

Article

Development and Evaluation of a Web-Based and Interactive Flood Management Tool for Awash and Omo-Gibe Basins, Ethiopia

Surafel M. Woldegebrael ^{1,2} , Belete B. Kidanewold ²  and Assefa M. Melesse ^{3,*} ¹ ENTRO, Addis Ababa 358, Ethiopia; surafel.m2@gmail.com² School of Civil and Environmental Engineering, Addis Ababa Institute of Technology, Addis Ababa University, Addis Ababa 358, Ethiopia; belete.berhanu@aait.edu.et³ Department of Earth and Environment, Institute of Environment, Florida International University, 11200 SW 8th Street, Miami, FL 33199, USA

* Correspondence: melessea@fiu.edu

Abstract: Flood risk management is used to monitor floodwater and mitigate flooding that impacts people, properties and infrastructures, and the environment. This study developed an interactive web-based “flood tool” for Awash and Omo-Gibe basins in Ethiopia to improve the flood monitoring services and facilities. The data used were real-time and seasonal rainfall-runoff forecasts, flood inundations, and other forecast products for the 2021 flood season (June to September) in a case study. Methods used were multiple scripts written in the Hypertext Markup Language (HTML) and the Visual Studio Code as a coding environment. The coefficient-of-determination (R^2) and efficiency (NSE) were used to evaluate the forecast products. The R^2 values for selected river stations were the Awash-Hombole (0.79), Mojo (0.64), Awash-7 (0.66), Awash-Adaitu (0.62), Gibe-Tolai (0.78), and Gibe-Abelti (0.70) rivers. The R^2 values for Koka and Gibe-3 reservoirs inflows (water levels) forecasts were 0.97 (0.96) and 0.93 (0.99), and the NSE values were 0.89 (0.88) and 0.92 (0.95) for each reservoir, respectively. Besides, the flood inundation extents (km^2) from satellite observation and model were compared for the main flood-prone areas and in agreement with very good performance. The flood tool can therefore present early warning forecast products and convey advice to decision-makers to take action for the people at risk.

Keywords: flood tool; flood early warning; Awash basin; Omo-Gibe basin; HEC-HMS; Ethiopia



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1. Introduction

Flood risk management is emerging as a range of measures to monitor floodwater (flow) and mitigate flood risks that impact people, properties and infrastructures, and the environment. It is a fundamental tool to evaluate flood risks through explicit approaches considering the human and socio-economic issues of planning and development aspects. Nowadays, development in flood-prone areas aligns with increasing extreme weather events and climate change making flood risk management more important than ever [1,2]. In Ethiopia, there is no well-defined flood management system at national and basin levels, unless some traditional and event-based flood monitoring efforts take place. Nevertheless, negative impacts from flooding along with the waterways [3] can be introduced with the importance of flood management interventions [4]. The flood risk management system requires the understanding of where the floodwater comes (*the source*), how and where it flows (*the pathways*), and who is affected by floods (*the receptors*) [5], such as the people, assets, and the environment. In high-risk areas, for instance, there is at least a chance of flooding, and in moderate to low-risk areas, there is a risk of being flooded.

The present study is therefore initiated to develop an interactive prototype flood tool (or flood dashboard) [6] to support the flood risk management system [7,8] for Awash

and Omo-Gibe basins where flood risk is an issue. The flood tool facilitates accessing the rainfall and runoff forecasts and flood inundation maps for flood early warnings and to mitigate flooding impacts. The flood inundation maps, for instance, help to outline risk areas and provide flood information, outreach to flood-prone communities, and support decision-makers to take action ahead of time. The role of the flood risk management system, in general, is as a tool to monitor flooding in consultation with decision-makers, flood vulnerable communities, and stakeholders. Since flood risks have never been controlled, and if it is beyond the capacity to reduce flooding impacts [9], this includes practices to adapt and live with minimized flood risks. The application of flood forecasting and early warning component as part of a flood risk management system to mitigate flood impacts is feasible and less costly to implement. Besides, it provides an emphasis on awareness, preparedness, and evacuation of people if they are at risk.

Once the flood forecasting and modeling systems were developed, the flood early warnings can be issued to a range of users, such as (a) creating readiness for operational and flood emergencies, (b) providing early warning in time about flood impacts including locations of the event, and (c) give time to undertake evacuation and emergency procedures in case of extreme floods. To enhance and improve the flood risk management plan [9] and decision-making facilities, this case study avails a strategic flood tool that possesses a sustainable flood management system [10]. Therefore, the flood forecasting and early warning system is an economical and time-saving monitoring system using the advantage of an interactive and responsive web-based flood tool. The flood tool supports in providing advice to decision-makers and the people at risk to deal with the negative impacts of flooding and take early mitigation actions. To protect flood-affected communities and supplement the flood warning system, flood warning and risk threshold levels are included in the flood tool. Some components considered in the flood management system to obey the flood warning system are: (1) noting the peak river runoff (or water levels) forecasts leading to flooding when it reaches the highest level, either warning or risk levels; (2) indicate and understanding of flood forecasting, where the floodwater will go and who will be affected by it; (3) prepare and communicate early warning messages and disseminate to users in time; (4) produce a timely response and act accordingly to reduce impacts from flooding; and (5) evaluate and improve the warnings by checking its performance after flooding.

In summary, an effective flood warning system helps to provide early warning flood information, threshold levels, flood travel time, flood inundation extents, and flood depths ahead of time. Flood threshold levels, such as flood warning levels and risk levels, are important references for the issue of flood warnings. The flood warning level is used, at which decisions are taken to issue flood warnings for a given point where flooding is occurring. In doing so, users have the opportunity to save lives and minimize damages to assets and the environment relaying the acceptable flood lead time. Due to the recurrent flooding impacts in model basins, the flood tool was developed to convey real-time and seasonal forecasts and improve early flood warning services. The flood management tool is a pilot web-based and interactive flood tool introduced in the model basins for the first time. Currently, the approaches used by the decision-makers and the communities were traditional and analog-based, demanding high human involvement. Most of the communications were oral using radios and phones. It was not effective and timely and also highly dependent on the local observers to make decisions on the incoming risks. This study shows a simple and automatic web-based tool that can provide reliable information for decision-makers and communities as well.

The specific objectives of this study are to (1) develop a web-based interactive and responsive flood tool to support flood monitoring systems, (2) facilitate and convey early flood warning information to users and decision-makers, (3) prepare a user manual on how to use the flood tool, and (4) identify key information users and propose institutional arrangements having different rights and responsibilities to access data and forecast information.

2. Materials and Methods

2.1. Study Area

The flood tool was developed for the Awash and Omo-Gibe basins (Figure 1) of Ethiopia, which is the major flood-prone basins with a history of flood-related damages. These study basins are located between $4^{\circ}45'/12^{\circ}50'$ N latitudes and $34^{\circ}50'/43^{\circ}19'$ E longitudes with approximate altitude variations of between 250 and 2900 m.

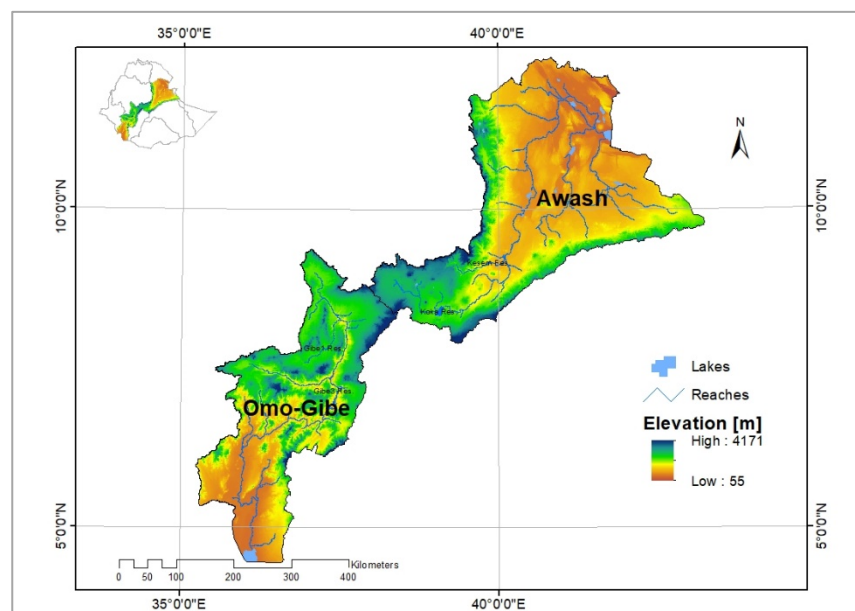


Figure 1. Location of model basins and surface aspects.

The flow rates from historical records (1981–2016) at different key river gauging stations were utilized for verification analysis of runoff forecasts. In the study basins, the mean annual rainfall is about 1220 mm in the high land areas to 300 mm in the lowlands. The daily average temperature values range from a minimum of 10.1°C to a maximum of 30.2°C [11]. The land use land cover of the study basins consists of forest, woodland, afro-alpine, shrub/bush, cropland, grassland, waterbody, wetland, bare land, and settlements. It was collected from the Water and Land Resources Center (<https://www.wlrc-eth.org/> (accessed on 25 May 2021)) of Ethiopia and used in the analysis. Similarly, the prominent soil types in the basins are Liptosol (50.61%), Cambisol (12.22%), Nitisol (9.69%), Alisol (6.56%), Vertisol (4.93%), Fluvisol (3.98%), and Luvisol (3.88%), and others are 8.13% which helps to understand flooding processes in a catchment. The soil data were accessed from the FAO database (<https://www.fao.org/soils-portal/> (accessed on 20 February 2021)). The Digital Elevation Model (DEM) data with 30-meter resolution from Shuttle Radar Topography Mission (SRTM) space center were also used in the analysis of geospatial data features of the study basins. In general, these study basins are impacted by recurrent flooding events in the past [11,12], mainly in 1996, 2006, 2016, and 2020 flood seasons.

2.2. Data Used

The in situ of satellite-driven gridded precipitation data (Figure 2) were accessed and used for real-time flood forecasts (hourly data) and seasonal flow forecasts (daily data) where the observed rainfall data are sparse on the ground.

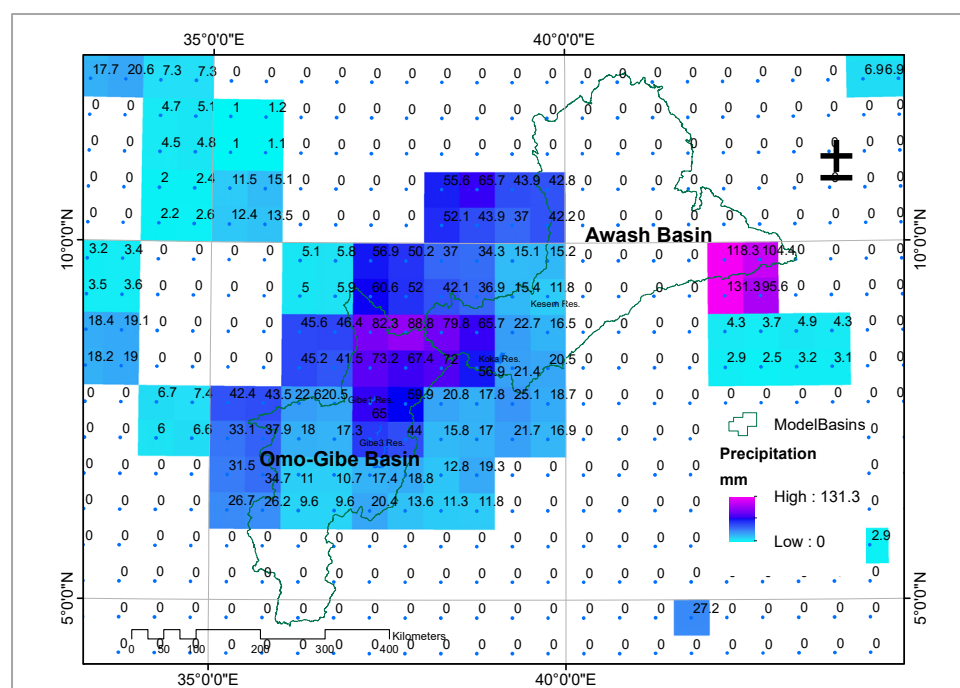


Figure 2. Gridded precipitation over the model basins.

In the real-time forecast, the precipitation data from the Global Forecast System (GFS) produced by the National Centers for Environmental Prediction (NCEP) at <https://nomads.ncep.noaa.gov/> (accessed on 20 August 2021) was used. It is available in 6-hour intervals of accumulated gridded precipitation data (00 h, 06 h, 12 h, . . . , 240 h) in the GRIB format. The precipitation data can be downloaded for 3, 5, 7, 10, or 14-day lead-time, whereas 10-day data were used to produce a real-time runoff forecast. In this case, a script in National Center for Atmospheric Research (NCAR) Command Language (NCL) was developed and connected with windows 10, Windows Subsystem for Linux (WSL) system to download the real-time precipitation data. The bash script uses the Climate Data Operator (CDO) tool to build and download, re-grid, merge the Network Common Data Form (NetCDF), and extract time-series data as discussed in the following steps (see Part I below). Then, we use the data in the Hydrologic Engineering Center's Hydraulic Modeling System (HEC-HMS) model to produce runoff forecasts, and finally, the runoff forecasts are used in the hydrodynamic model, Engineering Center River Analysis System (HEC-RAS), for flood inundation mapping (see Part II below).

Part I:

- Download 6-hour interval gridded precipitation using CDO bash script in Grib2 (*.grb2).
- Re-grid the 6-hour interval data into hourly data, and convert them to NetCDF (*.nc).
- Remap the 0.25 deg (27 km) hourly precipitation data to 0.05 deg (5 km) data (*.nc).
- Concatenate the gridded precipitation (prate data) data based on time step (*.nc), which can be bias-corrected (time series) before using it in modeling and further analysis.

Part II:

- Import gridded data in the hydrological model (HEC-HMS) wizard from the working directory (NetCDF or Grb2).
- Clip the gridded data for the model basins shapefile (*.shp), a project in Universal Transverse Mercator (UTM), and resample parameters based on the grid cell size of the model basins.
- Store the gridded precipitation data in the HEC-Data Storage System and Visual Utility Engine (HEC-DSSVue) and access them by the configured HEC-HMS model to generate runoff.

- Use the forecasted runoff in the HEC-RAS 2-Dimensional to generate flood inundation maps.

On the other hand, 180-day precipitation and temperature forecast datasets produced by NMME were accessed and used for seasonal flow forecasts. The seasonal precipitation was accessed from <https://climateserv.servirglobal.net/> service center and used for seasonal forecasts (accessed on 31 May 2021). These forecast datasets are produced along with Climate Hazards Group InfraRed Precipitation with Station (CHIRPS), 0.05 deg resolution historical data to connect the precipitation patterns from the past to future forecasts. The seasonal data were bias-corrected locally and verified with the observed data before use. Besides, observed rainfall data obtained from Ethiopia Meteorological Institute (EMI) and CHIRPS were used for data gap infillings. In the future, the national rainfall forecasts, produced by EMI using Weather Research and Forecasting (WRF) model, can be adopted and used as alternative model inputs if the satellite data source may cause an issue.

2.3. Methods

To address the challenges of flood forecast information dissemination for users and access, a user-oriented and interactive web-based functional flood tool was developed based on a conceptual framework, system design, and technologies [13]. The rainfall and flood forecasts, flood inundation maps, and flood depths were produced using hydrological and hydrodynamic models.

2.3.1. Bias Correction

Since the global data are generally biased [14–16], the data were bias-corrected [17,18] before using them in the forecast model. Observed rainfall data from EMI were used as a reference to correct the biased precipitation data [19,20]. In this analysis, a linear scaling (LS) correction method was applied. LS implements a constant corrected factor to estimate the difference between raw satellite-driven data and observations for each day and calendar month. LS was selected because of its simplicity, accuracy, parameter considerations, and previous works of literature in maintaining the reliability of the results after treatment [21,22]. It is capable of adjusting climatic factors when monthly mean values are included [15,21]. The multiplicative correction for precipitation and additive correction for temperature data are applied, as given in the following equations.

$$P_{h,m,d}^c = P_{h,m,d} \times \left[\frac{\mu(P_{O,m})}{\mu(P_{h,m})} \right] \quad (1)$$

$$T_{h,m,d}^c = T_{h,m,d} + [\mu(T_{O,m}) - \mu(T_{h,m})] \quad (2)$$

where $P_{h,m,d}^c$ and $T_{h,m,d}^c$ represent the corrected precipitation and temperature on the d^{th} day of a given month, respectively, and $P_{h,m,d}$ and $T_{h,m,d}$ are the precipitation and temperature from the original RCM outputs for a target period, respectively; d and m represent specific days and months, respectively, and μ represents the mean value.

2.3.2. Runoff Forecasting and Modeling Approach

The bias-corrected satellite-driven hourly (or daily) gridded precipitation and temperature forecasts were used in a configured hydrological flood model (HEC-HMS v4.9) to produce seasonal flow forecasts [23]. The flood models are mathematical models most often used to support the flood risk management system. This HEC-HMS model with its new features is a semi-distributed, physically based, and time-continuous hydrological model that was developed by the United States Corps of Engineers. The model basins were divided into 95 subbasins (Figure 3), and the runoff varying in time was introduced as an input coming from the uplands of the basins. Some selected 13 discharge stations, 8 in Awash and 5 in Omo-Gibe basins, in the model basins were used to drive calibration and verification of estimated runoff results. In this analysis, a daily time step was applied for the near real-time flood forecast simulations based on the time interval of the available observations.

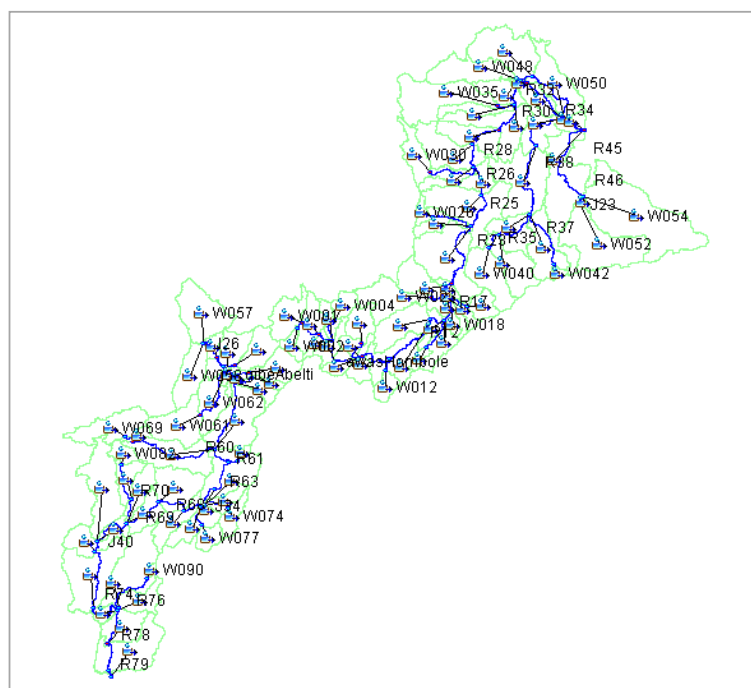


Figure 3. Processed HEC-HMS and schematization basin model for simulation.

In the model configuration, the Soil Conservation Services (SCS) curve number method implemented the SCS curve number loss method for real-time forecasting, and the one-layered deficit and constant loss method for seasonal forecasting was utilized. In the floodwater transformation method, the modified Clark (ModClark) spatially distributed or quasi-distributed [24,25] transform method to transfer grid-based excess precipitation to runoff was used. In terms of runoff routing, the Muskingum-Cunge routing method (or variable coefficient method), which is a combination of conservation of mass and diffusive conservation of momentum, was applied. Therefore, the calibrated HEC-HMS model was used and intended to be used in future flood forecasting and early warning system.

The initial conditions (ICs) and Boundary conditions (BCs) were also introduced in the hydrological and hydrodynamic models. ICs represent the runoff at the start of heavy rainfall, and it was defined as a global value used at different calculation nodes for the water depth and reaches segments. The time series was then used in model simulation to keep a hydraulic energy gradient line of the behavior of the hydrodynamic flows. BCs, on the other hand, are the values in unsteady flow system inputs that force the hydrologic system and cause it to change. In this case, precipitation served as BCs in the HEC-HMS model that caused runoff from a watershed. In turn, the runoff (flow) hydrographs were used in the HEC-RAS routing model as input to channel reaches. Research indicated that flow hydrograph is used as upstream BCs and water depths/stage hydrographs as downstream BC; alternatively, the normal depths or channel slopes served as downstream BCs. In this study, 22 external (inflow hydrograph to the 2D system) and 5 internal (inflow alignments) BCs were served to connect the SA and 2D areas.

2.3.3. Develop a Web-Based Flood Tool

The method used to develop the flood tool is intended to support ease and on-time access of early flood warning information [13,26] for flood monitoring and decision-making facilities. It is a web-based user interface tool developed using suitable technologies and programming languages on the client-side, such as JavaScript, Bootstrap (<https://getbootstrap.com> (accessed on 4 September 2021)), a Cascading Style Sheets (CSS), leaflet, and Plotly (<https://plotly.com> (accessed on 13 April 2021)), among others. The webpage was written in HTML language that describes the layout, format, and content of a page. In this case, the Visual Studio Code was utilized as a coding environment to develop a

responsive, easy-to-use, and compatible interface with all modern browsers, such as Edge, Chrome, Firefox, Internet Explorer 10+, Safari, and Opera browsers. The web browser then renders the page according to the HTML code.

A flood tool is an interactive tool that can be ready to launch using the Internet to access the flood forecast information. In this case, it receives the request sent by a browser, then the browser connects to the server through an IP address, and the IP address is obtained by translating the domain name; lastly, the server sends back the requested page accordingly. To visualize and present the flood forecast information, an interactive web-based flood tool can be used to facilitate the service. In this case, decision-makers at the Ministry of Water and Energy (MOWE), Disaster Risk Management Commission (DRMC), EMI, flood-prone community officials, and other stakeholders are involved as the responsible entities to receive flood forecasts and take early warning decisions on flooding impacts.

Once the webpage is developed and tested on a local machine, and organized with appropriate data directories, it works properly and becomes easy for future modifications. Nevertheless, it needs to register with a given domain name (e.g., www.mywebpage.com) with appropriate Internet Service Provider (ISP) hosting services. In this case, a server-side, either Hypertext Preprocessor (PHP) or Java server Page (JSP), Application Service Providing (ASP), or Practical extraction and report language (Perl), can be used. Therefore, the webpage will be ready to launch on the Internet, the following key issues are taken into consideration. These are as follows: (1) The server receives the request for a page sent by a browser. (2) The browser connects to the server through an IP address; the IP address is obtained by translating the domain name. (3) In return, the server sends back the requested page. The summary of the flood tool components and schema is presented in Figure 4.

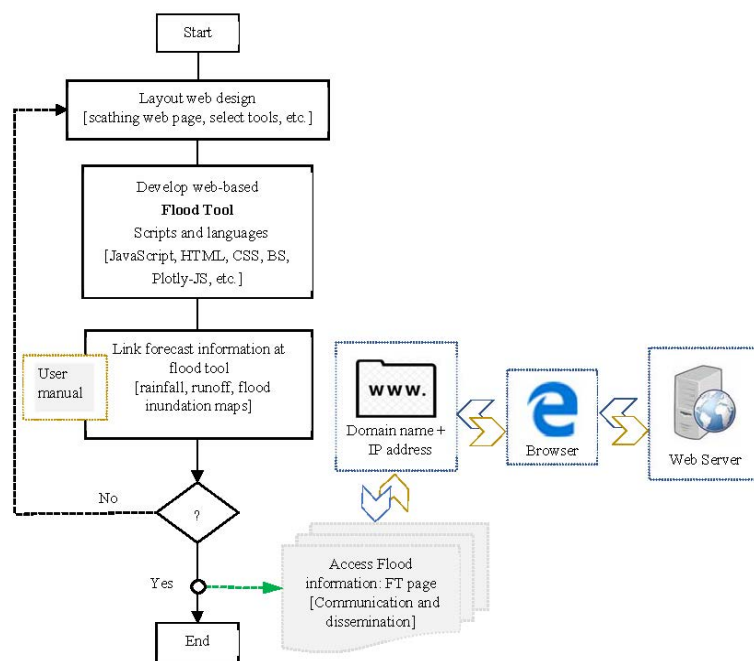


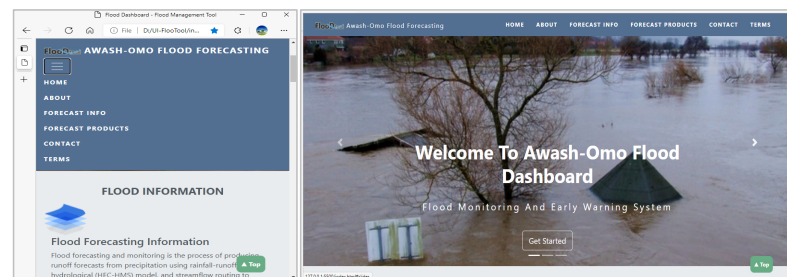
Figure 4. Schema of developing the flood tool and its purpose.

In general, gridded satellite precipitation forecasts were downloaded and imported to the configured HEC-HMS hydrological model to generate runoff (precipitation and outflow) and stored the results in the HEC-DSSVue database. Then the hydrodynamic model (HEC-RAS, 1D/2D) fetched the outflow (or runoff) data from the HEC-DSSVue database to route and produce the flood inundation extents and flood depths over the flood-prone areas using the flood mapper. Finally, both the rainfall and runoff forecasts can be exported to comma-separated values (CSV) (or the HTML platform) and the flood depths exported to the SQLite database (or images) to display on the webpage developed for the study areas.

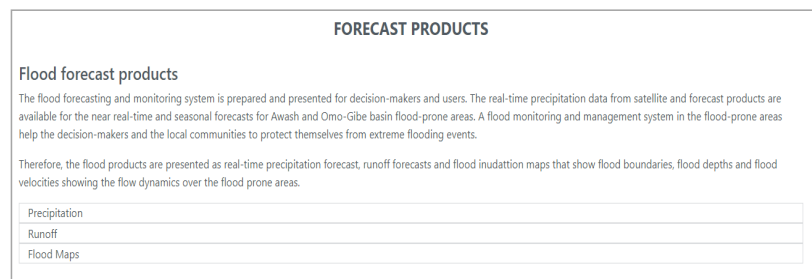
3. Results

3.1. Web-Based Flood Tool

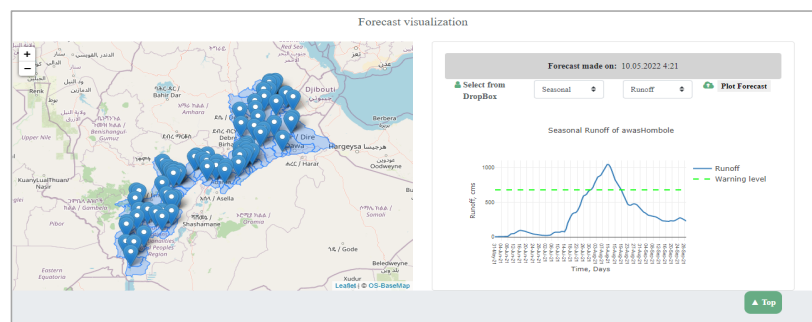
The web-based flood tool developed for the study basins is used to convey the forecast products (real-time and seasonal flood forecasts) to inform the decision-makers on flood early warning to take action. Therefore, the flood forecasts can be provided through the flood tool (Figure 5), which includes the rainfall and runoff forecasts (Figures 6 and 7), flood inundation maps that show flood inundation extents and depths over the flood-prone areas (Figure 8), and flood evacuation routes and flood occurring locations (Figure 9). Nevertheless, the users can have local knowledge about flood risks, roles of flood warning and dissemination, and actions they are required to take.



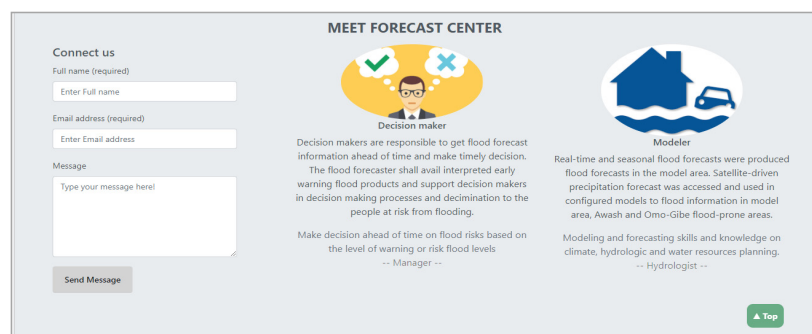
(a)



(b)



(c)



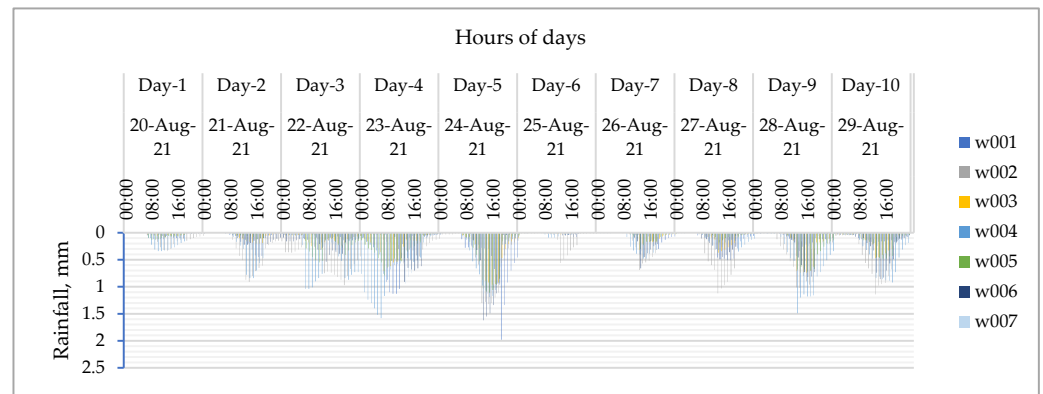
(d)

Figure 5. Cont.

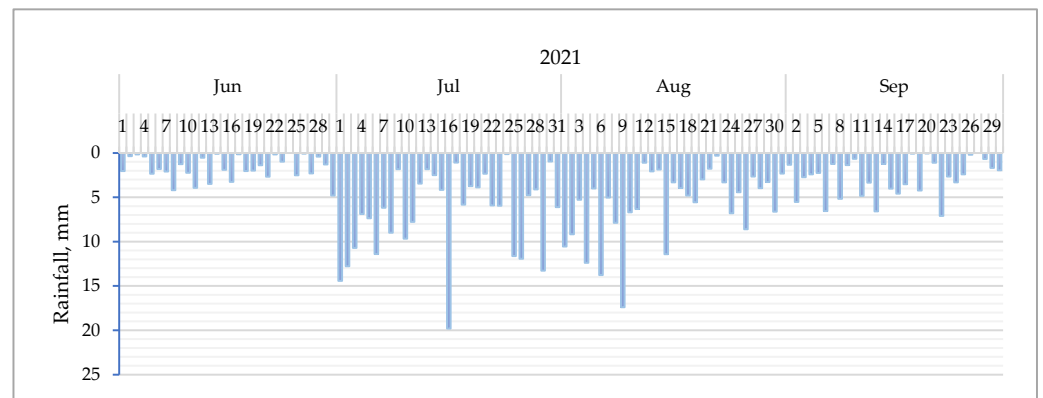


(e)

Figure 5. Web interface for Awash and Omo-Gibe flood monitoring system. The flood tool consists of (a) Home page (interactive and responsive), (b) Forecast products page (precipitation, runoff, and flood maps), (c) Visualization page (subbasins, river stations, and plot area), (d) Information page (contact us, decision-makers and forecasters), and (e) Footnote page (contact info, social links, and Top navigator).



(a)



(b)

Figure 6. Rainfall forecasts for (a) real-time forecast indicating accumulated hourly rainfall (20–29 of August 2021), and (b) seasonal forecast indicating daily mean rainfall for the 2021 flood season.

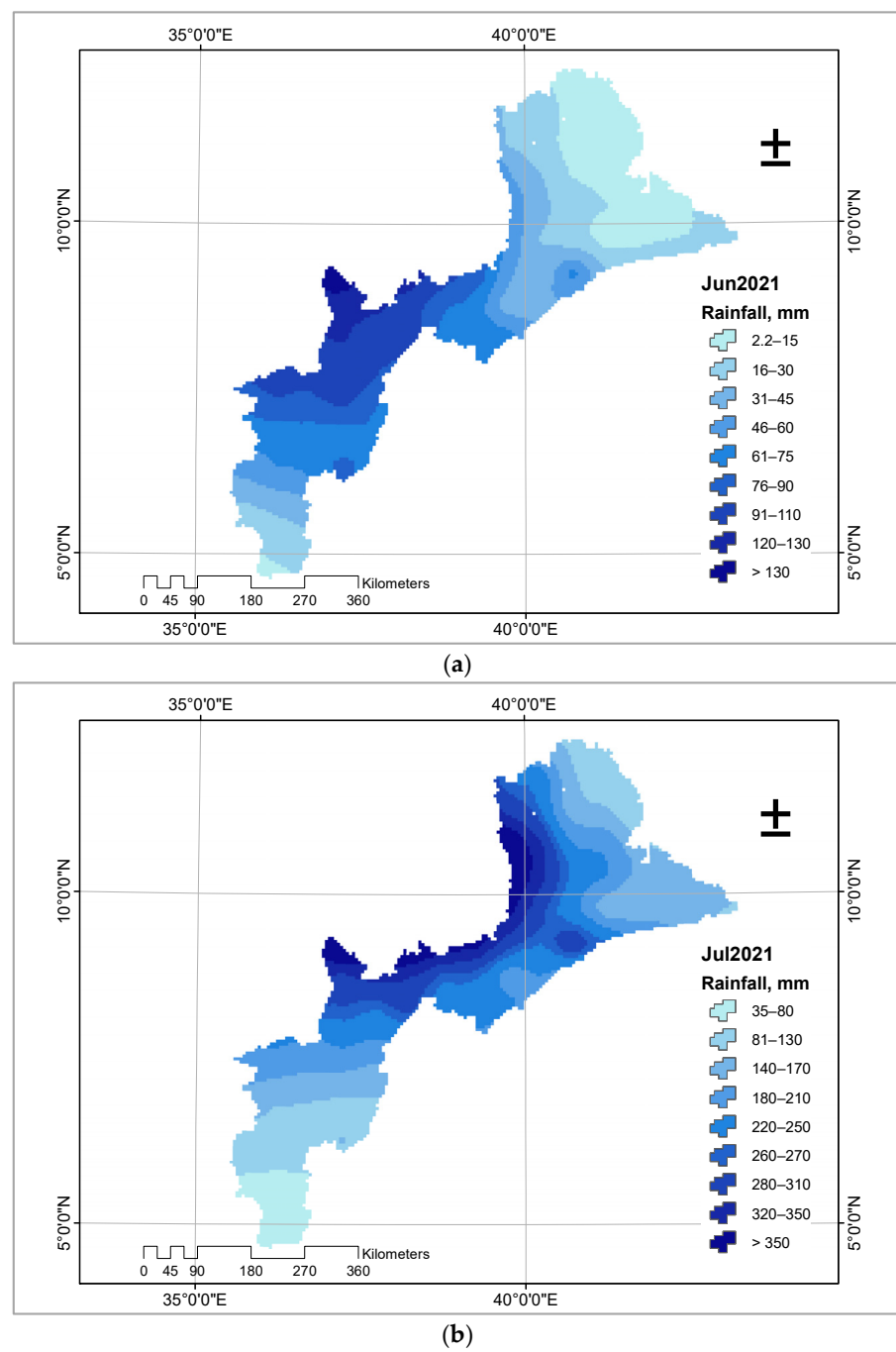


Figure 7. Cont.

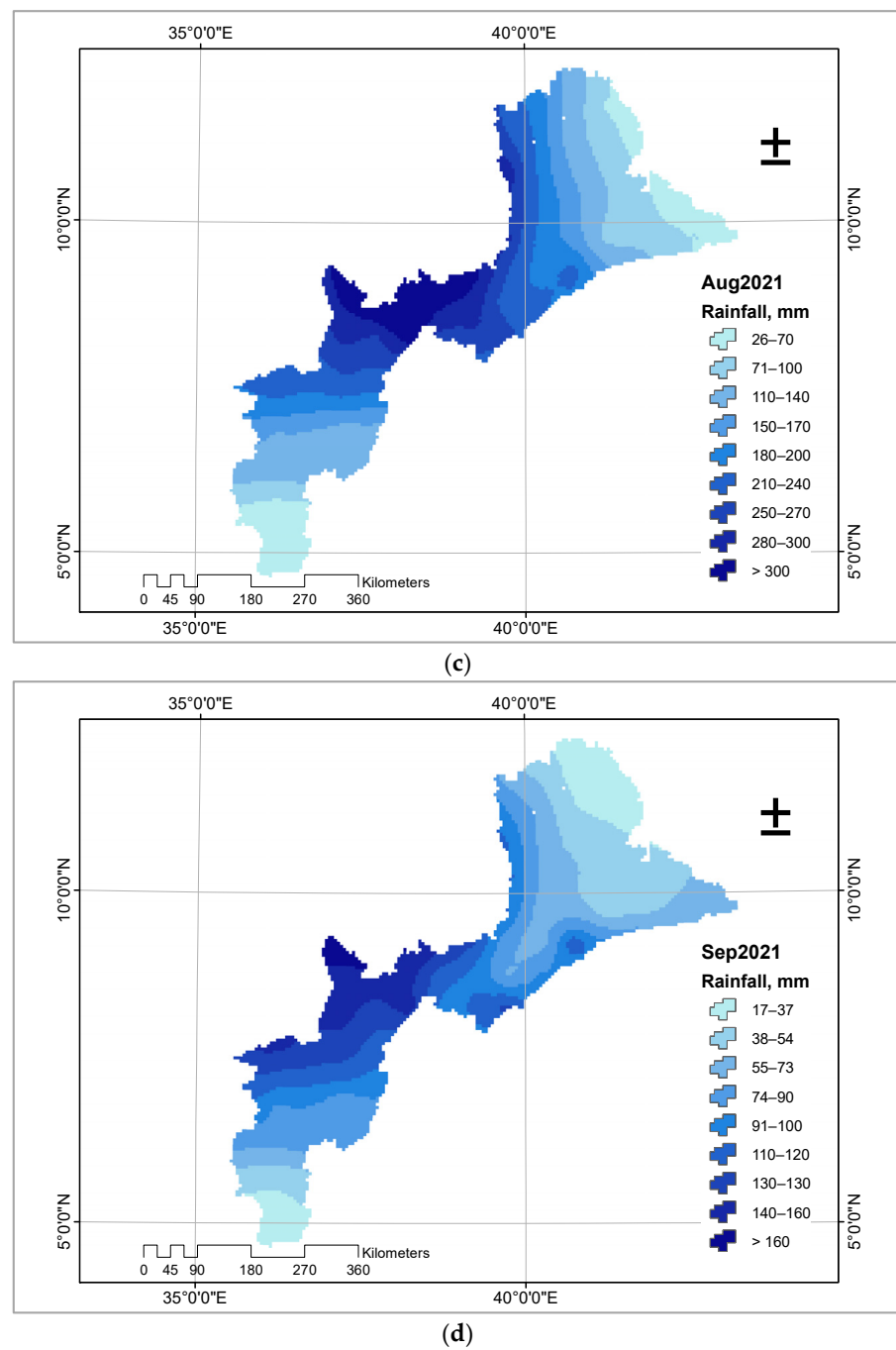
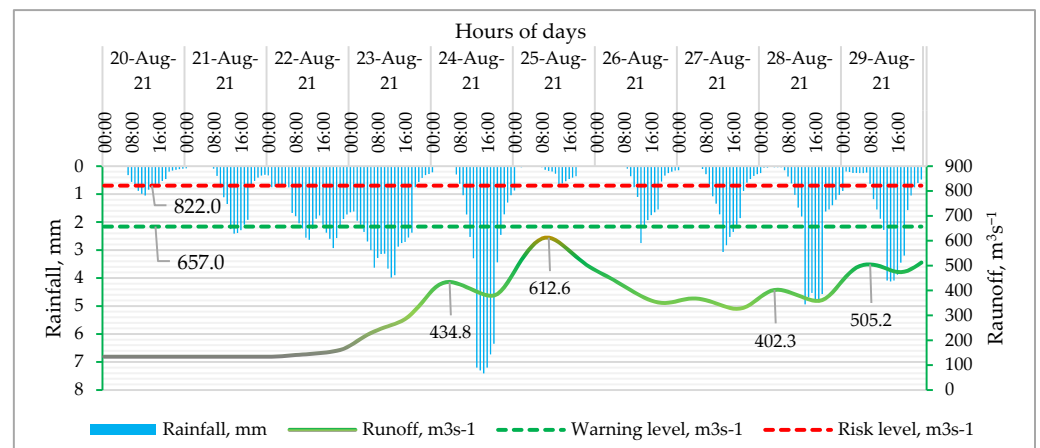
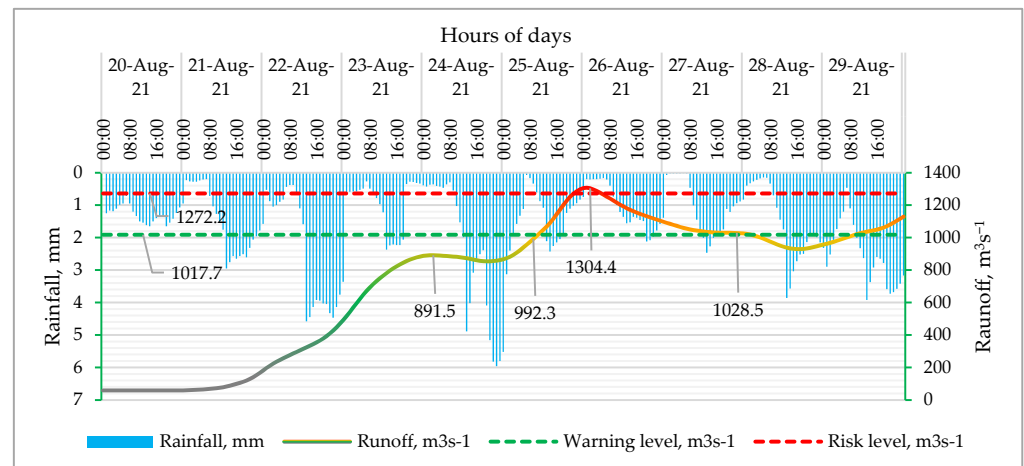


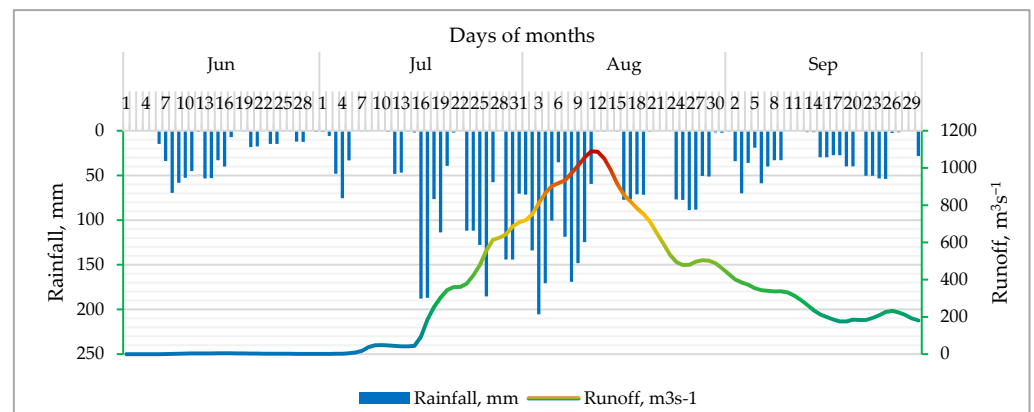
Figure 7. Spatial presentation of precipitation for the 2021 flood season. In essence, (a) the rainfall distribution for June, (b) the rainfall distribution for July, (c) the rainfall distribution for August, and (d) represents the rainfall distribution for the month of September.



(a)



(b)



(c)

Figure 8. Real-time ((20–29 August 2021 hourly data) and seasonal (daily data from June to September 2021) rainfall and runoff forecasts for selected river stations. Therefore, (a) shows real-time rainfall and runoff forecasts for Awash-Hombole River, (b) real-time rainfall and runoff forecasts for Gibe-Tolai, and (c) seasonal rainfall and runoff forecasts for Awash-Hombole River station.

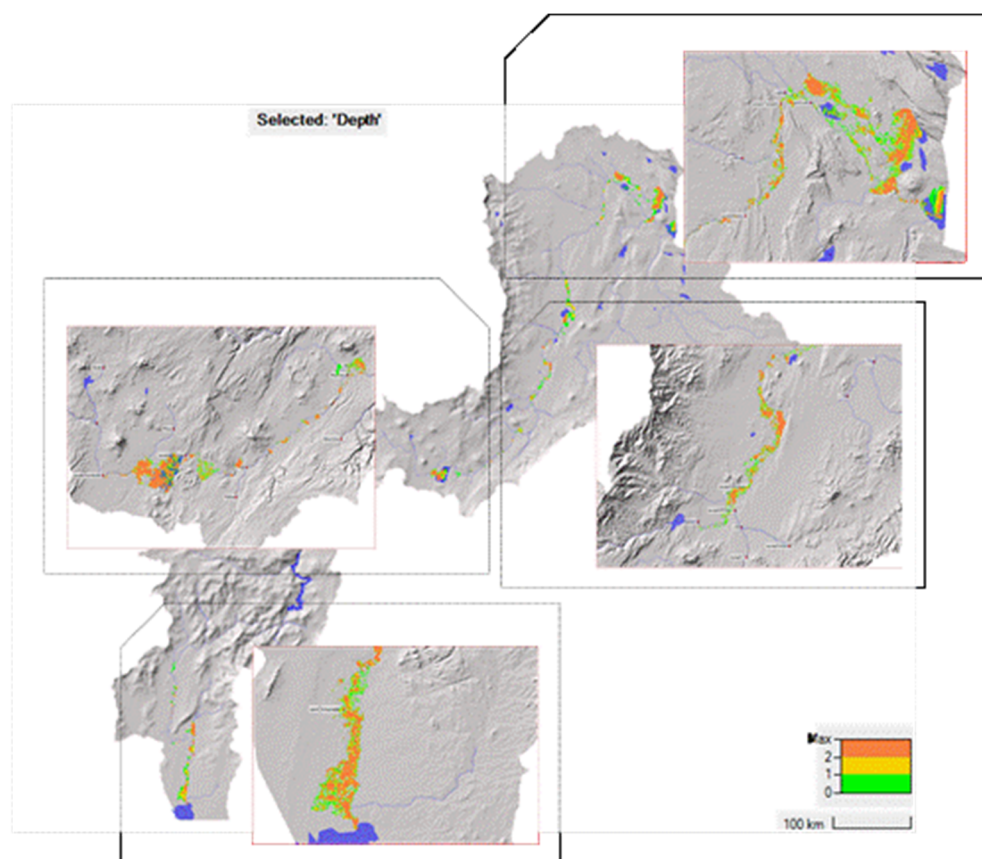


Figure 9. Flood inundation extents and flood depths from the model, August 2021.

The flood tool has different components in the web interface that are used for the navigation of flood forecasts, and it consists of the following navigation tabs. These are the Home, About, Forecast Info, Forecast Products, Connect, and Terms. The “Home” page (“WELCOME TO AWASH-OMO FLOOD DASHBOARD”) is a responsive landing page that displays the background of the Flood Dashboard with minimal information (Figure 5a). “Forecast Info” is a flood information page that provides an overview introduction about the flood forecasts and the sources of data used in real-time and seasonal forecasts. The “Flood Products” section (Figure 5b) is the main component of the flood tool with many interactive forecast products. It consists of the precipitation forecast, runoff forecast, and flood inundation maps from the downloads page. The visualization page (Figure 5c), the connect forecast center page (Figure 5d), and the contact links page (Figure 5e) are the main components of the webpage. In general, the main advantage of this interactive flood tool is that it is responsive and automatically adjusted itself to look good for all devices from small phones to large desktops.

Once the forecast products are produced by external models, prepared, and stored in the folder (or database), they can be fetched tool and displayed on the browser. In essence, the step-by-step user manual will be developed and can be used. Nevertheless, the following steps present how one interacts with the flood tool and access the forecast information.

- Check the forecast results (rainfall, runoff, and flood inundation) in the folder (or database) where they are stored.
- Open the flood tool on the browser, index.html.
- Move to the “forecast visualization” window page (Figure 5c) and click on a hydrologic element (sub-watershed or point) on the map on the left. If one selects a watershed or a point, and the forecast type from the dropdown menus (real-time or seasonal

forecast) and forecasted variable (rainfall or runoff), a plot is displayed on the right side of the page.

- Download and save the plot for either of the forecasts that one is interested in for later use.

3.2. Forecast Products

3.2.1. Forecast Performance

The performances of the model forecasts, both real-time and seasonal forecasts, were examined using statistical measures and the results are presented in Table 1. In real-time forecasts, the forecasted runoff results from the model were compared with observations for selected river gauging stations. The correlation values obtained using R^2 were then 0.80 for the Awash-Hombole River, 0.64 for the Mojo River, 0.66 for the Awash-7 River, and 0.62 for the Awash-Adaitu River in the Awash basin. Likewise, in the Omo-Gibe basin, the R^2 values for the Gibe-Tolai and Gibe-Abelti Rivers were 0.78 and 0.70, respectively. In seasonal forecasts, the R^2 values obtained for reservoir inflows (reservoir water levels) were 0.97 (0.96) for the Koka reservoir and 0.93 (0.99) for the Gibe-3 reservoir. Similarly, the NSE values obtained for the Koka and Gibe-3 reservoirs were 0.89 (0.88) and 0.92 (0.95), respectively (Table 1).

Table 1. Forecast model performance evaluation results.

River Name		Model Performance		Image Captured	Flood Inundation Map (km ²)			Model Performance
		R ²	NSE					
Runoff (m ³ s ⁻¹)	Awash-Hombole	0.80	-	3 September 2006	Upper Awash	Satellite	138.95	0.96016
	Mojo	0.64	-			Model	133.42	
	Awash Below Koka	0.82	0.45		Middle-Awash	Satellite	522.98	0.86879
	Awash-7	0.66	-			Model	454.36	
	Kesem	0.83	-		Lower-Awash	Satellite	793.93	0.89632
	Awash-Adaitu	0.62	0.51			Model	711.62	
	Gibe- Tolai	0.78	0.60					
	Gibe-Abelti	0.70	0.53					
Reservoir name								
Koka	Inflow to reservoir (m ³ /s)	0.97	0.89	21 August 2006	Lower-Omo	Satellite	241.17	0.77867
	Reservoir water level, (m)	0.96	0.88			Model	187.79	
Gibe-3	Inflow to reservoir, (m ³ /s)	0.93	0.92					
	Reservoir water level, (m)	0.99	0.95					

On the other hand, the flood inundation extents over the main flood-prone areas were determined using the hydrodynamic model (HEC-RAS, 2-dimensional) mapper through routing considering runoff forecasts as upstream and friction as downstream boundary conditions. The flood inundation maps from satellite observations and estimated by the model were then compared and verified, and the results showed agreement for the main flood-prone areas. The flood inundation extents (km²) obtained from the satellite (model) for the upper Awash was 138.95 (133.42), the middle Awash was 522.98 (454.36), and the lower Awash was 793.93 (711.62), and the lower Omo-Gibe was 241.17 (187.79) as presented in Table 1.

3.2.2. Rainfall-Runoff Forecasts

The rainfall and runoff forecast products, hourly (and daily) rainfall forecasts, at a grid cell (or sub-watershed) in the model basins, were extracted and are presented in Figure 6. It presents the rainfall magnitude from the first forecast hour to the forecast length (10 days, in this case) for the case of real-time forecast (Figure 6a), and from June to September (122 days) for the case of seasonal forecast (Figure 6b).

On the other hand, the spatial rainfall distribution and magnitudes that the catchment receives and contributes to flooding over the flood-prone areas are presented in Figure 7.

In this sense, the rainfall distribution showed increasing trends from June to August and decreasing trends from August to September. It indicated that the rainfall in the upper catchment of the model basins, for instance, receives more rainfall than induces more runoff that contributes to flooding.

The real-time and seasonal runoff forecasts obtained from the precipitation are presented in Figure 8. In a real-time runoff forecast (Figure 8a), for instance, the peak rainfall on 23 August 2021 results in a peak runoff of $427.6 \text{ m}^3/\text{s}$ on 24 August around 5:00. The peak runoff induced from sub-watersheds gives time to peak values, which helps to determine the lead time to the outlets. The rainfall on 24 August results in peak runoff values of $612.6 \text{ m}^3/\text{s}$ on 25 August around 11:00 and starts decreasing until the end of 28 August and starts increasing again. The peak runoff on 24 ($434.8 \text{ m}^3/\text{s}$), 29 ($505.2 \text{ m}^3/\text{s}$), and 25 ($612.6 \text{ m}^3/\text{s}$) August approaching the warning level ($657.0 \text{ m}^3/\text{s}$) and may result in flooding impacts upstream of Koka dam. Similarly, the peak rainfall on 24–25 August 2021 (Figure 8b) results in a peak runoff amount of $1304.4 \text{ m}^3/\text{s}$ on 26 August around 02:00. The peak runoff induced from the sub-watersheds gives time-to-peak values, which help to determine the lead time to the outlet of a sub-watershed. The peak runoff on 25 ($1068.8 \text{ m}^3/\text{s}$) August exceeds the warning level ($1017.7 \text{ m}^3/\text{s}$) and the peak runoff on 26 ($1304.4 \text{ m}^3/\text{s}$) August exceeds the risk level ($1272.2 \text{ m}^3/\text{s}$) and may result in flooding impacts to downstream flood-prone areas.

In addition, results showed that the flood travel time estimated from flood warning levels and risk levels (m^3/s), determined from historical flood records, can be used to provide flood early warning information. The travel time is also important in providing and linking information with the flood routing from a river station to the point where the flood inundation started. The flood warning level, for instance, reached at the beginning of 24 August (Figure 8a) and it can be used to issue decisions on early flood warnings. On the other hand, the flood risk level reached its risk level on 25 August, when flooding was occurring.

3.2.3. Flood Inundation Map Results

The flood inundation maps over the flood-prone areas of the model basins showed there are locations with high-, moderate-, low- and indecisive-flood impacts. Based on the degree of the flood depths (e.g., warning or risk levels), flood inundation extents, and flood depths to indicate different levels of flood impacts. The flood impacts can be indicated based on conventional color-coded information assigned to the ranges of flood depths, such as “green” color to indicate low risk, “yellow” color to moderate risk, and “red” color to indicate high flood risk conditions. This helps decision-makers to take action where the flood depths are categorized as low-, moderate- and high-risk areas.

In addition, the flood depths and velocities produced from the real-time runoff forecasts obtained on 21 August at a given grid cell, for instance, was 1.406 m (Figure 10a) and velocity was 1.283 m/s (Figure 10b). The magnitude of flood depths and velocities help to evaluate the floodwater flow direction based on the shape of the river during evacuation if the flood depth is increasing above the threshold values.

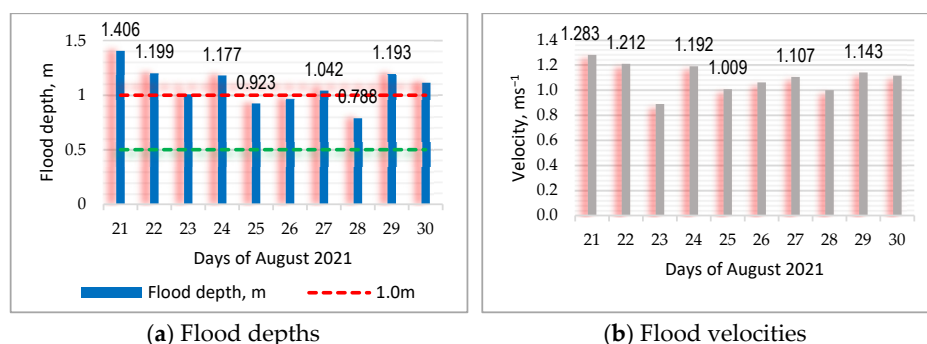


Figure 10. Plots of (a) flood depths and (b) velocities at an arbitrary grid cell.

3.2.4. Evacuation Routes

In the flood-affected areas where recurrent floods occurred, flood evacuation is one of the floods forecasting and early warning components. If the flood depths at the prone area increase above its warning level, for instance, evacuation measures shall be followed to evacuate people at risk to safer places. Evacuation is the process of emergency, insurance, recovery, and resettlement of people at risk from flooding.

Based on the flood inundation extents and flood depths, some evacuation routes (Figure 11) to evacuate people at risk, 11 locations were identified where the evacuated people were staying; accordingly, 5 locations in upper Awash—from upstream of Koka dam to Methara flood-prone areas, 2 locations in middle Awash (i.e., Awash Melka-Werer areas), and 2 locations in lower Awash (i.e., Logia and Tendaho areas) were identified with an average shortest distance of 2 to 12 km away from the flood inundated areas. Similarly, in the Omo-Gibe basin, 2 locations of the 11 locations were identified in lower Omo-Gibe flood-prone areas (i.e., at Omorate, Dasenech, and Gniyangatom areas) with an average shortest distance of 2 to 15 km away from the flood inundations.

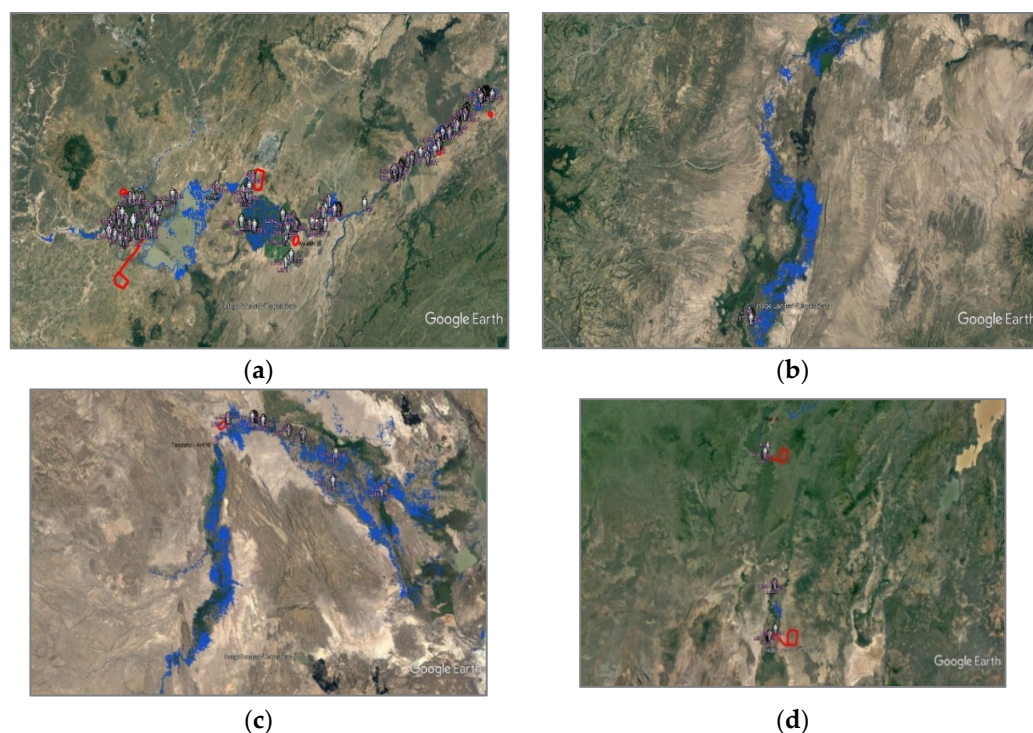


Figure 11. Routes of evacuation in the flood-prone areas. These evacuation routes are (a) 5 locations in the upper Awash sub-basin, (b) 2 locations in the middle Awash sub-basin, (c) 2 locations in the lower Awash sub-basin, and (d) 2 locations in the lower Omo-Gibe sub-basin.

3.3. Communication and Dissemination

Flood forecasting information makes sense if the forecast results reach the flood-affected people easily as possible and on time. The flood forecast information is produced and summarized from the time when the flood alert service is triggered until it stops. The flood information/report can then be available for users on time with ease of access, understanding, and well-coordinated information. In this context, the flood forecasting and monitoring center is required to issue the initial warning and the flood reports (the PUSH), and those affected (the PULL) receive the information. The flood monitoring center triggers the flood alert service if the flood warning or risk level at one of the gauging stations is exceeded. Once, an initial warning is prepared, the flood-affected communities can get early warnings so that local defensive measures can be initiated in advance of time.

The summary of flood forecast information that shows the current flood situation can be offered to the flood-vulnerable communities and decision-makers using the flood tool interface. The MOWE, for instance, can operate the flood forecasting and warning system with the involvement of EMI, DRMC, water bureaus, local administrations, and stakeholders. In this case, the flood monitoring center informs the general public and the flood-affected communities and localities about the development of flooding events on the major waterways based on the updated flood forecasts, floodwater depths, and status reports. The flood level measurements are updated depending on the river flow conditions and its gauge levels, and the forecast normally covers 3 to 14 days for the real-time forecast (10 days in this case) and 122 days for seasonal forecasts (June to September). The flood travel time expected to reach the flood-prone areas was determined. The estimated travel time, for instance, from the Awash-Hombole River gauging station to the floodplain areas upstream of the Koka dam takes about 7 to 9 h and 2 to 3 h from the Mojo River gauging station.

Once, the flood forecast results are ready and interpreted, they can be disseminated to users in a standard format to reduce the time required for warning using the flood tool. The choice of communications considers its timeliness and speed of forecast delivery to allow for sufficient lead time for response. Back-up of the warning information, feedback, and the effectiveness of the communications that target flood-vulnerable communities are important to consider in the system. On top of these, institutional setup on how flood forecasting and early warning information shall be accessed and disseminated on time and if in case the webpage is not responding in no Internet option. In this case, the flood early warnings responsible institutions can use an alternative mode of communication, such as text messaging, phone calls, email, radio, etc., among others.

3.4. Information Exchange System

In flood forecasting and monitoring system, institutional arrangements (Figure 12) having different rights and responsibilities to access, exchange, and data/information are required. The main recommended actors shall be MOWE, EMI, DRMC, basin offices, regional bureaus, media, and other relevant stakeholders.

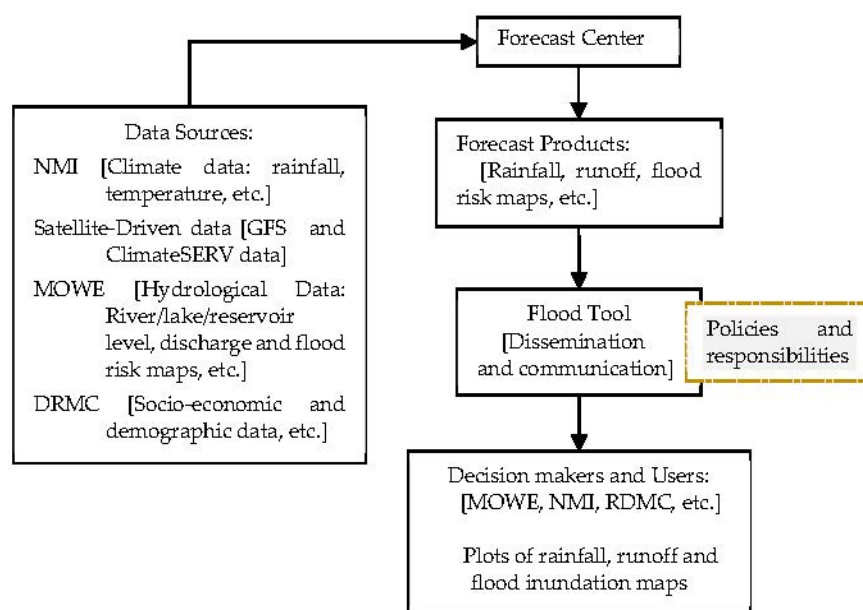


Figure 12. Flood forecast and warning system and exchange.

Lastly, a user manual that guides and helps users how to interact with the flood tool and familiar with accessing and sharing early flood warning information and make decisions. The “User Manual” consists of procedural information, institutional arrangements,

and the need of training for different experts who deal with the flood tool is prepared. The training is acquired for each discipline since the scientific and technical advancements are activity change over time. The real-time flood forecast and modeling based on satellite-driven rainfall, accessing data using automatic hydrometric instruments (e.g., telemetry systems) for instance, are advanced and need training.

4. Discussions

The flood risk management tools are proposed as a range of measures to monitor floodwater to mitigate flood risks and use the excess floodwater for future uses. In the study basins, however, there is no well-established flood monitoring infrastructure, but rather exercised traditional and simple techniques. This involved data and information collected from flood-prone areas, such as rivers and reservoir water levels, using telephone and radio (telemetry) transmission techniques. This monitoring approach is not effective in transferring data to the forecasting center and delays to prepare and disseminating the flood warning information to decision-makers and the flood-prone areas, delaying the flood early warning information, which may cause recurrent flooding impacts and damages in the study basins.

As discussed above, river floods are triggered by heavy rainfall in upstream areas of the study basins in addition to ground conditions related to soil, vegetation cover, and land cover/land use, which have a direct bearing on the amount of runoff generated and inundates flood-prone areas downstream. For instance, changes in catchment surface characteristics can modify the characteristics of river floods requiring planning and flood risk management and sustainable developments [27,28]. The hydrologic process influences flooding extent and characteristics [29,30] of river floods that occur when the river runoff volume exceeds the local flow capacities. The river levels rise slowly, and the period of rising and fall is particularly long-lasting a few weeks or even months, particularly in areas with flat slopes areas. In addition, failure of dykes or uncoordinated operation of reservoirs (Koka and Gibe-3 reservoirs in this case) or flood control works upstream can also lead to riverine flooding downstream.

From the literature and experiences, for instance, the “Flood Management Tools Series” [31] is composed of short technical publications intended to give quick guidance on relevant and specific aspects of flood management practitioners. The tools cover a broad range of flood-related issues within the framework of an integrated approach to flood management. In the context of increasing flood risks as well as the potential for flooding to challenge the European Union’s sustainable development goals, a desire to increase societal resilience to flooding has prompted the introduction of the European Framework [32–34]. This provides a legal and policy analysis of the implementation of the “Floods Directive” in six transboundary countries in Europe. The research highlights that the effect of the Floods Directive on increasing societal resilience has been nationally variable, in part because of its focus on procedural obligations, rather than on more substantive requirements. Analysis shows that flood risk management to the directive could be strengthened by requiring more stringent which directly affect flood risk outcomes. Overall and from the literature, the flood mitigation measures range from simple (or traditional) to sophisticated monitoring techniques to compare and evaluate performance.

In this case, the flood tool developed provides an overview of approaches and practical actions to reduce flood risks associated with flooding events in the study basins. Flood forecasting and early warning systems are expected to play an important role in flood management through scientific and technical limits to provide accurate and timely warnings [35]. The flood risk management tool is considered a strength in various literature in monitoring the impacts of riverine flooding [4,35]. In some cases, variability of flooding and incompatibility of approaches can reduce the effectiveness of flood risk management systems. In essence, a flood risk management tool is an effective flood monitoring system to convey forecast products and early warning information ahead of time and inform

decision-makers to mitigate the likelihood of flooding impacts [36] induced by extreme weather events [37].

In this study, therefore, an interactive web-based “flood tool” was developed to cope with the gaps and delays in the dissemination of forecast products and inform decision-makers to protect the flood-prone communities, properties, infrastructure, and the environment in the study basins. It is a responsive, easy-to-use, and compatible interface with all modern browsers to visualize and convey advice on flood forecasts and early warning information with a specific lead time. The interface adjusts itself automatically to look good for all devices from small phones to large desktops. The forecast products from the model and evacuation routes can be presented with the flood tool for different users. In this case, the real-time and seasonal forecasts were produced and compared with observations for selected river stations before use in early warnings.

It is clear that the developed flood tool in the present study has lots of benefits; nevertheless, it has some limitations to operationalize, as follows: (1) reaching the wider users and familiarizing the flood tool (with the current technology) may take a longer time to implement for the planned early warning services; (2) the tool may need regular updates since technologies keep changing; (3) the flood tool and the forecast model for the domain basins run stand-alone and needs quite some time to put the forecast products on the dedicated access point or database; (4) a legal and policy analysis of the implementation of the flood tool is not in place to increase societal resilience to flooding; and (5) the tool is intended to automate and integrate the model input datasets from satellite, the model runs, and the flood tool requires resources, for instance, if hosting the tool and running the forecast models on the Cloud in the future.

5. Conclusions

Flood risk management is an effective flood monitoring system where the likely changes in precipitation, streamflow, and other hydrological variables induce flooding in Awash and Omo-Gibe flood-prone areas. Besides, recurrent flooding impacts in the model basins, people accepted the tradeoffs between flooding risks and the potential source of economic benefits living near water. In such circumstances, the flood forecast information was produced and used ahead of time to protect the flood-prone communities from the negative impacts of flooding. The method adopted to access and interact with the flood forecasts and early warning information was a web-based, interactive, and responsive “flood tool” developed using different programming languages and scripts.

The developed web-based flood tool is a responsive, easy-to-use, and compatible interface with all modern browsers to visualize and convey advice on flood forecasts and early warning information with specific lead time. The interface adjusted itself automatically to look good for all devices from small phones to large desktops. The forecast products, such as the rainfall and runoff forecasts, flood inundation maps, flood depths and velocities from the model, and evacuation routes, can be presented with the flood tool for different levels of use. The real-time and seasonal forecasts were produced and compared with observations for selected river stations before use in early warnings. The R^2 and NSE values were obtained for selected river stations and are presented for Awash and Omo-Gibe basins. In seasonal forecasts, for instance, the R^2 values obtained for reservoirs inflows (water levels) were 0.97 (0.96) for the Koka reservoir where the maximum reservoir level is 110.3 m, and 0.93 (0.99) for the Gibe-3 reservoir where the maximum reservoir level is 892.0 m. Similarly, the NSE values obtained for the Koka and Gibe-3 reservoirs were 0.89 (0.88) and 0.92 (0.95), respectively. The flood inundation extent (km^2) obtained from satellite observation (and model) for upper Awash was 138.95 (133.42), the middle Awash was 522.98 (454.36), the lower Awash was 793.93 (711.62), and the lower Omo-Gibe was 241.18 (187.79). This indicated that model results are in agreement with satellite observations and the model performs very good as presented.

The flood tool can therefore be used to facilitate and convey forecast products and information sharing between different actors to take mitigation action ahead of time and

reservoir water use strategies. It pursues state-of-the-art technology to produce and deliver forecast products and early warning information to different users, decision-makers, and people at risk from flooding. In general, the in-situ rainfall and runoff forecasts, flood inundation maps, flood depths, and other forecast products have significant importance in flood management systems, reservoir water monitoring, and of course, for citizens and science. The services of the flood tool can also be upscaled (at the national level) to enhance the flood early warning systems mainlining with development strategies in flood-prone areas.

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