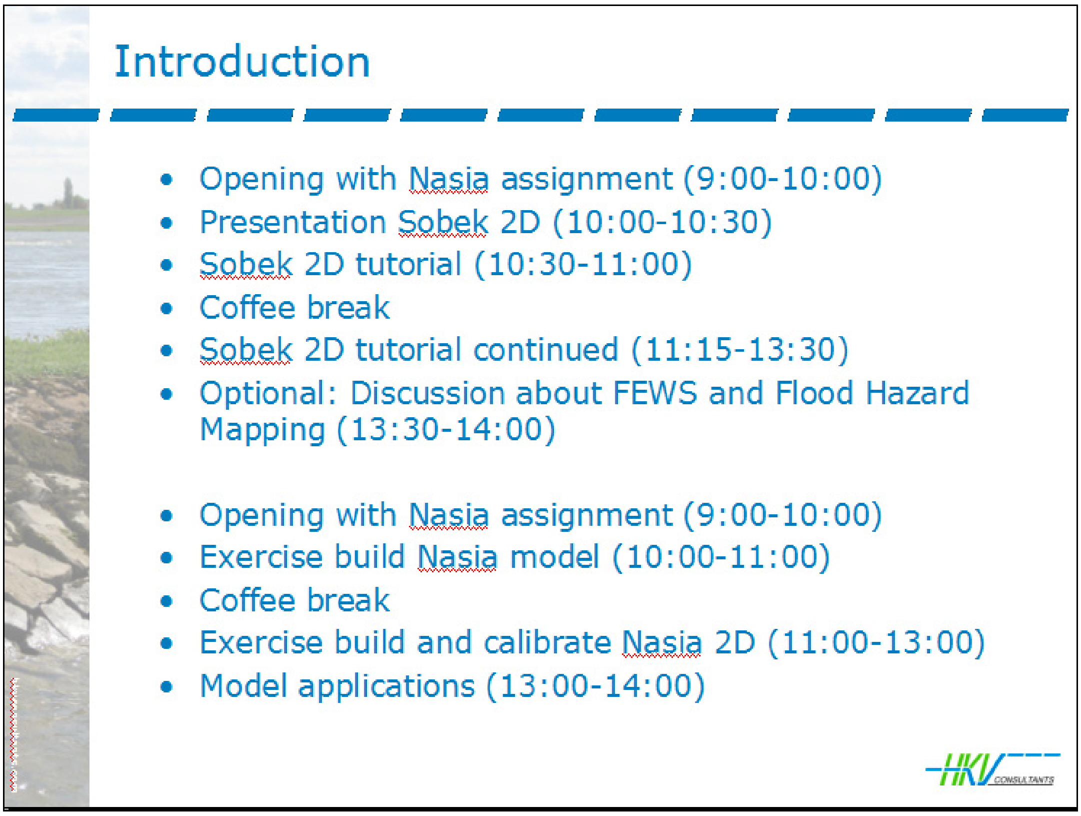


Figure J- 4 Programme training 4 and 5

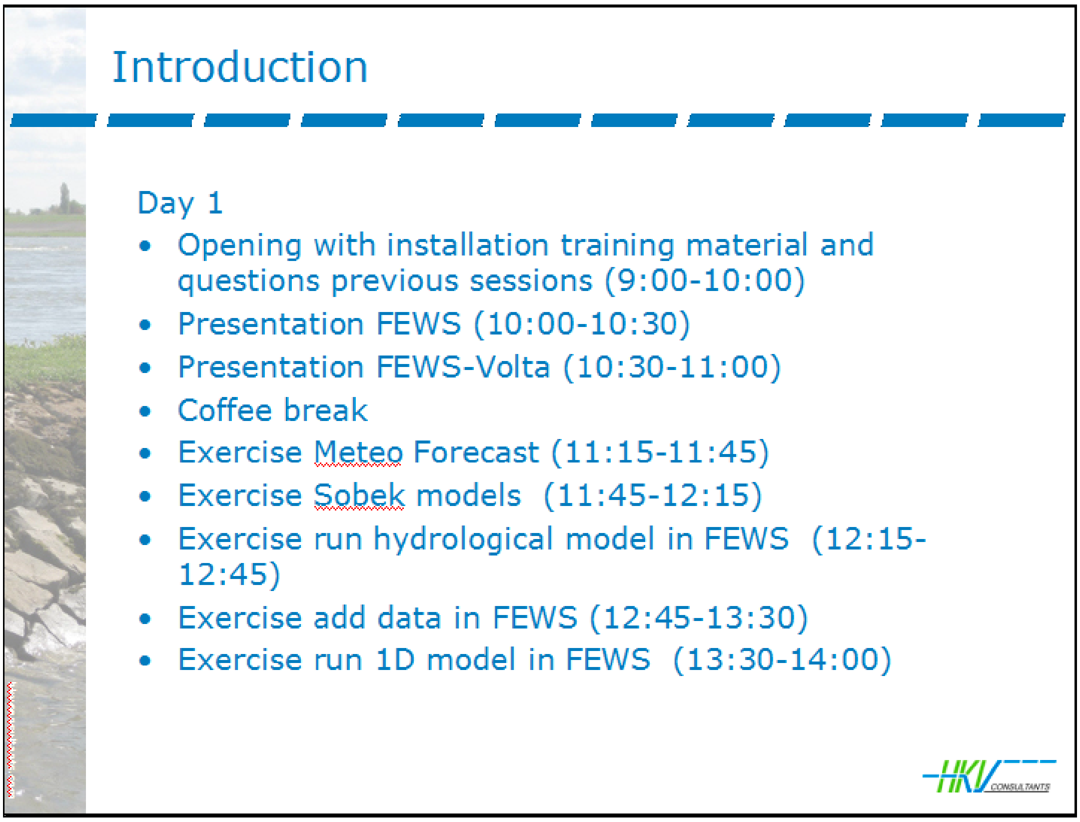


Figure J- 5 Programme training 6

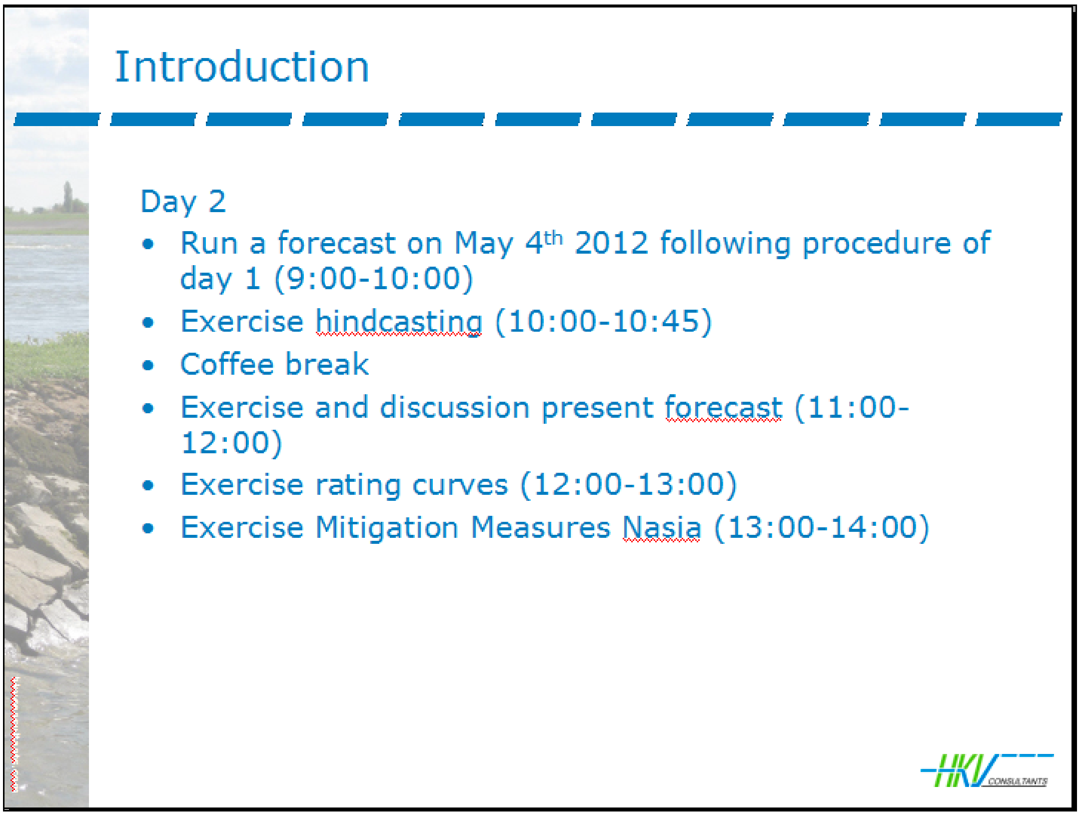


Figure J- 6 Programme training 7

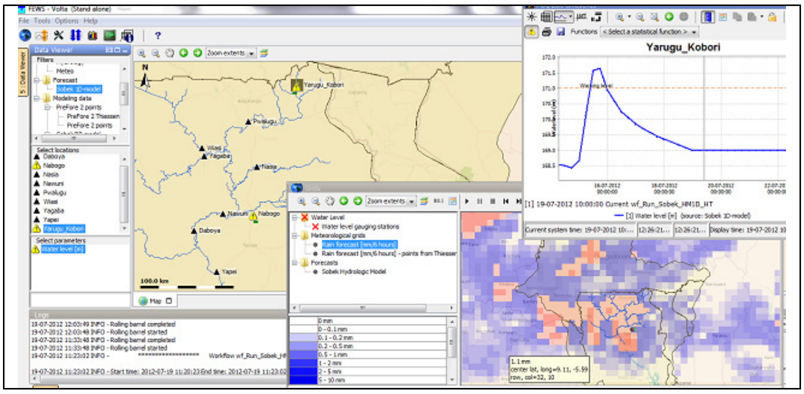
Appendix K: FEWS-Volta update and evaluation, Deliverable 9

Client:
World Bank

NORTH GHANA SUSTAINABLE DEVELOPMENT, DISASTER PREVENTION AND WATER RESOURCES MANAGEMENT

FLOOD HAZARD ASSESSMENT WHITE VOLTA

FEWS-Volta update and evaluation – deliverable 9
APPENDIX K



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MSc. T.G.J. Bijkerk

PR2147.10 December 2012

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1 Introduction

1.1 Background

Ghana is one of the countries in West Africa most affected by multiple hazards in Sub-Saharan Africa, particularly droughts and floods occur frequently. Ghana is a focus country for disaster risk reduction activities of GFDRR (Global Facility for Disaster Reduction and Recovery). Since 2007, floods along the White Volta River have been a recurrent annual phenomenon due to heavy rainfall in the basin and (partly) coinciding with spilling from upstream Bagré reservoir in Burkina Faso. The floods of the last four years rank 1^{st} , 4^{th}, 7^{th} and 8^{th} highest in the series of Nawuni station at the White Volta since 1936. These floods affect development and livelihood in the three northerly regions of Ghana but on the other hand bring fertile sediments to the floodplains.

The government of Ghana is committed to provide long-term solutions in the three regions of the North and in particular to initiate a comprehensive development plan to support economic growth opportunities in that region. As part of that effort a project was initiated targeting water and particularly flood management, following re-occurring floods in the three Northern provinces. Its main component is a study providing technical assistance to the Government of Ghana for coping with this problem.

The study will investigate the scale and severity of flood hazards, the exposures of various assets and communities and assess the effectiveness of structural and non-structural measures to reduce or eliminate flood damages in the future. Results of this analysis will support the National Strategy for Disaster Prevention and development plans for the growth and development of the North, including development partner supported projects such as the Northern Growth Project financed by IFAD and the African Development Bank.

With this as background, HKV CONSULTANTS was appointed by the World Bank to perform a Flood Hazard Assessment study for the White Volta River.

1.2 Scope of work

The scope of work for this study includes the following:

- Flood hazard modelling for the White Volta from the Ghana-Burkina Faso border to Lake Volta, including vulnerable reaches of the main tributaries;
- Flood risk assessment by combining the flood hazard with the vulnerability of the communities and land use in the flood prone areas;
- Assessment of the effectiveness of structural and non-structural flood management/protection measures;
- Flood forecasting and input for a Flood Early Warning System (FEWS);
- Provision of basic input to the development of the Emergency Preparedness Plan, and
- Training of staff of the various stakeholders in the development, application and operation of the modelling tools to be prepared and use of the modelling results through on-the-job training of scientific staff and through a workshop for users of FEWS output.

The study will produce the following deliverables:

1. An inception report, spelling out methodology and roadmap for project implementation.
2. A GIS database including the applied topographical (DEM/DTM), land use and developed inundation extent, depth and duration maps, flood hazard and flood risk maps.
3. A hydrological database including all raw and validated meteorological and hydrological data used in the project.
4. A combined hydrologic and hydraulic model of the White Volta and its tributaries for flood flow simulation including 3 licenses for model use and adaptation.
5. A FEWS of the White Volta basin for forecasting of flood levels, including 3 licenses for system use and adaptation and a web-page for dissemination of the forecasting results.
6. A mid-term report on the development, calibration and validation of the hydrological and hydraulic models.
7. Inundation extent and duration maps of the 2007 – 2010 flood on the White Volta and its tributaries
8. Flood hazard and flood risk maps on flood extent and duration maps for floods on the White Volta and its tributaries of selected return periods of 2, 5, 10, 25 and 50 years. Three copies of such plasticized maps covering the district is required of 1:25,000 scale maps for each district assembly and for all stakeholders in the Steering Committee 1: 50,000 scale flood hazard/risk maps.
9. Workshop for FEWS output users.
10. Final Report, summarizing the Project findings and recommendations with annexes on:
    a. Hydraulic model development, calibration and validation;
    b. Hydrologic model development, calibration and validation;
    c. Development and operation experiences with White Volta FEWS;
    d. Genesis of floods on the White Volta;
    e. Flood hazard and flood risk mapping;
    f. Effectiveness of structural and non-structural flood management/prevention measures;
    g. Input for Emergency Preparedness Plan;
    h. Workshop contents and participation.

In addition to the deliverables as described above the World Bank has commissioned HKV to carry out extra activities as described in an addendum to the contract. This includes:
- Development of a preliminary morphological model and training of relevant stakeholders with it and
- the extension of FEWS-Volta with satellite-based real time precipitation measurements (TRMM).

This report describes the **evaluation of FEWS-Volta** (deliverable 9) as well as the **update of the FEWS-Volta** system with TRMM data.

TRMM data was assessed for the use of model calibration and flood forecasting in FEWS-Volta in order to increase the sustainability and robustness of the system. Parallel to this project HKV carried out a project commissioned by Wienco Ghana Ltd. in which the hydrological models of the Sisili and Kulpawn were recalibrated based on TRMM data. This model improvement is described in chapter 4 and included in the FEWS-Volta update.

Deliverable 9, workshop for FEWS-output users, was carried out by operating the system during September 2012, when the peak of the wet-season reached North-Ghana. The relevant stakeholders made daily forecasts and disseminated the information. The process was actively supported by HKV. The evaluation on FEWS-Volta is based on the forecast process in September and described in this report.

2 TRMM data

2.1 Introduction

The Tropical Rainfall Measuring Mission (TRMM) is a joint mission between NASA and the Japan Aerospace Exploration Agency (JAXA) designed to monitor and study tropical rainfall. Tropical Rainfall Measuring Mission. Gridded (0.25o x 0.25o or 27.5 x 27.5 km) TRMM data is available in near real time and covers the Volta basin as well as shown in the figure below.

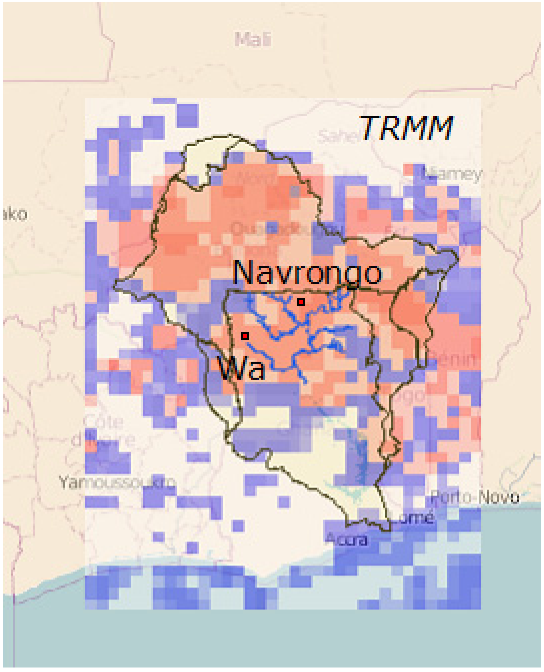


Figure 1 TRMM data in the White Volta catchment

TRMM data is available in near real time (TRMM RT) and as validated data (TRMM daily). Both can be downloaded from an ftp-site (ftp://trmmopen.gsfc.nasa.gov/pub/merged/calibratedIR/ for TRMM RT and ftp://disc2.nascom.nasa.gov/data/TRMM/Gridded/Derived_Products/3B42_V7/Daily/2012/ for TRMM daily data). The difference between both data sets is described in the next chapter.

In order to assess TRMM and compare it with meteorological ground stations and the meteorological forecast a script was developed to download the data. TRMM was downloaded for 1998-present and included in FEWS-Volta as indicated in the figure below.

The analysis in the following paragraphs were mainly carried out within FEWS-Volta using tools available. This made it possible for us to carry out the TRMM assessment within the limited time available.

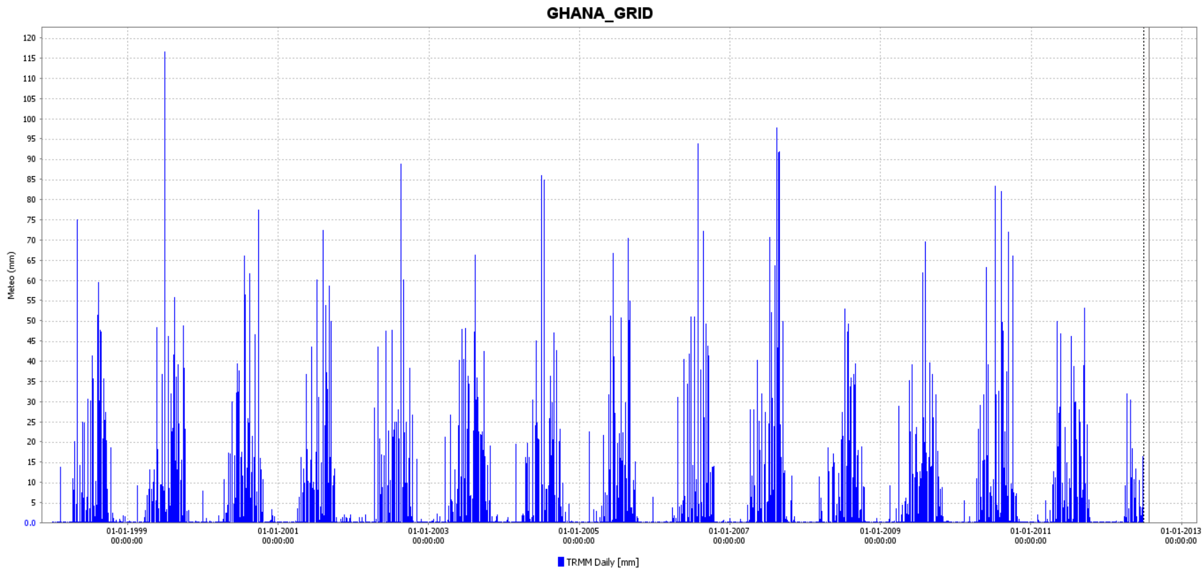


Figure 2 TRMM data downloaded in FEWS-Volta

2.2 Assessment TRMM data

2.2.1 TRMM daily versus TRMM RT

TRMM daily data is validated and corrected with data from synoptic stations made globally available by national meteorological services. It becomes available several months after it has been collected. TRMM RT data is made available almost within a few hours.
FEWS-Volta was set up in such a way that it downloads both data sets when they are available on the ftp-site.
Figure 3 shows the difference between TRMM daily and RT data extracted at Tumu and Bolgatanga. The trend is the same, but the validated daily data is 20-35% lower.

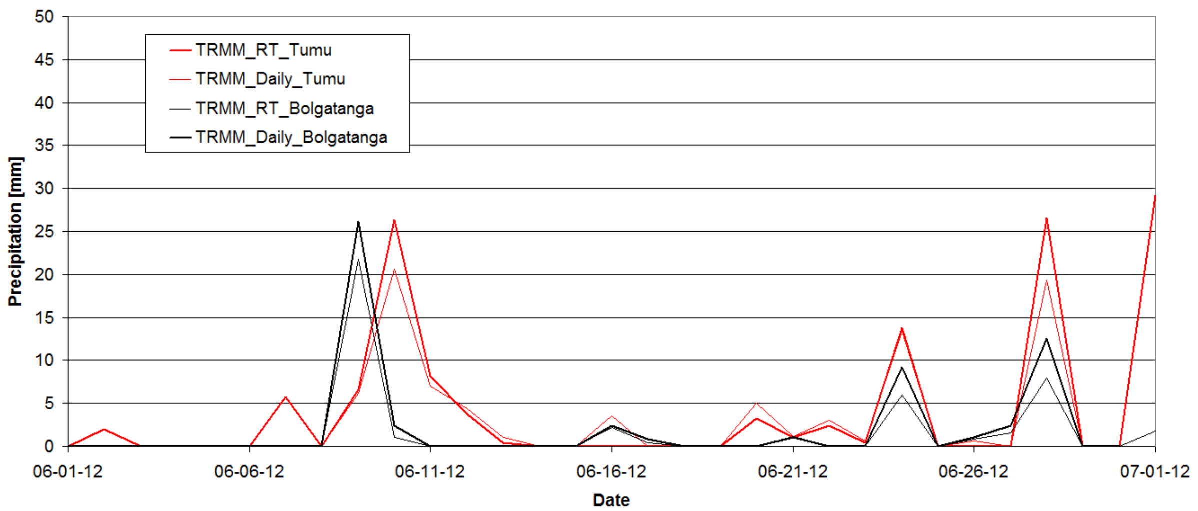


Figure 3 TRMM daily versus TRMM RT

2.2.2 TRMM versus ground data

The accuracy of the TRMM data is not known. To verify the accuracy we compared the TRMM daily data of individual cells (27.5 x 27.5 km) with the available data of gauging stations located in that cell. The ground stations are presented in Figure 4.

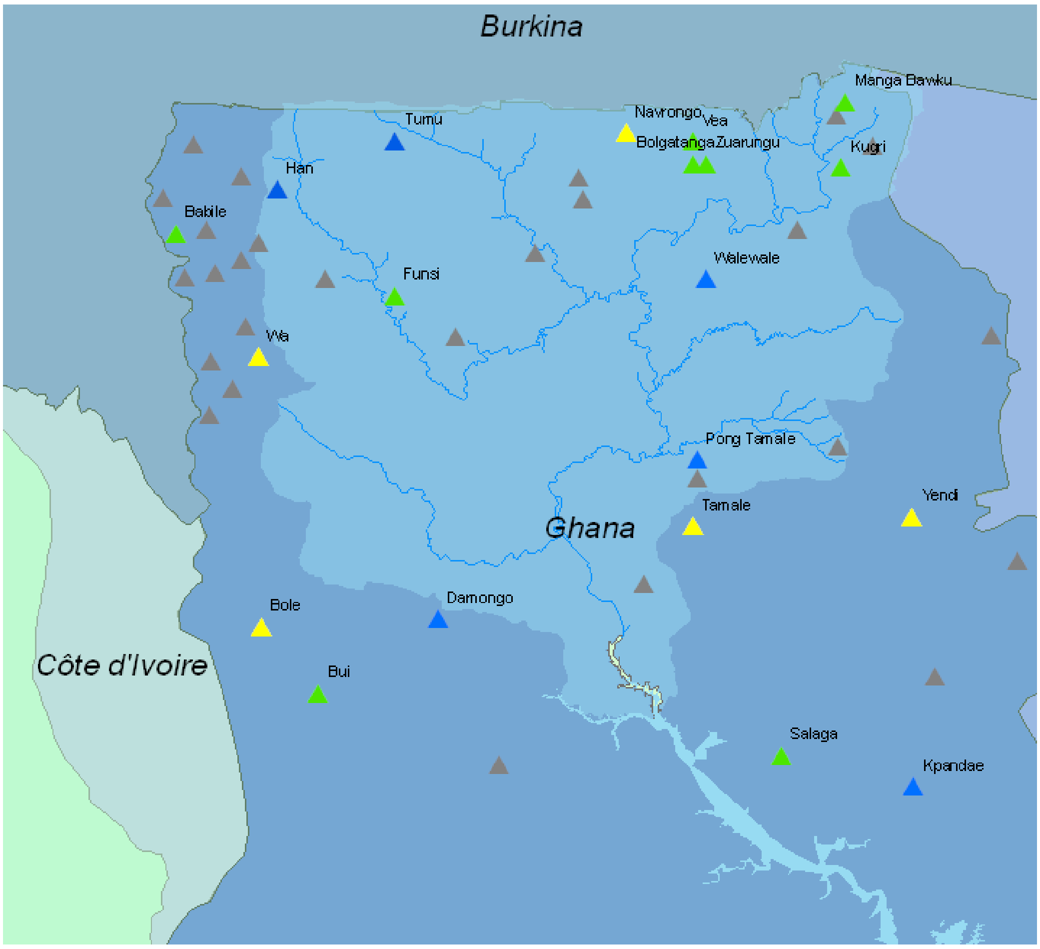


Figure 4 Locations of the synoptic (yellow), Agro (blue), CLIMD (green) and rainfall stations (brown)

First we compared the annual precipitation between 2003 and 2010. Figure 5 shows the difference between the 2 data sets (TRMM minus ground stations). The figure shows a trend break after 2006. Before 2006 TRMM shows higher values. After 2007 TRMM data measured less precipitation.
Table 1 shows the average difference from 2003 – 2010, 2003 – 2006 and 2007 – 2010 for the station locations.

It looks like the TRMM calibration method or procedure might be changed after 2006. On average the total average differences have improved slightly in time. Table 1 also shows that the relative difference is small, mostly below 5% for 2006-2010.

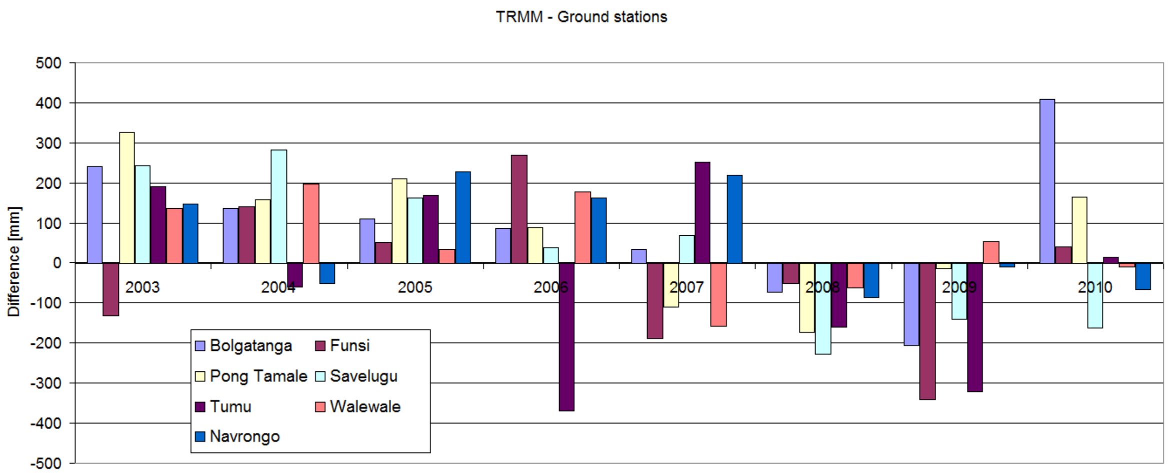


Figure 5 Difference annual precipitation between TRMM daily and ground stations

		2003-2010	2003-2006	2007-2010
Bolgatanga	average TRMM	1030	1039	1021
	average ground	938	896	980
	difference	92	143	41
	percentage	9%	14%	4%
Funsi	average TRMM	1097	1037	1157
	average ground	1123	955	1292
	difference	-26	82	-135
	percentage	-2%	8%	-12%
Pong Tamale	average TRMM	1173	1177	1168
	average ground	1092	982	1201
	difference	81	195	-33
	percentage	7%	17%	-3%
Savelugu	average TRMM	1173	1177	1168
	average ground	1140	996	1283
	difference	33	181	-115
	percentage	3%	15%	-10%
Tumu	average TRMM	1090	1027	1152
	average ground	1125	1044	1207
	difference	-36	-17	-54
	percentage	-3%	-2%	-5%
Walewale	average TRMM	1035	1059	1011
	average ground	989	923	1055
	difference	46	136	-45
	percentage	4%	13%	-4%
Navrongo	average TRMM	1074	1094	1084
	average ground	953	1081	1017
	difference	121	13	67
	percentage	11%	1%	6%

Table 1 Average precipitation difference 2003-2010

On a daily basis the TRMM data and data of a gauging station located in the 27.5 x 27.5 km area of the TRMM pixel show differences in precipitation. These differences are explained by the difference in representation of the data:

- TRMM data is the averaged rainfall over an area of 27.5 x 27.5 km;
- gauging data is the rainfall on one point in that area.

Because of the spatial and temporal heterogeneity in precipitation the gauging data will always differ from the TRMM data.

The figures below show the monthly averages and 2003 daily precipitation values for locations Walewale and Bolgatanga. The rainfall trends are more or less similar. Absolute values however can differ strongly. Walewale 2007 shows a large difference also visible in Figure 6. Bolgatanga shows a large difference between TRMM and ground stations in 2010 as presented in Figure 7.

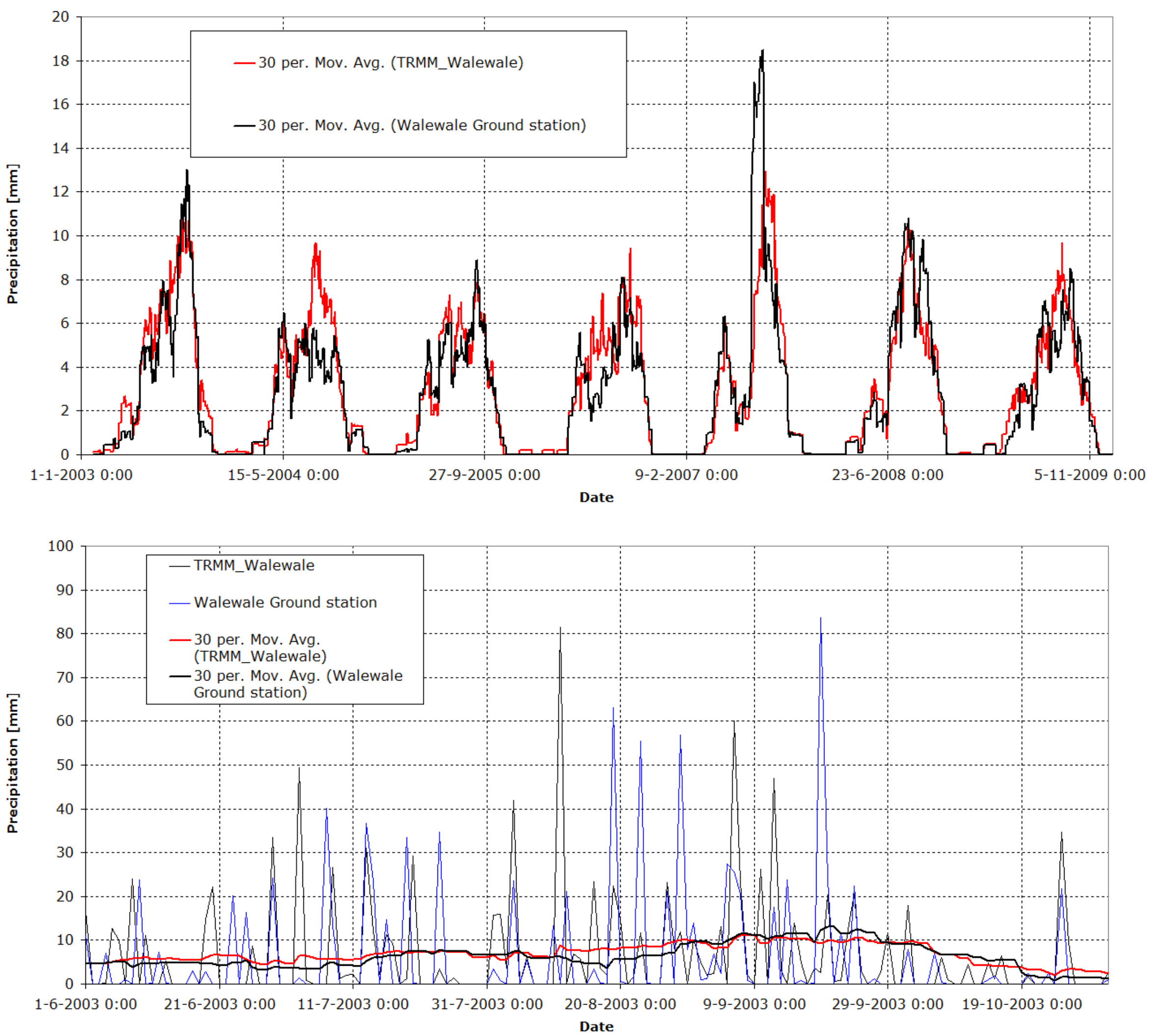


Figure 6 Monthly and daily precipitation at Walewale, TRMM versus ground station

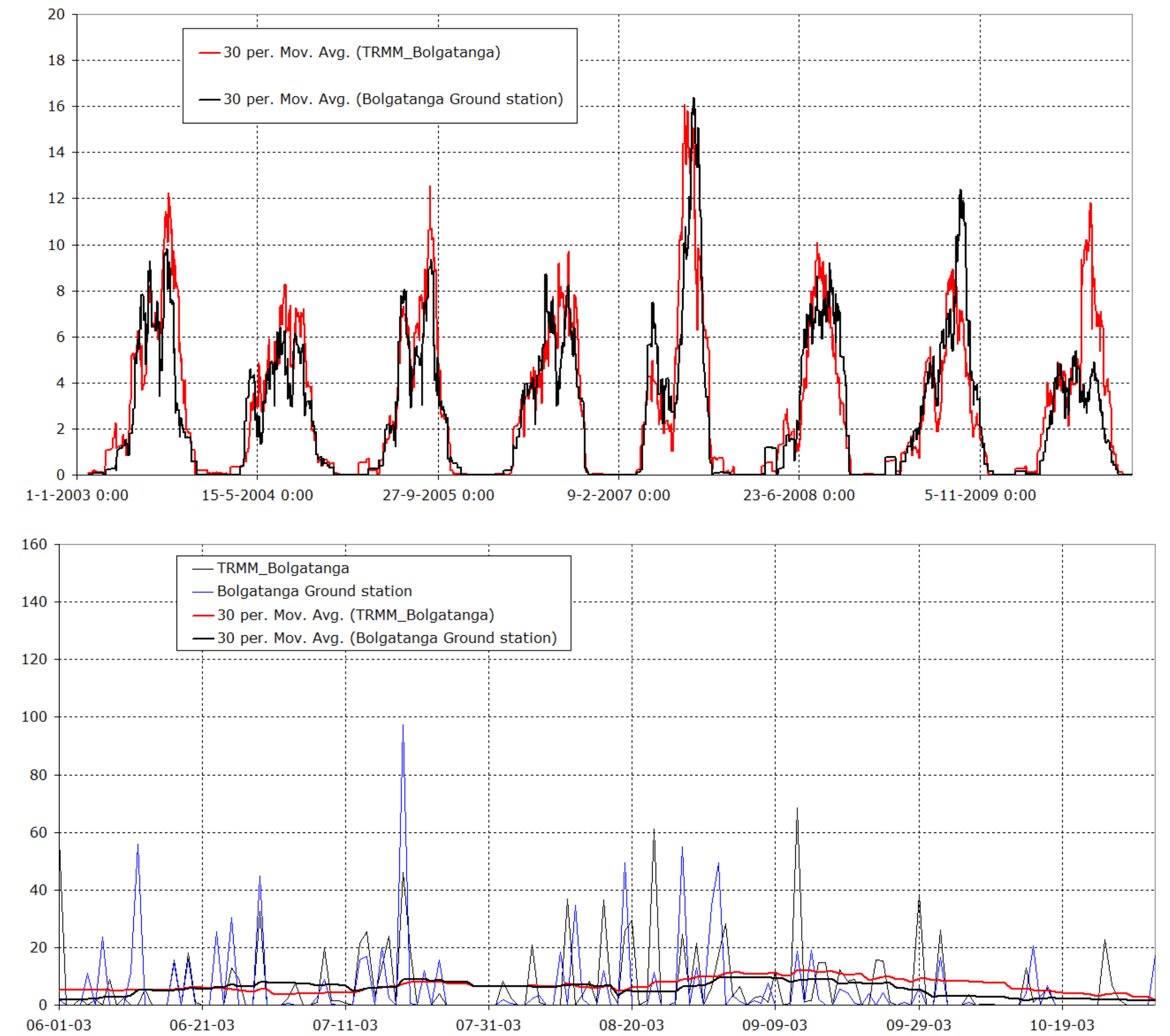


Figure 7 *Monthly and daily precipitation at Bolgatanga, TRMM versus ground station*

2.2.3 Thiessen average comparison

As described in reports deliverable 4 and 10 (HKV, 2012) the meteo input to the hydrological models was determined based on Thiessen polygons derived from the meteo station locations. It was decided to follow the same method in defining the meteo input with the TRMM data. We therefore present not a basin average comparison of TRMM and ground station data but a comparison on Thiessen polygons related to the ground stations. The figure below illustrates this: left shows the Thiessen distribution according to the meteo station locations. Right shows how the TRMM data is aggregated to the same Thiessen distribution.

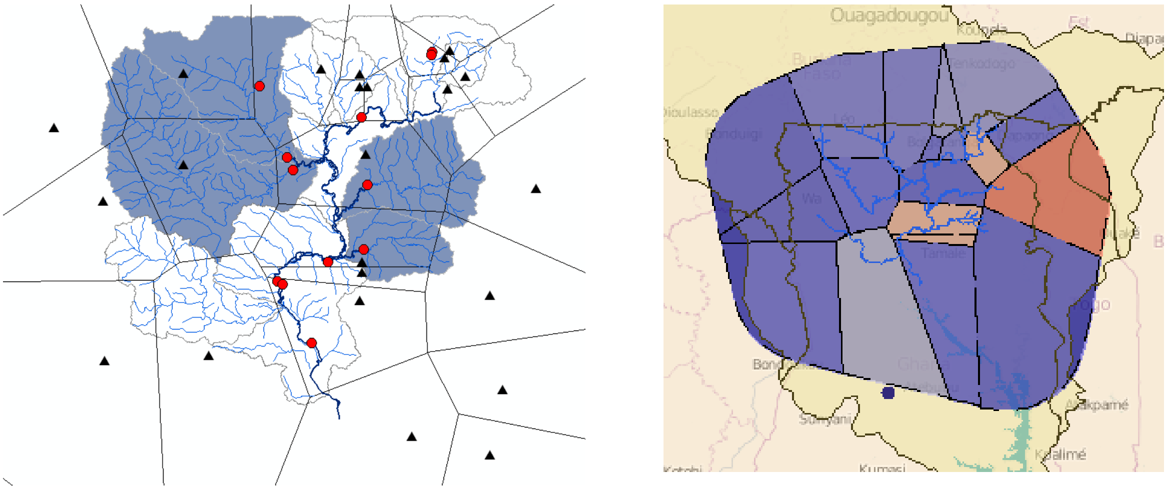


Figure 8 Thiessen distribution based on meteo stations

Figure 9, Figure 10 and Figure 11 present the cumulative yearly and monthly rainfall for the Thiessen polygone representative for Wa. As Wa is a synoptic station the ground station data should be relatively good. When looking at the figures yearly totals are relatively similar. The monthly totals can differ, for instance for the wet months in 2007. Similar figures are presented for Navrongo, Bolgatanga and Babile in Figure 12 to Figure 20. Navrongo, another synoptic station shows similar values for the TRMM and ground station data. Bolgatanga and Babile do not.

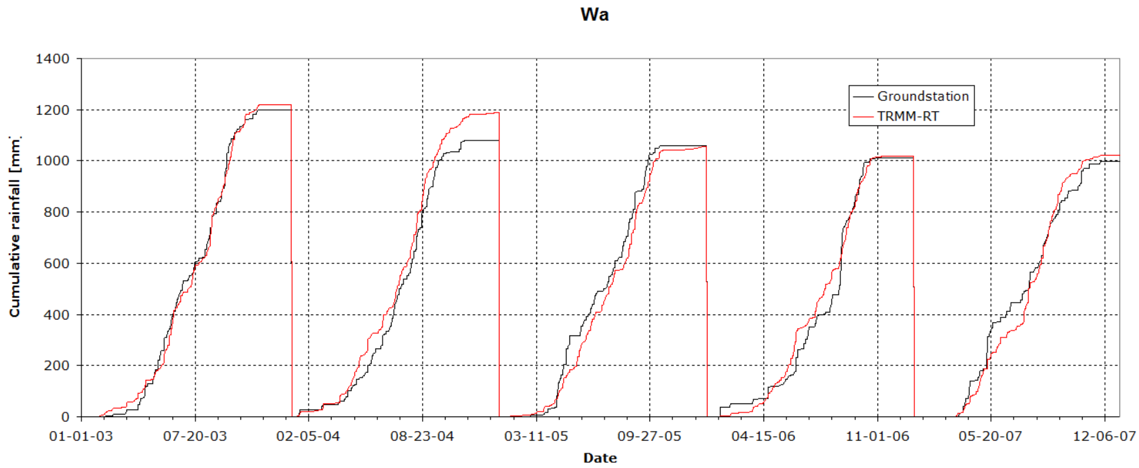


Figure 9 Yearly cumulative TRMM and ground station 2003 Wa

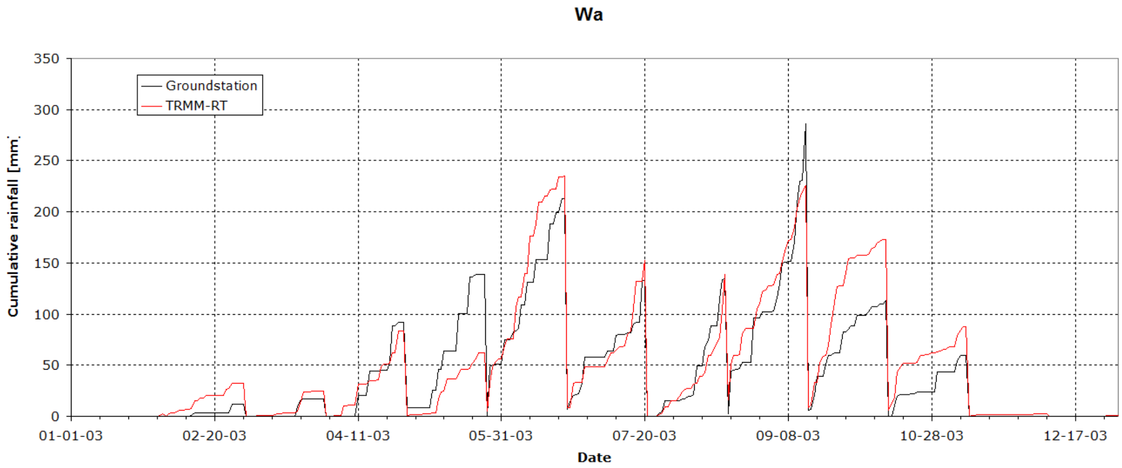


Figure 10 Monthly cumulative TRMM and ground station 2003 Wa

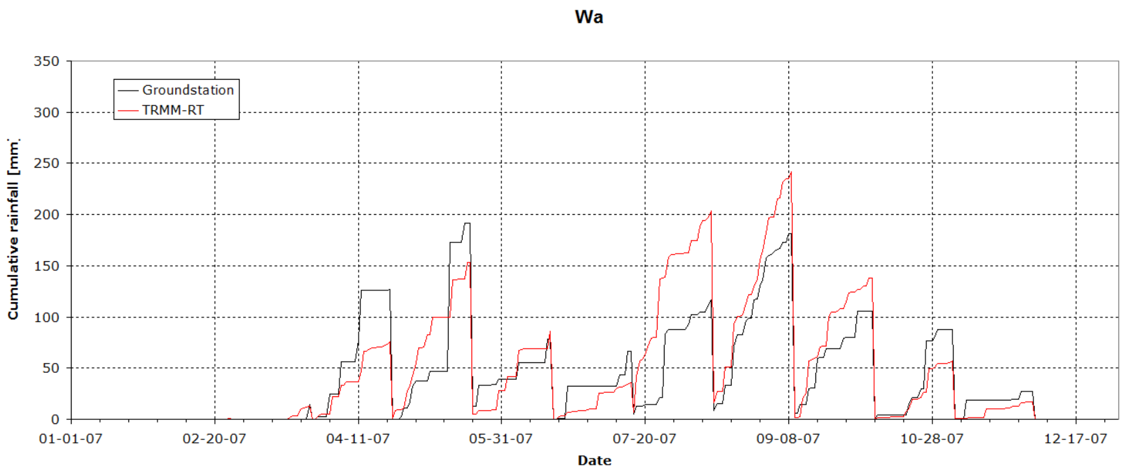


Figure 11 Monthly cumulative TRMM and groundstation 2007 Wa

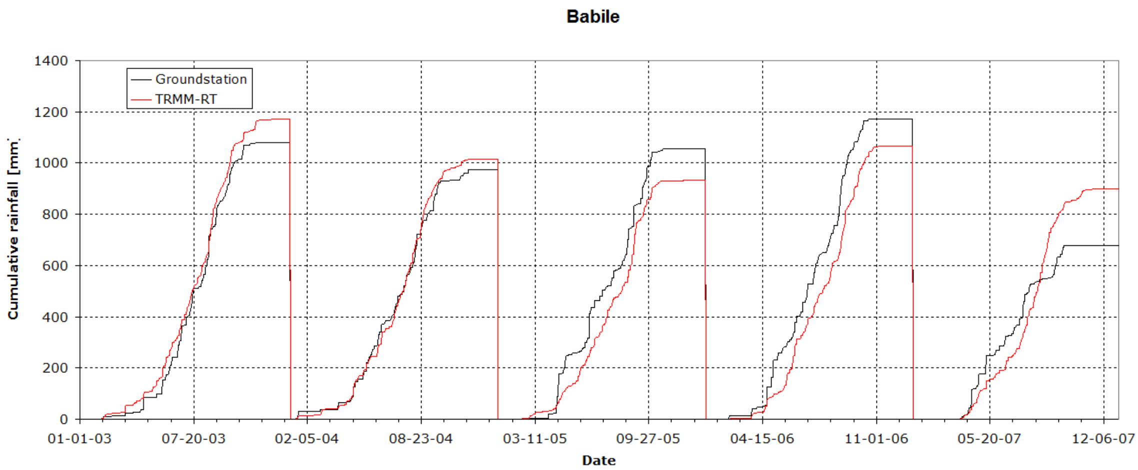


Figure 12 Yearly cumulative TRMM and groundstation 2003 Babile

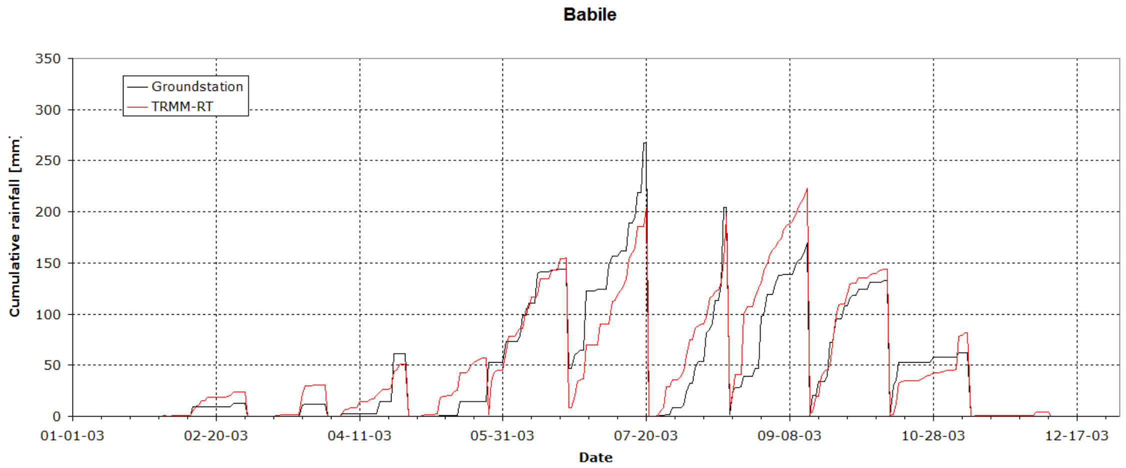


Figure 13 Monthly cumulative TRMM and groundstation 2003 Babile

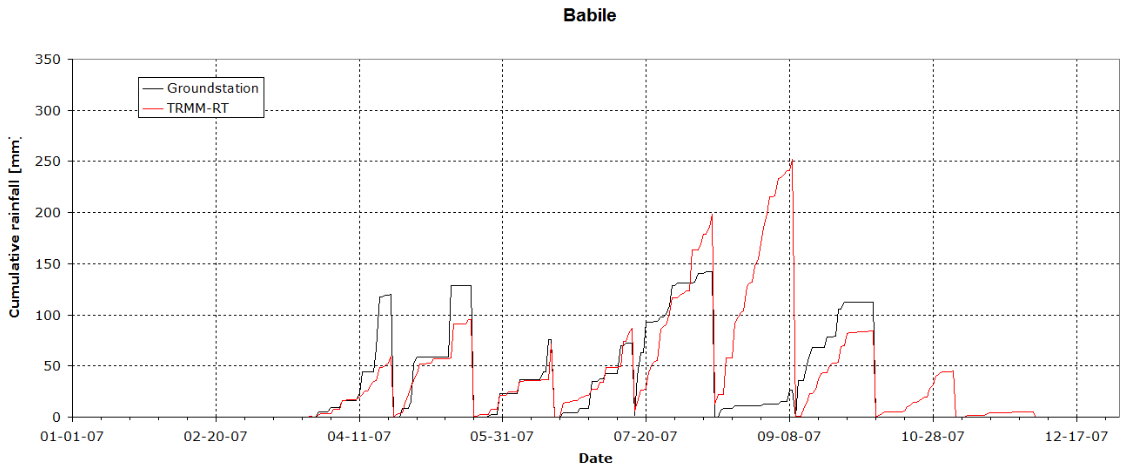


Figure 14 Monthly cumulative TRMM and groundstation 2007 Babile

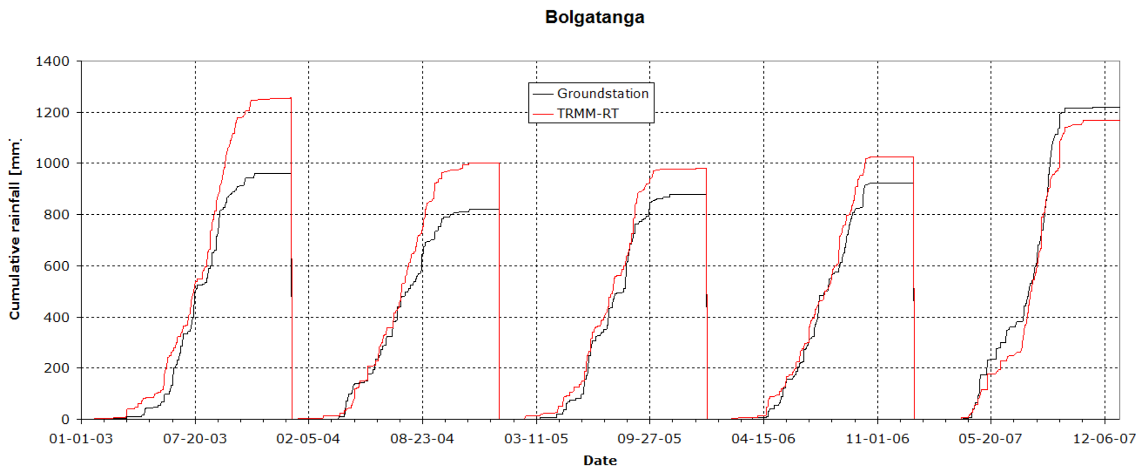


Figure 15 Yearly cumulative TRMM and groundstation 2007 Bolgatanga

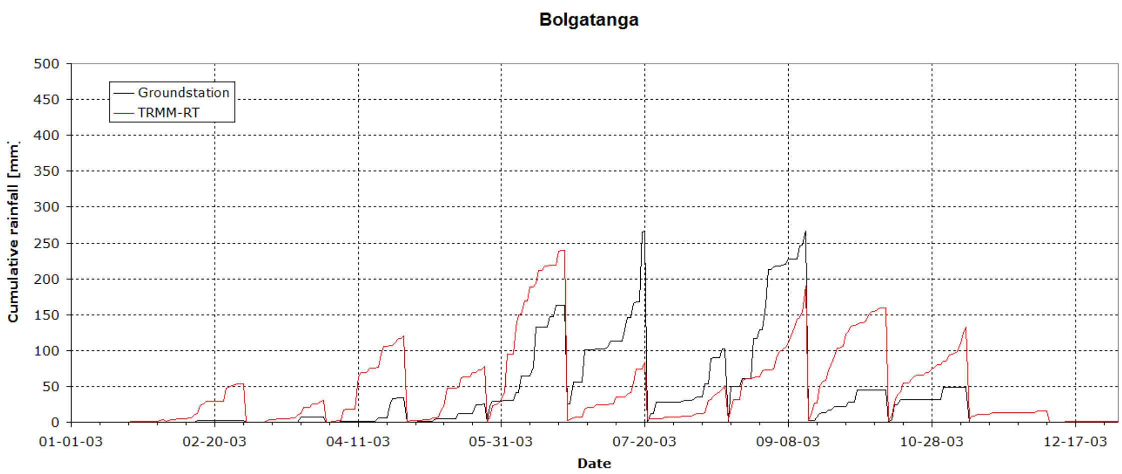


Figure 16 Monthly cumulative TRMM and groundstation 2003 Bolgatanga

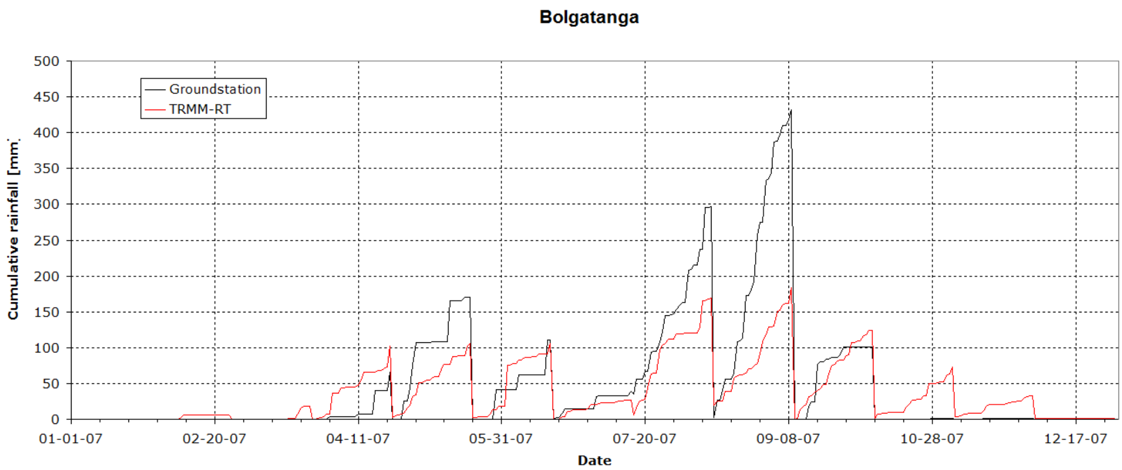


Figure 17 Monthly cumulative TRMM and groundstation 2007 Bolgatanga

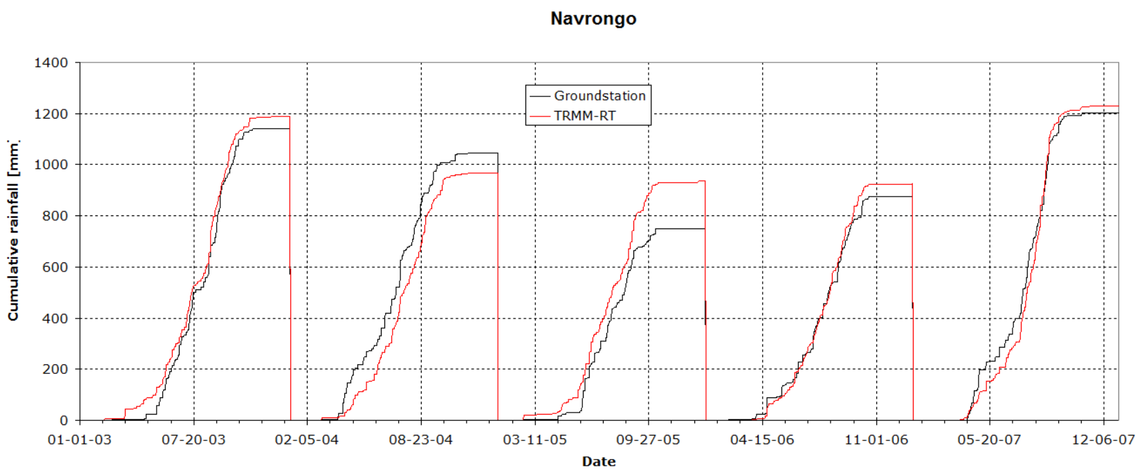


Figure 18 Yearly cumulative TRMM and groundstation 2003 Navrongo

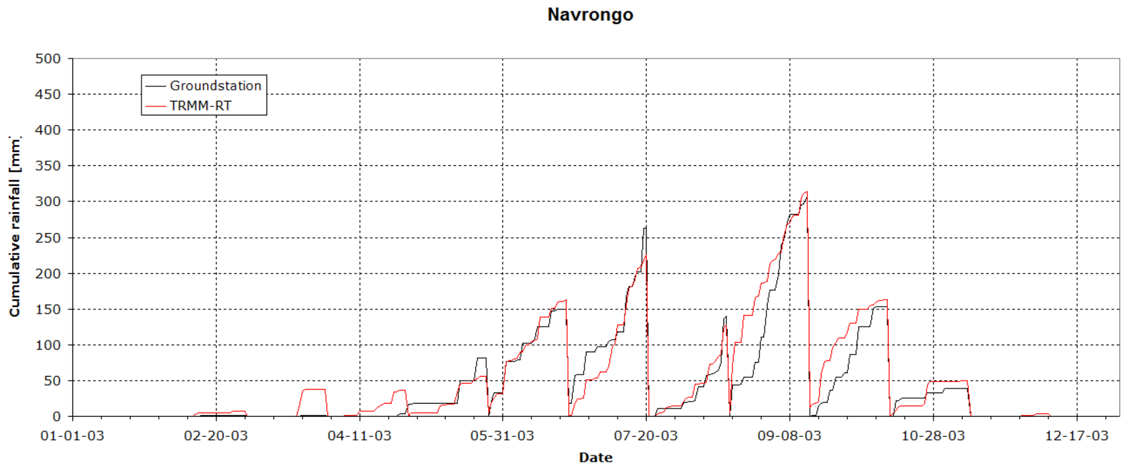


Figure 19 Monthly cumulative TRMM and groundstation 2003 Navrongo

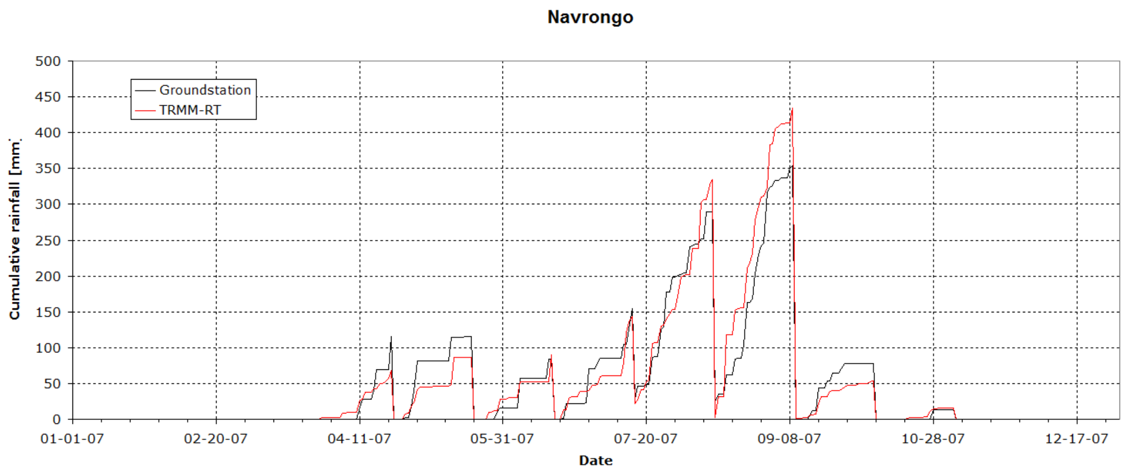


Figure 20 Monthly cumulative TRMM and ground station 2007 Navrongo

2.2.4 TRMM versus meteo forecast

The meteo forecast is available from the end of March 2012. We compared the meteo forecast with TRMM RT data, as the calibrated TRMM daily data is (at this moment) only available until 1st of August 2012, meaning the overlapping period hardly contains rainfall events.

The figures below show the daily rainfall of the meteo forecast and TRMM RT near Bolgatanga and Tumu from 1-6-2012 to 9-9-2012. The figure below shows the cumulative differences. In general the daily events differ in time and absolute value. The difference near Tumu is very large. When looking at average values for this period it looks like TRMM RT shows too high values. We emphasize the TRMM RT data still needs to be calibrated for this period, which might lead to better results when comparing TRMM daily (calibrated) with the meteo forecast.

Location	**TRMM RT Cumulative rainfall [mm]**	**Meteo forecast Cumulative rainfall [mm]**	**Difference [mm]**
Bolgatanga	487.2	507.6	-20.4
Tumu	996.2	555.8	440.4

Table 2 TRMM RT versus meteo forecast

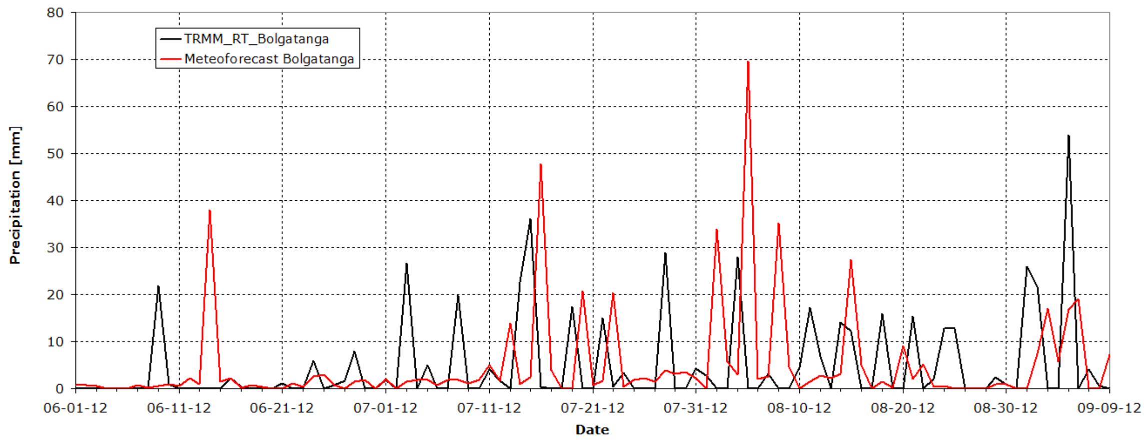


Figure 21 *Daily rainfall near Bolgatanga for TRMM RT and meteo forecast*

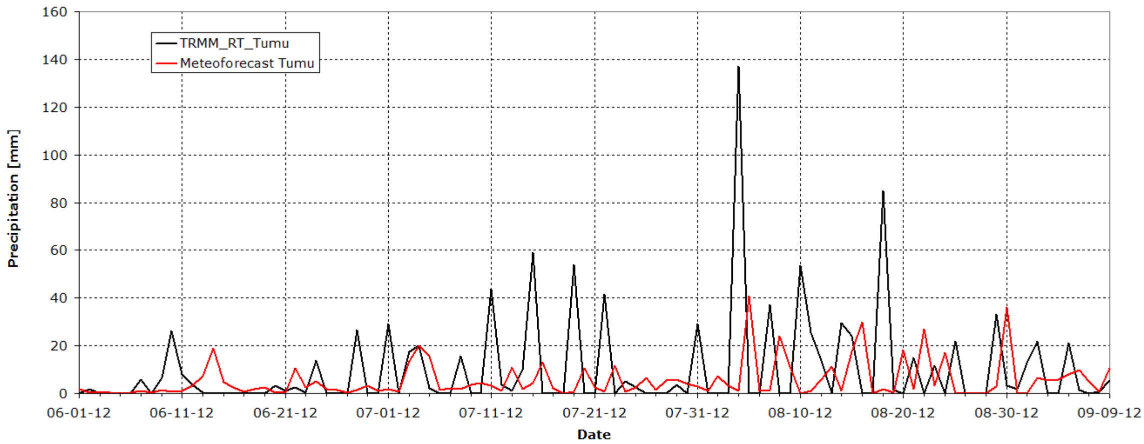


Figure 22 *Daily rainfall near Tumu for TRMM RT and meteo forecast*

2.3 Conclusion

From the above the following can be concluded:

- TRMM daily data shows large differences especially on daily basis compared to the ground station data. Differences occur on monthly and yearly basis as well. This is partially due to the spatial difference in comparing a point with a surface (27.5x27.5 km).
- TRMM daily data distributed as Thiessen polygons is more comparable with the ground station Thiessen distribution. Especially the synoptic stations show similar values. However very large differences, especially with non-synoptic stations occur.
- It is not possible to properly validate the meteo forecast data. This should be done once TRMM daily data is available for the whole 2012 wet season.

Furthermore it should be emphasized that the precipitation data included in FEWS-Volta is available until 2010. We did not receive data for 2011. The rainfall runoff models in FEWS-Volta need about 2 years of initialization. It was therefore decided to use 2010 precipitation to fill the 2011 precipitation gap. Precipitation data for 2012 was made available using the meteo-forecast data. The TRMM module now enables us to use TRMM daily data for 2011. This should improve the FEWS-Volta results in 2012, as described in the next chapter 4.

TRMM daily data is available only every 2-3 months, but should be used once available, to replace the raw TRMM RT data and meteo forecast in the FEWS.It wasd decided to include the following hierarchy in FEWS-Volta for the rainfall runoff model input:

1. meteorological data from ground stations, if not available;
2. TRMM daily, if not available;
3. TRMM RT, if not available;
4. Meteo forecast.

All data series are merged as one set, which is used to calculate the hydrological models with as illustrated in Figure 23.

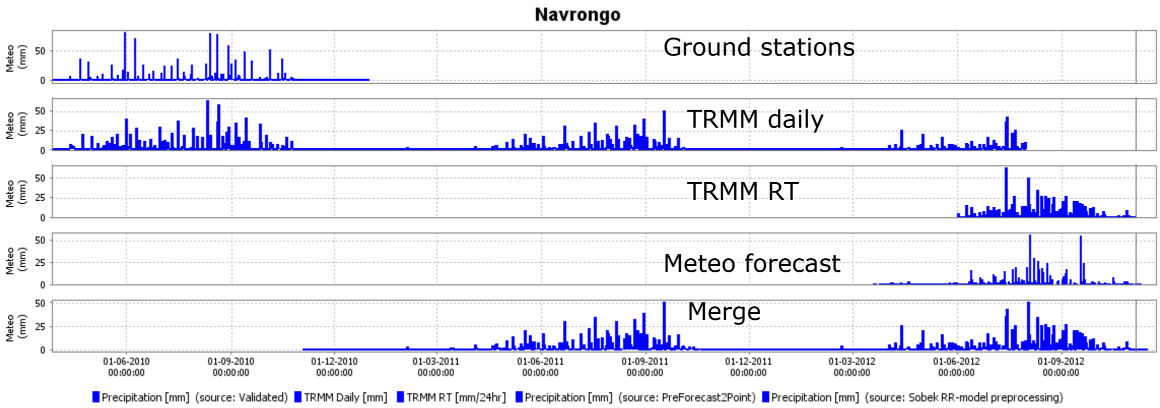


Figure 23 Rainfall data hierarchy in FEWS-Volta

3 Hydrological model improvement

3.1 Introduction

Rainfall Runoff models were build and calibrated for the Flood Early Warning System of the White Volta in Ghana. These models are calibrated using precipitation data from the meteorological stations present within the catchment. Precipitation was spatially distributed over the catchments using Thiessen polygons. The number of (reliable) meteorological stations in Ghana is relatively low (HKV, 2012). Therefore large areas of terrain are covered by only a few meteorological stations. During the construction of the Flood Early Warning System, it was concluded that the uncertainty within the calibration results is mainly a consequence of the lack of data and the uncertainty within the available data. It is recommended to further optimize the rainfall runoff models but above all more reliable data is required.

HKV carried out a project commissioned by Wienco Ghana Ltd. during which TRMM rainfall data was used as input for the Sisili and Kulpawn rainfall runoff models. The models were recalibrated using this input. It was decided to use these recalibrated hydrological models in FEWS-Volta as well.

This chapter describes the model improvements using the recalibrated model results. It also describes the differences between the model results using TRMM (daily) data as input and meteorological ground stations as input.

3.1.1 Improving the calibration results

The hydrological models of the Sisili and Kulpawn were recalibrated based on TRMM data for the period of 2003 to 2007. Sacramento parameters where manually changed (increased or decreased) to improve the model performances. The former and final optimized parameter set are shown in Table 3.

The effect on the model output can be observed in Figure 24.

As can be observed in these graphs the calculated discharges for the Sisili catchment become more gradual and less spiky. The timing of the discharge improves especially for the year 2007. The results for the Kulpawn show a small increase of discharge when using the new parameter set. The timing of the discharge remains similar to the original dataset. We emphasize that the observed discharge data for 2007 at Kulpawn (Yagaba) is incorrect. This was already observed and described in the report deliverable 10 and deliverable 4 (HKV, 2012).

The effect of the new parameter set, when calculating with the meteo stations as input is shown in the Figure 25. The conclusions are similar: the calculated discharges for the Sisili catchment improve with the new parameter set. The calculated discharges for the Kulpawn catchment slightly increase.

	Sisili		Kulpawn	
	Old	New	Old	New
UZTWM	100	200	250	225
UZFWM	75	150	150	150
LZTWM	400	500	500	500
LZFSM	200	150	150	50
LZFPM	250	150	150	50
UZK	0.3	0.3	0.3	0.175
LZSK	0.1	0.008	0.06	0.008
LZPK	0.2	0.004	0.04	0.004
ZPERC	5	70	10	60
REXP	2	0.9	2	1.1
PFREE	0.2	0.05	0.2	0.05
RSERV	0.2	0.05	0.2	0.01
PCTIM	0	0.001	0.001	0.001
ADIMP	0	0.01	0.01	0.01
SARVA	0	0.0125	0.0125	0.0125

Table 3 The old and new parameter sets after calibration using the RR models with the TRMM data. UH settings have not been changed.

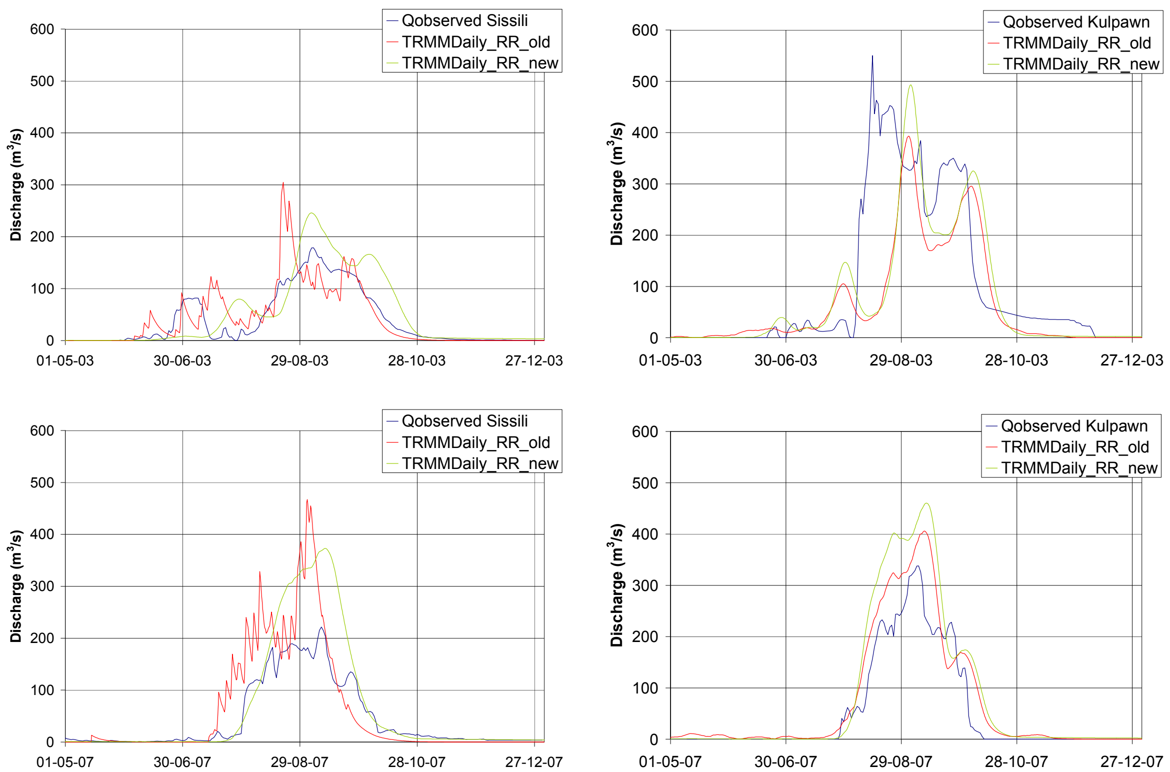


Figure 24 The calculated discharge when using TRMM precipitation as input for the old (red) and new (green) parameter set

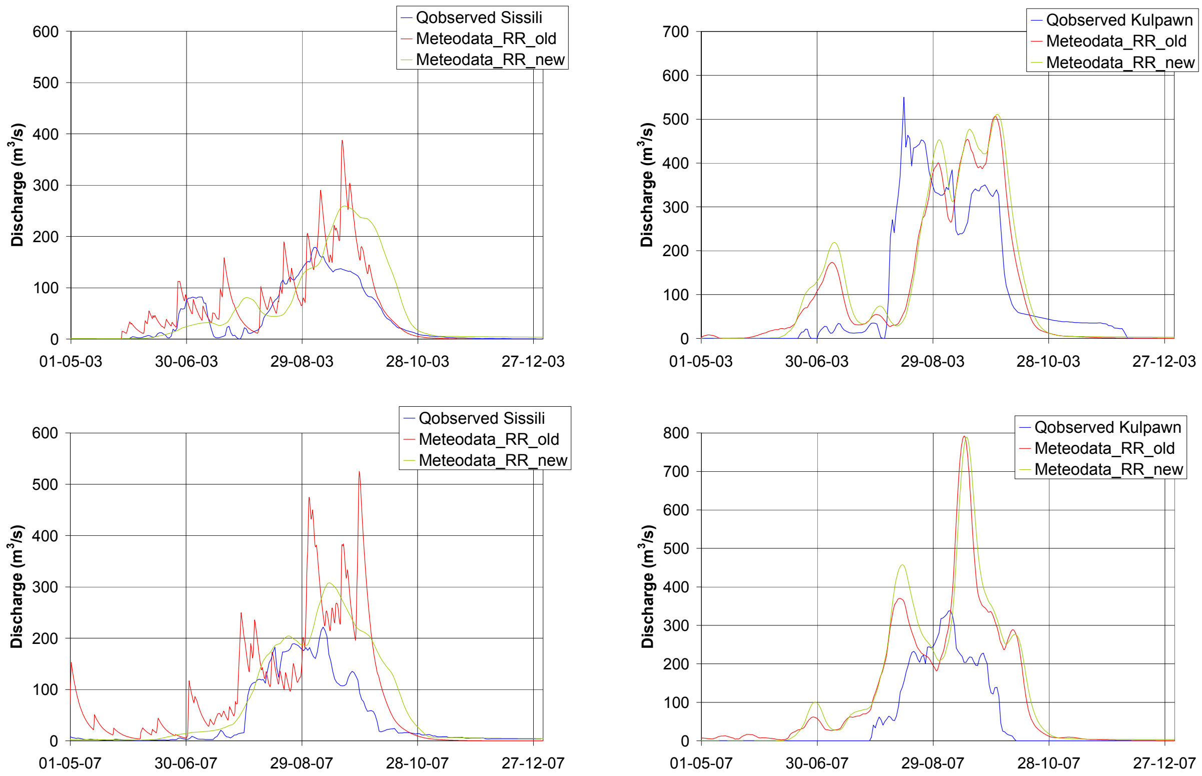


Figure 25 The calculated discharge when using precipitation data from the meteorological station as input for the old (red) and new (green) parameters

3.1.2 Differences in meteo input

We also analyzed the differences in calculated discharges when using the TRMM-RT and meteorological station data when using the new parameter set. The results are presented in the figures below.

The results for Nabogo show only a slight change when using TRMM data for 2007. The results for 2003 become slightly worse especially regarding the timing of the peak.
The results for the Nasia catchment improves for 2007. Again the results for 2003 slightly decrease compared to the model output when using the meteorological data.
As can be observed the model performances for both the Kulpawn and Sisili increases. Volume, shape and timing are better represented by using the TRMM data. Only the 2007 peak of the Sisili becomes more extreme under influence of the TRMM data.

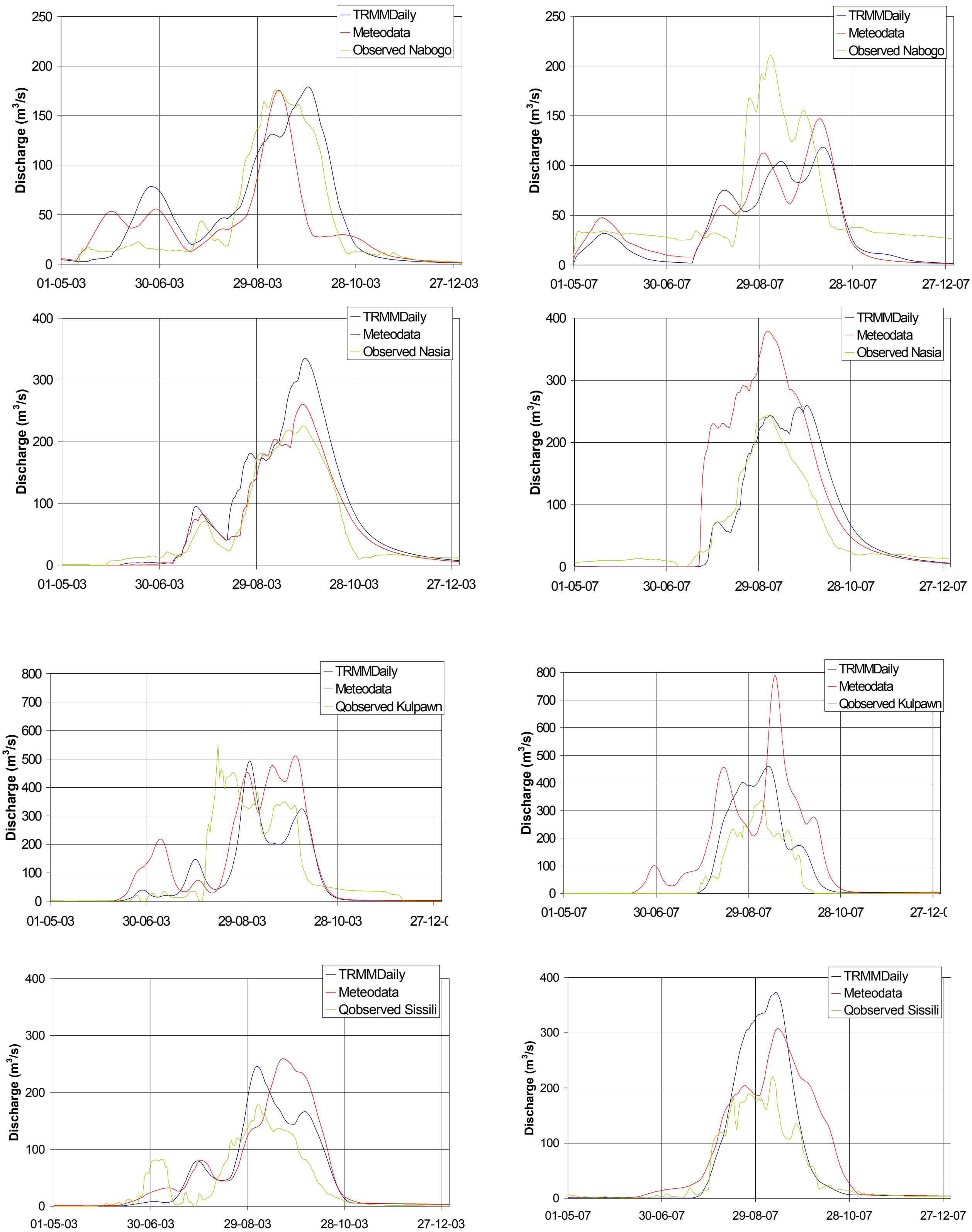


Figure 26 The calculated discharge when using precipitation data from the meteorological station and TRMM daily data as input for the hydrological models

3.1.3 Conclusion

When observing the results it can be concluded that the recalibrated model performs better for the Sisili River. This is the case for meteorological station input as well as for TRMM data as model input. The calculated discharges respond less lively and show a more gradual course. The results for the Kulpawn are less affected. The discharges tend to increase slightly with the new calibration set.

As the Sisili catchment parameter set is used for a number of ungauged catchments, we decided to use the new model calibration set in FEWS for both Sisili and Kulpawn models as well as the ungauged models that use the Sisili parameter set (see report deliverable 4 and 10).

It is not possible to state whether TRMM data input improves the results for the historical calculations as such: some results are more similar to the observed discharges, some are not. We *can* conclude that TRMM data input probably results into similar rainfall runoff results compared to the ground station data, under the condition that the models are (re-)calibrated.

When (real time) data from meteorological stations remains scarce, it is recommended to recalibrate all hydrological models with TRMM data as input.

4 FEWS-Volta evaluation

4.1 General

The previous chapters showed that including TRMM data improves FEWS-Volta in terms of robustness and sustainability. It was also explained that the recalibrated hydrological models based on TRMM give acceptable results compared to ground station data. Based on these findings it was decided to use a combination of ground station data, (raw) TRMM RT data, (validated) TRMM daily data and meteorological forecast data. The evaluation of FEWS, or rather, a hind cast of the 2012 flood season, was based on these different input data sets. In the following sections the hind cast results are illustrated per station for which observed data was available.

4.2 2012 flood season

The 2012 flood season was dominated by very large Bagre spills over a long period. Figure 25 shows the spilling lasted for more than a month, with a peak of 1400 m^3/s. The resulting water levels at Yarugu Kobori, the most upstream gauging station, is presented in the figure as well. The spilling resulted in the highest water levels ever recorded in Yarugu and flooded the area around this section, cutting of the important highway between Bolgatanga and Bawku. The exceptionally high discharge from the dam resulted from heavy rains in the upper White Volta basin. The rains in the Ghanaian parts of the White Volta basin did not lead to extreme flood events in the White Volta River and its main tributaries. Downpours that caused local floodings were recorded, for instance in the Tamale area.
As described in chapter 5 of the main report, the effect of discharge from Burkina Faso mainly causes floods between Pwalugu and Yarugu. Extreme floods more downstream will only occur due to a combination of high discharges from Burkina and extreme runoff from the Ghanaian White Volta basin. The next paragraph shows that this was not the case in 2012.

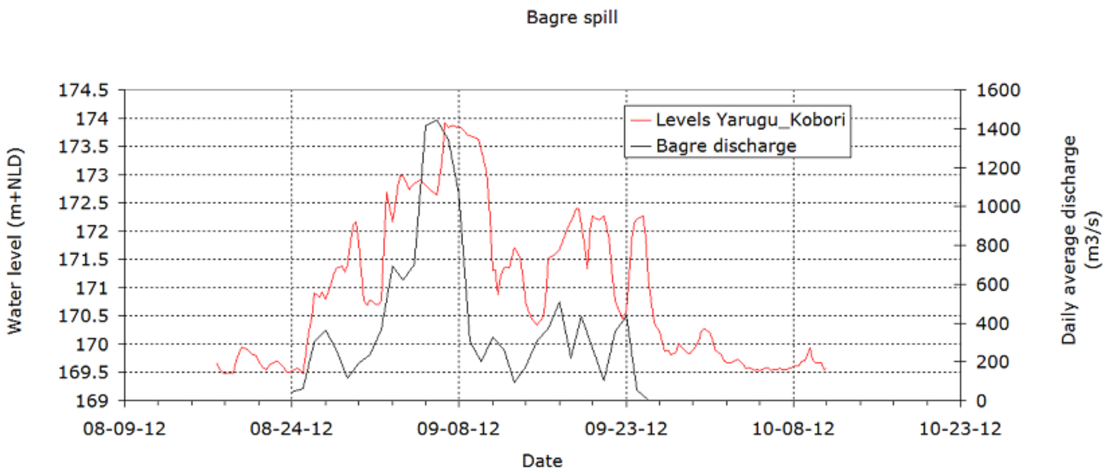


Figure 27 Discharge from Bagre dam and water levels at Yarugu Kobori

4.3 Hind cast 2012 flood season

During and after the 2012 flood season HSD provided us with water level data for several hydrological stations in the White Volta basin. FEWS-Volta was used to recalculate the water levels based on meteo forecast, raw TRMM data and validated TRMM data and compare the calculations with the observed readings. The results are used to assess both the FEWS-Volta accuracy as well as the effect of using different rainfall data sources. The results are presented per station.

Pwalugu and Yarugu Kobori

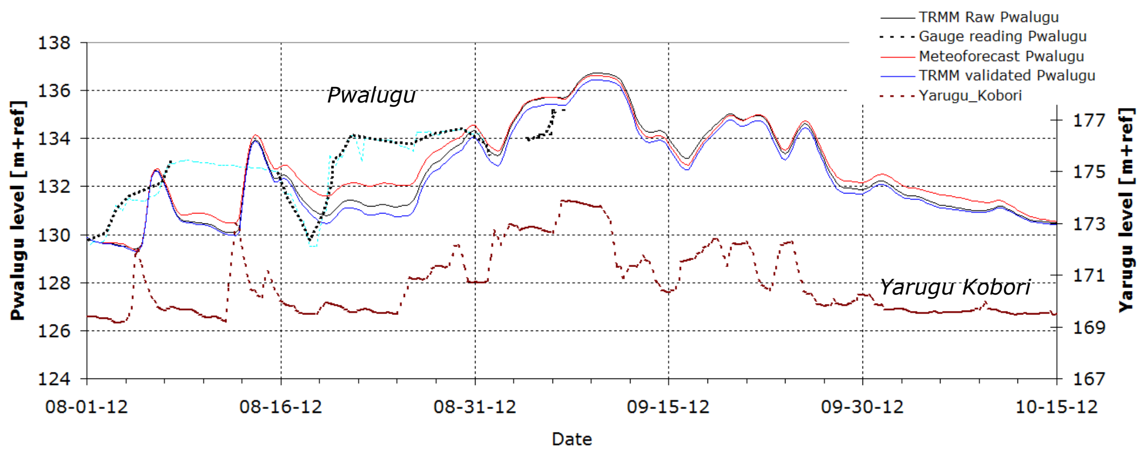


Figure 28 Water levels 2012 at Pwalugu and Yarugu Kobori

Figure 28 shows that the observed gauge readings from Pwalugu are not always in line with the calculated levels at Pwalugu. Whether this is caused by doubtful gauge readings or model uncertainty is not clear. The difference between the observed water levels at Yarugu and the gauge readings at Pwalugu suggest doubtful readings both in value as well as in time. Figure 28 also shows that the calculated water levels using raw TRMM data (RT), validated TRMM data (daily) and meteo forecast precipitation do not differ much. This is because the calculated Pwalugu water levels are dominated by the water levels at Yarugu Kobori and not by rainfall based inflow from tributaries.

Nawuni

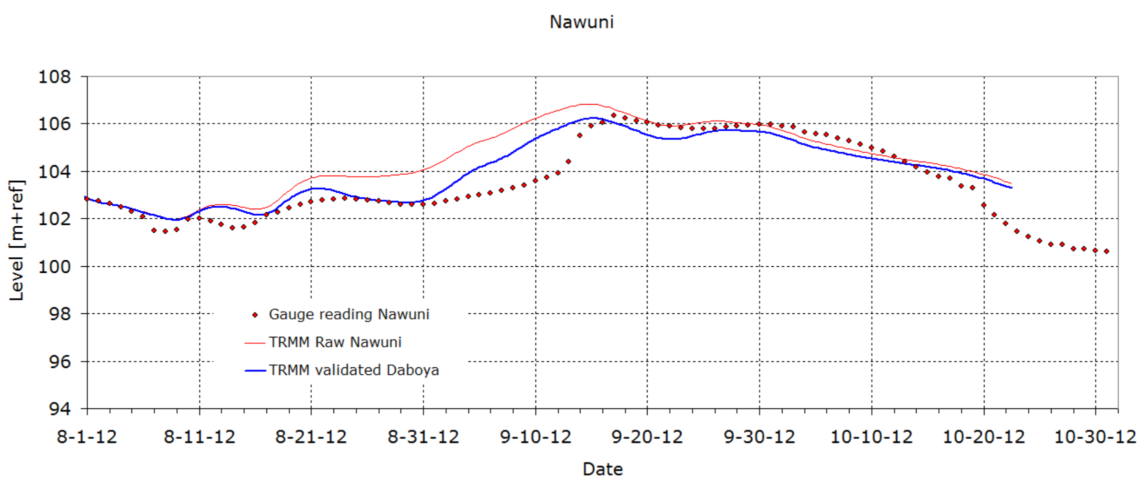


Figure 29 Water levels 2012 at Nawuni

Figure 29 shows the observed and calculated water levels using TRMM data at Nawuni. The first part of the rising limb, the falling limb and the peak value are represented relatively well. The second part of the rising limb was calculated higher compared to the observed values. This is probably caused by a relatively high calculated total discharge from the tributaries.

Daboya

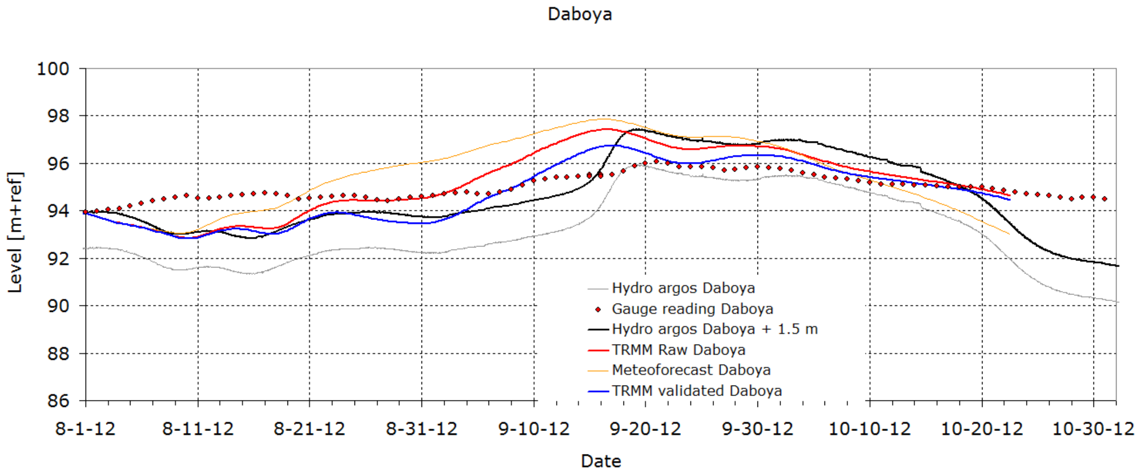


Figure 30 Water levels 2012 at Daboya

During the flood season it was concluded that the Hydro Argos readings at Daboya registered water levels approximately 1.5 m too low. Figure 30 also shows the gauge readings provided by HSD. The readings show a relatively flat line and are considered doubtful. It was decided to evaluate the FEWS-Volta hind cast based on the Hydro Argos water levels with 1.5 m increase as presented in Figure 30.
Similar to Nawuni, the first part of the calculated flood wave rise is similar to the observed water levels. The flood peak calculated with raw TRMM data is very similar to the observed peak, while the validated TRMM data results in an underestimation and the meteo forecast results in an overestimation of the peak. A relatively high calculated total discharge from the tributaries probably causes the second part of the flood rise to be overestimated by the model.

Yapei

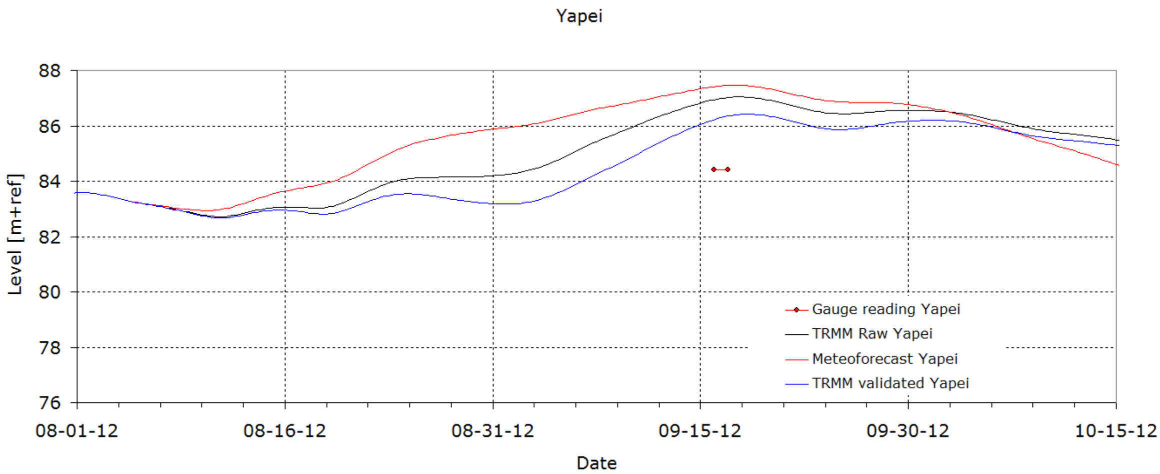


Figure 31 Water levels 2012 at Yapei

Figure 31 shows that only one gauge reading was available until now for Yapei. The model overestimates the reading with approximately 2-3 m.

Nasia

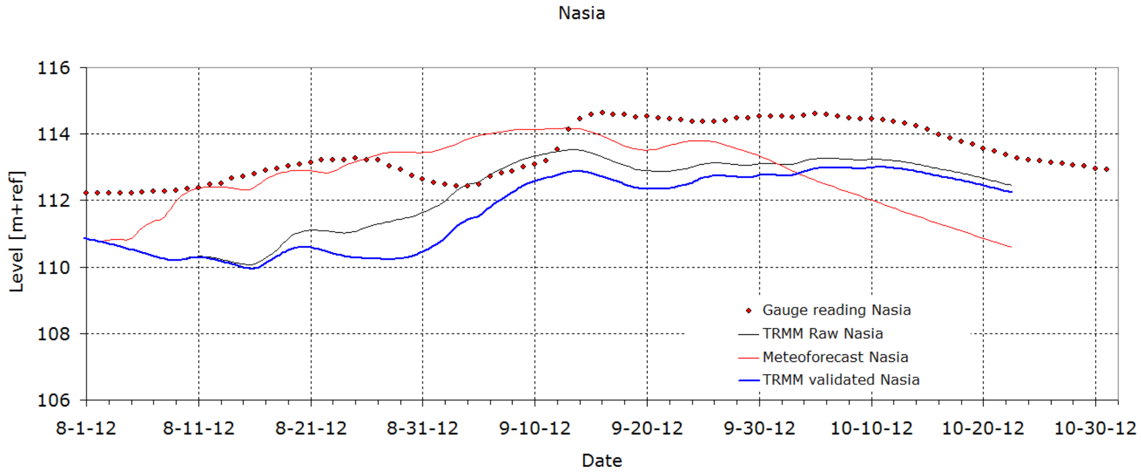


Figure 32 Water levels 2012 at Nasi

Figure 32 shows that the model in general underestimates the observed data at Nasia with approximately 1-2 m.

Yagaba

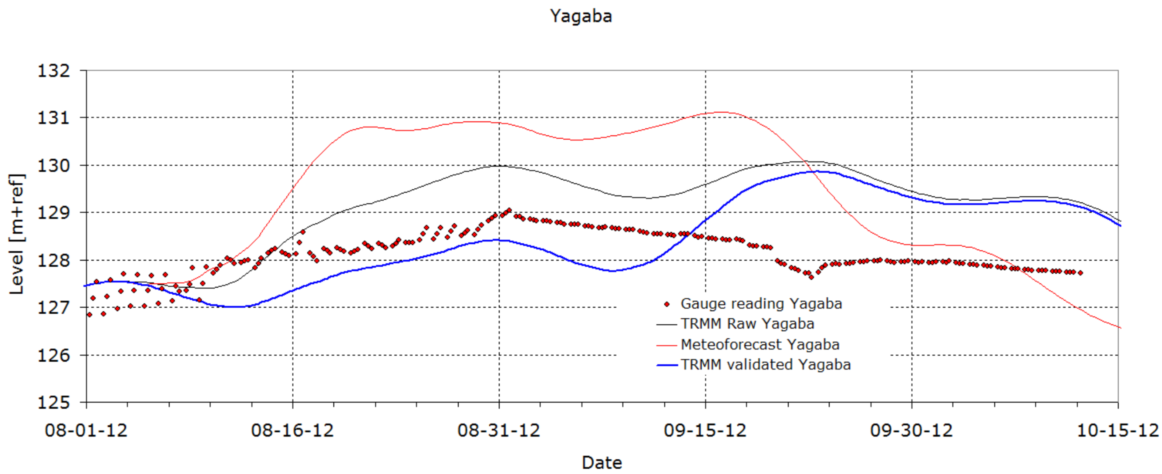


Figure 33 Water levels 2012 at Yagaba

Figure 32 shows that the model results based on validated TRMM data during the first period of the wet season is relatively similar to the gauge readings. The raw TRMM data results in an overestimation of maximum 1 m. Using meteo forecast the model overestimates the observed data with a maximum of 2 m. On the other hand, the readings show some irregularities in the beginning and a relatively flat registration over the whole period, which makes the observed data somewhat doubtful.

Wiasi

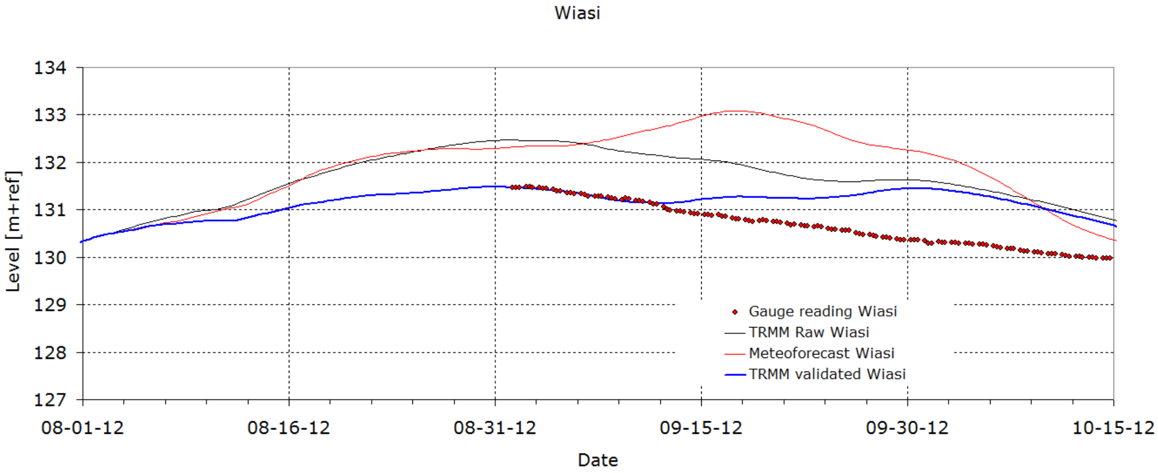


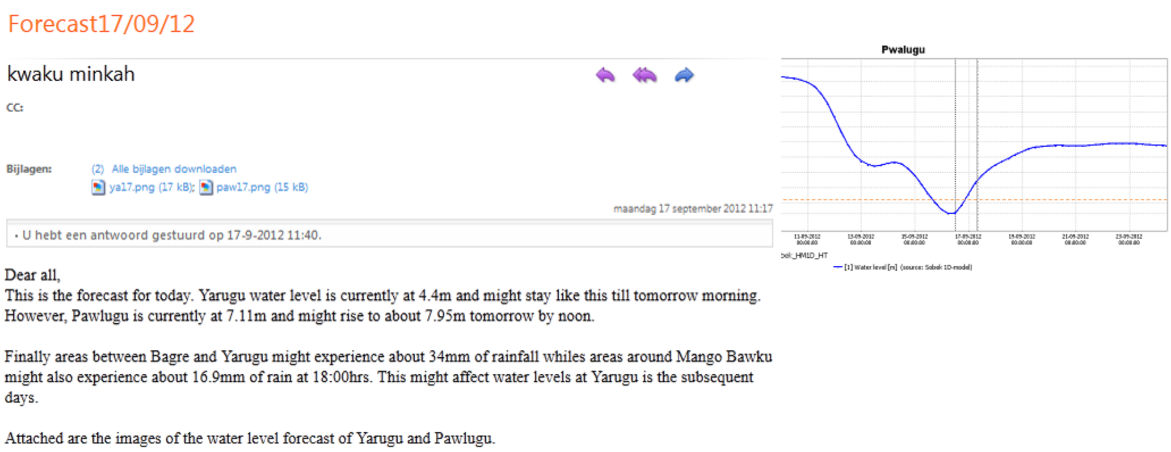
Figure 34 Water levels 2012 at Wiasi

Figure 34 shows that the observed values during the peak are very similar to the results based on the validated TRMM data. The falling limb of the wave is not properly represented for all model calculations. Both Wiasi and Yagaba show that the model calculated a second flood wave, which was not registered in the observed water levels.

4.4 FEWS-Volta communication

During the 2012 flood season several important communication processes and actions were carried out with relevance for flood disaster management:

- Sonabel informed the Ghanaian authorities two weeks in advance that Bagre dam spilling will commence.
- NADMO warned farmers in the Yarugu – Pwalugu section to harvest their crops and evacuate the flood plains as soon as possible.
- An email communication group was formed consisting of HSD, VRA, WRC, GMET, NADMO and HKV.
- HSD has been forwarding daily emails to these group members with river water level and meteo forecast data. Figure 35 shows an example of such an email.


Forecast17/09/12

kwaku minkah

CC:

Bijlagen: (2) Alle bijlagen downloaden
ya17.png (17 kB); paw17.png (15 kB)

maandag 17 september 2012 11:17

• U hebt een antwoord gestuurd op 17-9-2012 11:40.

Dear all,
This is the forecast for today. Yarugu water level is currently at 4.4m and might stay like this till tomorrow morning. However, Pawlugu is currently at 7.11m and might rise to about 7.95m tomorrow by noon.

Finally areas between Bagre and Yarugu might experience about 34mm of rainfall whiles areas around Mango Bawku might also experience about 16.9mm of rain at 18:00hrs. This might affect water levels at Yarugu is the subsequent days.

Attached are the images of the water level forecast of Yarugu and Pawlugu.

Figure 35 Forecast communication: example forecast email

- HSD has been collecting readings and footage during the flood season to support the FEWS-Volta evaluation.

It is not clear to what extent the forecast information was used as no feedback was provided to HSD yet. It is therefore recommended to evaluate the disaster communication with the relevant stakeholders. During the evaluation it is recommended to assess the forecast alert levels with information from the field provided by HSD, NADMO or local people.

4.5 Conclusions and recommendations

The following can be concluded from the hind cast analysis:

- Observed data was assumed doubtful for several cases. HSD has indicated it will continue collecting and validating the data. Once this process is finished we recommend updating the hind cast with the validated and extended observations to get a complete picture.
- Validated TRMM data provides the best results, although still not in line with the observed data. Validated TRMM data is available only once every 2 months and cannot be relied upon for flood forecasting. Raw TRMM data shows better results compared to meteo forecast based results. The results strengthen the decision to firstly use validated TRMM, if not available use raw TRMM data and if not available use meteo forecast data. The forecast is made with a merge of these data sets.
- Table 4 shows the difference on the peak for the calibration periods and the 2012 flood season. The results on the main and most flood prone parts of the White Volta, represented by stations Pwalugu, Daboya and Nawuni show results deviating maximum 0.5 m from the calibration results. Yapei and the tributaries show very poor results.
- Based on the results and expert judgment it is concluded that FEWS-Volta is able to forecast water levels on the White Volta with an accuracy of about 1 m and a lead of 3-5 days. The lead time in the Yarugu – Kulpawn section is about 0-3 days with an accuracy of about 1 m.

	Difference on peak (m)	
Station	**Average station (2003-2007)**	**2012**
Yarugu	-0.15	
Pwalugu	0.65	0.1 - 0.5
Nawuni	-0.13	0.5 - 0.75
Daboya	0.04	0 - 0.7
Yapei	-0.23	2 - 3
Wiasi	0.06	0 - 1
Yagaba	0	0 - 2
Nasia	0.2	1 - 1.75
Nabogo	0.12	
Average total	-0.11	

Table 4 Difference with peak for calibration period and 2012 flood season

Recommendations

- It is strongly recommended to use real time input from the hydrological stations at the 1d model boundaries of Wiasi, Yagaba, Nasia and Nabogo, the same as the water levels at Yarugu are used as model boundary. This will strongly improve the model forecast for 1-3 days lead time.

- FEWS-Volta has a large amount of information. It can easily be used to evaluate what happened during the flood season. The trained stakeholders should continue using with it.
- Automatic Weather Station data from GMET and hydro-argos data from HSD will become available in the future. This should be used to validate, update models and update FEWS. As mentioned HSD should continue collecting and validating hydrological data at the relevant stations.
- Forecasts for the Upper White Volta section can be improved by extending FEWS-Volta into Burkina Faso.