Chapter 7
Advanced Tools for Flood Management: An Early Warning System for Arid and Semiarid Regions

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Abstract Technologies concerning integrated water resources management, in general, and flood management, in particular, have recently undergone rapid developments. New smart technologies have been implemented in every relevant sector and include hydrological sensors, remote sensing, sensor networks, data integration, hydrodynamic simulation and visualization, decision support and early warning systems as well as the dissemination of information to decision-makers and the public. After providing a rough review of current developments, we demonstrate the operation of an advanced system with a special focus on an early warning system. Two case studies are covered in this chapter: one specific urban case located in the city of Parrametta in Australia in an area that shows similar flood characteristics to those found in arid or semiarid regions and one case regarding the countrywide Flash Flood Guidance System in Oman (OmanFFGS).

Keywords Flash management · IWRM · Flood early warning systems · OmanFFGS

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7.1 Introduction

There has been a rapid development of a new generation of “smart” tools concerning flood management. Such tools can assist in decision-making in various phases of flood management, ranging from predictions to live monitoring. These tools support and strengthen each other. Monitoring tools based on smart sensor networks provide detailed information about the past and current state of a flood event. Recorded observations enable modeling tools to identify the hot spots of high vulnerability and to predict inundation scenarios (de Risi et al. 2018). These high-risk locations need to be considered in early warning issuances (Wicht and Osinska-Skotak 2016), rescue operations, intervention measures (Webber et al. 2018), and other management decisions. Flood early warning systems (FEWSs) are an integral part of the range of advanced tools.

In arid and semiarid areas, water managers deal with periods of drought and short periods of severe rainfall. Flood hazards can occur quickly and unexpectedly. Therefore, it is important to be able to forecast these events as accurately as possible. Flash floods can endanger communities and vital infrastructures. Early warnings with sufficient lead times would significantly benefit the ability of water managers to warn communities to take the necessary safety precautions. In this situation, the operation of FEWSs can be crucial.

Recent developments in flash flood early warning methods, described in the tool set section below, imply significant improvements for early warning systems. As examples, more detailed explanations and focus will be given in this chapter on two systems: An early warning system set up in the Australian region of the city of Parramatta and a countrywide flash flood guidance system in the Sultanate of Oman. Both systems consist of a combination of tools, including hydrodynamic modeling software and tools used to force models with up-to-date precipitation forecasts, and the tools are connected to decision support systems (DSSs).

7.2 Tool Set for an Urban Area

A survey concerning new tools within the framework of integrated water resources management (IWRM) was recently presented by Holzbecher et al. (2019). The framework contains various aspects concerning water resources management, from measurements and data availability to decision-making platforms. Advanced tools are available and are in development in all areas of IWRM. For example, information about the actual conditions of the real world is improving due to sensor developments, remote sensing techniques, and satellite data. There are increased amounts of easily accessible data thanks to improved storage and sharing options in cloud solutions and better data transfer. Moreover, these data can also be used more efficiently in modeling tools based on new techniques, and models now run with increased computer power. Advances have been made in techniques to optimize calibration processes and sensitivity studies. New visualization techniques allow much more intuitive images of outcomes, which can also serve as inputs to DSSs. In urban planning, new tools are highly appreciated in discussing, designing, and building means for hazard prevention and mitigation. Flood hazard maps and vulnerability maps can be combined with flood risk maps that enable users and urban planners to identify (new) risk areas (Tingsanchali 2012) and to plan measures for reducing vulnerability.

Early warning systems are integrated in this framework of IWRM tools. In short, FEWSs detect impending disasters, give information to people at risk, and enable those in danger to make decisions and take action (Mileti 1999). According to Manual 21 (Attorney-General's Department 2009) in Australia, effective flood warning systems have six components.

1. Monitor changes in the environment that can lead to flooding.
2. Define the impacts of the detected floods on communities.
3. Construct warning messages containing information about predicted events.
4. Disseminate warnings to organizations and people at risk.
5. Generate appropriate actions of the communities and involved authorities.
6. Review the system after the event to improve the performance of the system.

Early warning systems are an integral part of flood management toolsets and consist of monitoring, modeling, risk analysis, decision-making, and warning. Early warning messages occur at the end of the complex system of components and are related to dissemination and communication with the local community. It is crucial for the acceptance and success of an early warning system that its predictions are as exact as possible. Warnings should be given for at-risk locations in case of inundation. There should be no warnings for locations that are not at risk. A crucial factor for the correct operation of a FEWS is thus the hydrodynamic modeling software that simulates and predicts the development of a flood. In the following section, we briefly describe 3Di as an example of advanced hydrodynamic modeling software belonging to the new generation of IWRM tools.

The 3Di software accepts input data from monitoring systems, performs flood simulations, and delivers forecast results to a data analysis platform called Lizard (Lizard 2020; 3Di 2020). The 3Di system is cloud-based, allows interactions during its simulations, and provides intuitive visualizations. The input data necessary to build a 3Di model consist of vector and raster data that describe the digital elevation model (DEM) and the local structures, obstacles, etc.

The computational core of 3Di computes flow in 1D and 2D based on shallow water equations. The 2D computations make use of the subgrid technique (Casulli 2009). The subgrid technique, illustrated in Fig. 7.1, allows coarse computational cells with the incorporation of high-resolution information. For example, bathymetry (DEM), infiltration, and roughness information can be defined at high resolutions using the subgrid technique (Volp et al. 2013; 3Di 2020). Moreover, the subgrid technique makes the computational core favorable for the computation of flooding and drying cycles.

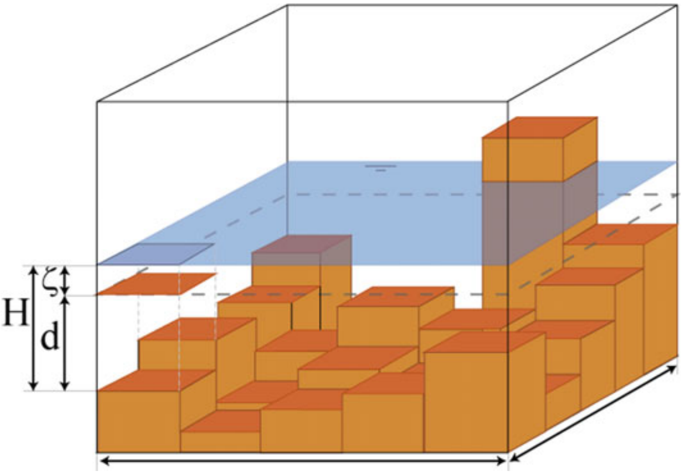


Fig. 7.1 Illustration of a coarse computational cell with varying bathymetry (Volp et al. 2013)

In addition, 3Di supports full interaction with 1D components within the computational domain (Casulli and Stelling 2013). Pipes and structures, such as weirs, are often critical for determining the water distribution. The 3Di model allows these components to be defined within the 2D domain and to be fully integrated in the computations.

The simulations of the 3Di model can be forced in several ways through boundary conditions, precipitation events, and wind. The precipitation information used in the model consists of spatially and temporally varying forecasts and uses the technology of Lizard (2020).

During the initiation phase of an early warning system, the model is calibrated and validated against the model results and measurements. A QGIS environment (QGIS 2020) offers the possibility to fully analyze all variables computed by 3Di, but this analysis can also be done via other means. In addition, the modeled water levels can be depicted live in an aerial view on maps (Fig. 7.2).

The flood forecast results are sent to the cloud-based analytic system. Here, the flood forecast results can be analyzed on interactive flood maps, including the resulting discharges, velocities, and water levels (Fig. 7.3).

In the initiation phase of setting up the early warning system, "observation" locations can be defined, where the forecasted water level results will be analyzed automatically. For these locations, trigger levels are defined. Depending on the level of exceedance and the period of time before the actual event, different warning levels are reached. Per the warning levels, different groups of stakeholders are warned. The stakeholders can be local authorities or residents of certain areas. This service is supported by Lizard Technology (Lizard 2020).

In this setup, various major challenges associated with the development of new tools that were previously mentioned (ITU-T 2014) are addressed: (1) Real-time

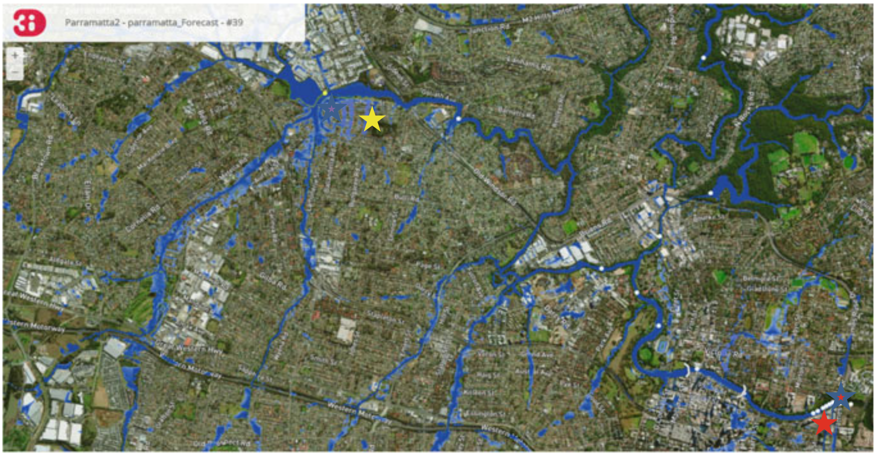


Fig. 7.2 Results simulated by in the live site of 3Di. The yellow star denotes the upstream urban area, and the red star denotes the outflow location. The depth values and discharges can be viewed directly

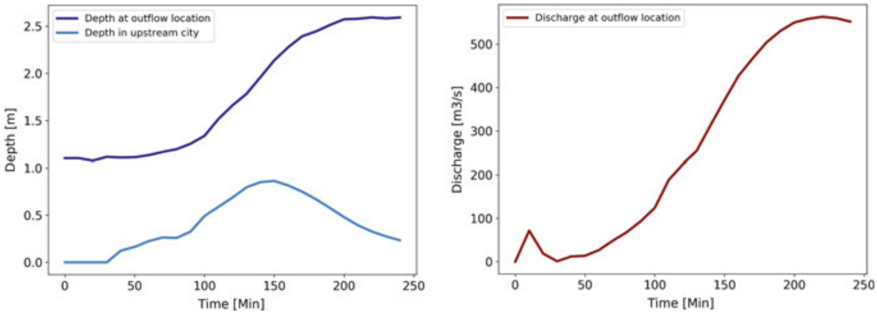


Fig. 7.3 Inundation development at the locations indicated in Fig. 7.2 by the stars; scenario simulated using 3Di

data and measurements are easily collected through sensor networks and low-cost innovative communications and protocols; and (2) better-informed decisions are made through the use of advanced analytics that translate raw data into actionable intelligence.

7.3 Flood Early Warning System in Action

The flash flood forecasting service (FLASH®) that is installed in the Australian city of Parramatta serves here as an example of an early warning system for flash floods on the scale of an urban area (Flash 2020). The city of Parramatta is located near Sydney, and the Parramatta River runs through the city. The region is known to suffer from severe hydrological events. In a recent event, 194 mm of rain fell in 72 h. The majority of precipitation events in the upper watershed show high spatial and temporal heterogeneity, as shown in a study using rainfall semi-variograms (Umakhanthan and Ball 2002).

The flood characteristics in Parramatta are typical of flash flood catchments, such as those seen in wadis in arid and semiarid climates. For the watershed in question, Morrison and Molino (2016) stated that floods arrive quickly and without significant warning time and then recede quickly. The flash flood risk is high, as a relatively small riverbed crosses through a relatively large urbanized area (Fig. 7.4). In a probable maximum flood event, the flooding would be extensive, deep, and fast-flowing and could reach up to several meters deep across wide areas (Morrison and Molino 2016). The DEM in Fig. 7.5 shows the gradual changes in height that serve to focus water flows in a particular direction (Fig. 7.5). Figure 7.6 shows the effect before and after the occurrence of a rainfall event and shows the river in a base flow situation and during a flood event occurring due to a high rainfall event upstream.

The Australian Bureau of Meteorology (BoM) offers new precipitation forecast data every half an hour. Based on these forecasts, which include spatially and temporally varying precipitation data, 3Di computes the resulting water levels and

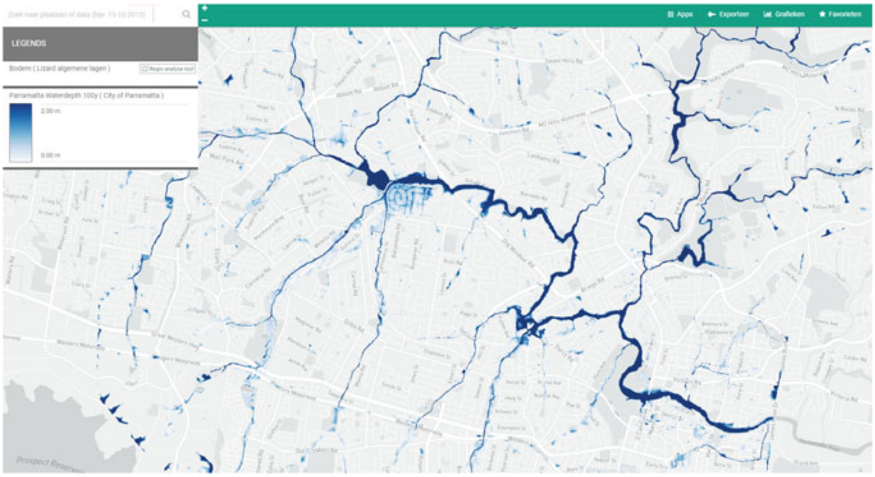


Fig. 7.4 Flood map of the Parramatta region based on a 1-in-100-year precipitation event. The water depth ranges from 0 to 2 m outside the riverbanks

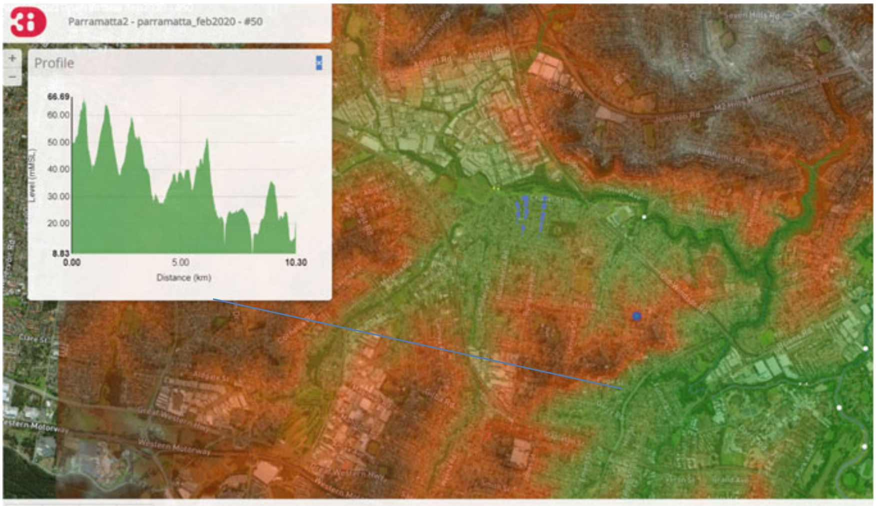


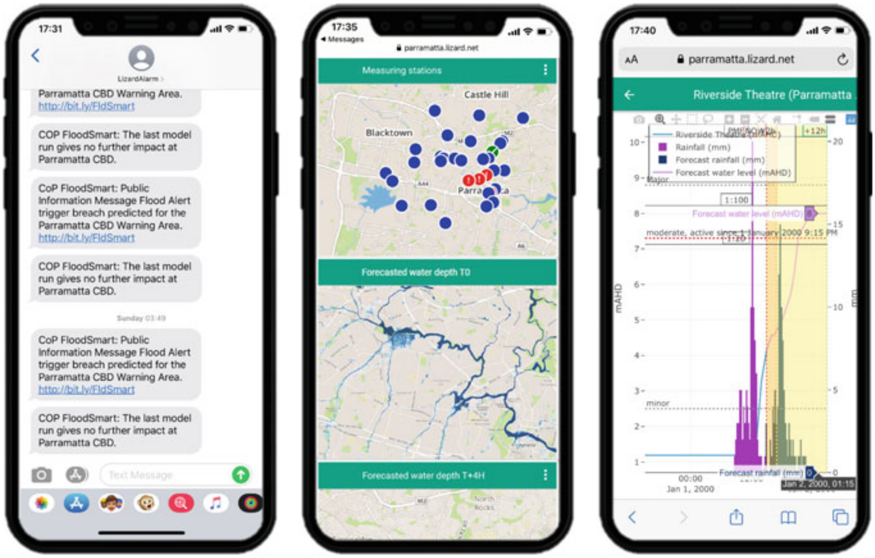
Fig. 7.5 DEM of the Parramatta region with a cross section over the white line

Fig. 7.6 Parramatta River before and after an extreme rainfall event

flows for the next 12 h. The 3Di model can produce accurate and reliable flood forecast results within 15 min (Fig. 7.4).

When 3Di predicts water levels above the trigger levels, messages are sent. The results of the modeling tool can be analyzed interactively by the authorities and decision-makers (Fig. 7.7). The flood maps and warning levels are updated with every new precipitation forecast to offer the best-known information for the involved parties to support their decision-making processes.

This set of tools offers the communities and authorities of the city of Parramatta the time necessary to make the correct decisions and take safety precautions. In the



Parramatta CBD Warning Area.
http://bit.ly/FldSmart

COP FloodSmart: The last model run gives no further impact at Parramatta CBD.

CoP FloodSmart: Public Information Message Flood Alert trigger breach predicted for the Parramatta CBD Warning Area.
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CoP FloodSmart: Public Information Message Flood Alert trigger breach predicted for the Parramatta CBD Warning Area.
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COP FloodSmart: The last model run gives no further impact at Parramatta CBD.

Fig. 7.7 Early warning in three steps: (1) the local authorities receive a flood warning message, (2) clicking on the message gives the user access to the flood management dashboard, and (3) information about recorded and forecasted water levels, interactive flood maps, and rainfall forecasts is given

event described above, the authorities and residents had 11 h to respond suitably and take necessary precautions for the coming rain.

The FEWS installed in Parramatta performs well for all six characteristic components of a flood warning system mentioned above and defined by the Australian authority (Attorney-General's Department 2009). The predictive component (1) is covered by the 3Di model, which is forced by forecasts from a local meteorology bureau. The interpretation phase (2) is based on automatically generated flood maps with predefined trigger levels. Once these trigger levels are reached, messages are sent with the information needed for the local authorities to respond accordingly. If necessary, the residents are warned as well (3, 4, 5). The results can be thoroughly analyzed afterward (6). It is a key that after a flood event occurs, the system can be triggered again with the actual measured precipitation levels, and the results can be compared with the observations. Additionally, precipitation forecasting is uncertain due to rapidly changing conditions and limited resolutions. In particular, severe precipitation events can have strong local variations.

7.4 Wadi Flows and Hydrometric Network Development in Oman

As is the characteristic of arid and semiarid climates, precipitation events in Oman are highly variable both temporally and spatially. A wadi may flood several times in one year and see no flow over the next several years. There is also high spatial variability in precipitation intensity. One basin or subcatchment may produce major flooding, while the adjacent catchments do not have noticeable runoff. The flooding durations are short in general. An entire flood may occur within a few hours. Most flood hydrographs, particularly those representing the upper hard rock reaches of wadis, peak very quickly and dissipate rapidly. Heavy sediment loads, both bed loads and suspended loads, characterize wadis in Oman, particularly when floods are at such levels that they cut into higher terraces of the alluvium. However, the infiltration rate, in general, is high in downstream alluvial reaches (Al Hinai and Abdala 2020).

The annual average wadi flow is 330 Mm^3. Eighty-five percent of wadis in Oman flow from mountainous areas toward the plains and finally drain to the sea. The rest drain to the interior (desert) or out of the country. The largest wadis catchments are Andam Halfayen (34,220 km^2) and Al Batha (5,740 km^2).

FEWSs are set up based on hydrometric data networks. In Oman during the 1970s, some scattered water monitoring points started to be installed through different exploration and research projects. In the early 1980s, the expansion of the complete hydrometric network started, and the system reached its maximum size in the late 1990s. The Monitoring Network Department was formed by 1997 to supervise, organize, and assess all monitoring activities in the country. Evaluations and upgrades of the monitoring network took place in 1998, 2005, and 2016. Water balance results for the sultanates were available by 2013. Figure 7.8 illustrates the temporal development of the network. Table 7.1 provides an overview of its spatial distribution.

7.5 The Oman Flash Flood Guidance System

Recently, the Directorate General of Meteorology and the Directorate General of Water Resources Assessment in the Sultanate of Oman defined the cooperation framework that is used to manage and run the Oman Flash Floods Guidance System (OmanFFGS). Such collaborative efforts will allow the use of climate predictions in water management, in addition to improving flood forecasting services.

The Oman Flash Flood Guidance System (OmanFFGS) is hosted by the Oman Multi-Hazard Early Warning Center, Directorate General of Meteorology. It was developed by the Hydrologic Research Center (HRC), a USA-registered non-profit organization. The primary purpose of installing the system was to assist operational forecasters in issuing reliable flash flood warnings. OmanFFGS offers baseline

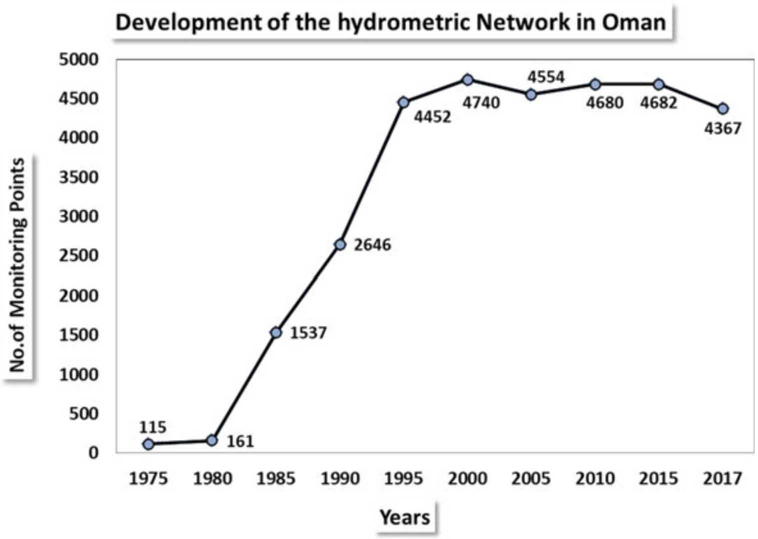

Fig. 7.8 Development of the hydrometric network in Oman between 1975 and 2017

Table 7.1 Recent number of monitoring points per region as of 2017

Hydrometric network by assessment areas										
			Rainfall stations					Salinity		
Assessment areas	Wadi flow	Dams	Gage	Inhacement	Wells	Aflaj	Springs	Well	Falaj	Total
Muscat	17	3	43	8	100	20	6	45	75	317
South Al Batinah	21	10	36	29	112	79	1	22	72	382
North Al Batinah	17	5	45	23	157	29	3	38	24	341
Musandam	7	6	23	0	60	0	0	0	1	97
Al Buraimi	6	6	21	17	169	20	0	9	18	266
Ad Dhahirah	12	1	39	41	238	70	0	25	70	496
Ad Dakhliyah	18	9	57	48	287	117	6	71	119	732
North As Sharqiya	16	4	51	35	164	41	1	15	116	443
South As Sharqiya	11	1	27	0	117	186	0	32	40	414
Al Wusta	0	0	11	0	14	0	0	0	0	25
Dhofar	11	2	60	20	655	0	14	96	0	858
Total	132	47	413	221	2,073	562	31	353	535	4,367
			634					888		

products that must be carefully evaluated by forecasters in real time before a flood warning can be issued. The product console provides a collection of real-time data products in text, image, and CSV file formats with updates every hour.

The Oman Flash Flood Guidance System uses a hydrological model with inputs of rainfall observations, forecasts, and soil properties of each catchment to detect and predict soil oversaturation. The system uses many sources of precipitation data, which can be categorized into two types. The first type includes precipitation input data from near-real-time observations, namely ground-based radars, microwave-adjusted satellite-based precipitation estimates, satellite-based precipitation estimates, and rain gage mean-areal precipitation (see Fig. 7.9). However, the input precipitation data used in flood calculations vary according to the availability and accuracy of the data sources. Currently, ground-based radar data are given the highest priority for use in the calculations when they are available, while rain gage mean-areal precipitation data are given the lowest priority due to the relatively low-density rain gage network. Therefore, the output products should be evaluated according to the assessed accuracy of the input data before they are used for the creation of warnings.

The second type of precipitation input data is rainfall forecasts from atmospheric models. The system is fed by the COSMO model, a nonhydrostatic limited area atmospheric prediction model, which provides two different resolutions: horizontal mesh sizes of 2.8 and 7 km (Fig. 7.10). Currently, this model is in the process of being replaced by the ICON (Icosahedral Nonhydrostatic) limited area atmospheric prediction model.

The OmanFFGS basically uses the same process to generate flood assessment products for both aforementioned precipitation data types. However, the products

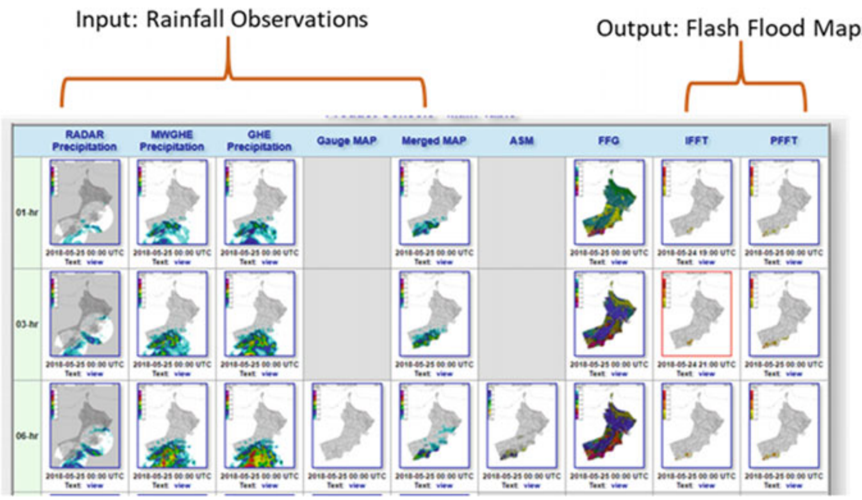

Fig. 7.9 Console of the OmanFFGS rainfall input data from near-real-time observations for Cyclone Mekunu, which occurred in May 2018

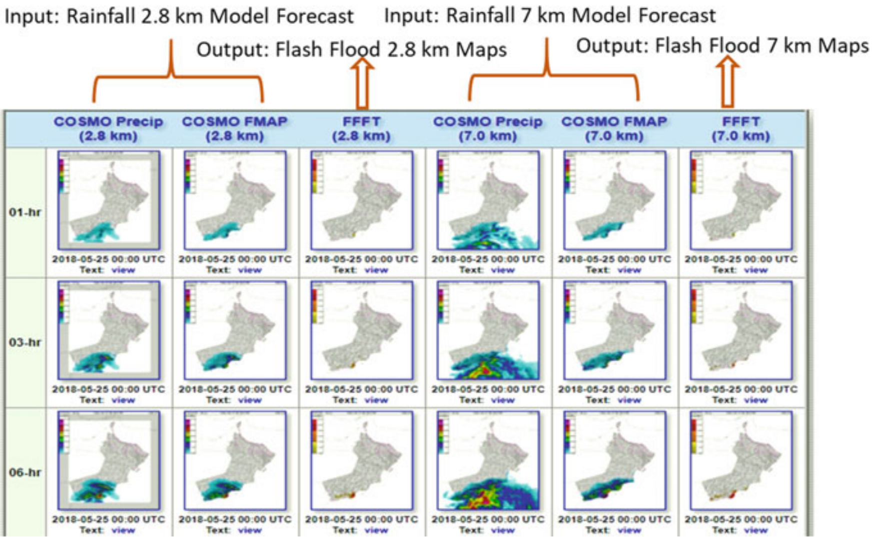

Fig. 7.10 Console of the Oman flash flood guidance system representing rainfall input data from atmospheric models

generated by using the second type should be treated with extra caution due to the high uncertainty present in the data, which might result in a false warning.

Although the system is a large step forward and has been beneficial throughout the last seven years of its operation, the users reported several limitations and challenges. First, the system works best with radar data to indicate whether there will be an imminent flood in the upcoming 1–6 h. However, difficulties have been reported in keeping the radar network running, which eventually resulted in depending on satellite data for the rainfall inputs throughout most of the operational time of the system. Since satellite-based rainfall estimations are less accurate than radar-based rainfall data, the system flood products became less accurate. A higher density of rain gages might provide an alternative solution to this challenge. The Directorate General of Water Resources Assessment has a higher-density rain gage network. Recently, the Directorate General of Meteorology and the Directorate General of Water Resources Assessment agreed on streaming real-time data from the high-density rain gage network of the Directorate General of Water Resources Assessment to be used as input data to run the Oman Flash Flood Guidance System.

From another perspective, many users have requested more than 6 h of flood forecasts with higher confidences. This would require human intervention to modify the precipitation forecast maps. There are currently efforts in this avenue. Other users have requested an interactive background map with the names of dry rivers (wadis), which are not available in the current operational version.

Finally, an essential aspect of any forecasting system is the verification of its products for future improvements and more effective uses as well as verifications of the reliability of the products. Product verification requires water stream and inundation data, which are collected by the Directorate General of Water Resources Assessment. This is another avenue of potential future collaboration between the system developers, users, and data collectors.

7.6 Conclusions

Advanced technical tools for integrated water resources management are either available or are still in development. A combination of tools can be used for smart sensors with powerful networks. Satellite data are available, and some are available at no charge. Processing, cloud storage and wireless communication advances have enabled powerful tools for simulation, visualization, and modeling that can be utilized by all involved parties. The results can be integrated for optimization and decision-making. Finally, warnings can be issued, and measures can be disseminated to at-risk communities. Due to the ability of previous systems to quickly generate reliable results, new modeling tools allow a much more flexible approach to flood management as well as to natural disaster management and long-term planning.

An application of a flood early warning system in an urban area was presented, concerning an implementation that is installed in the region of the city of Parramatta, Australia. This system fulfills the six components of FEWSs that are described in Manual 21 (Attorney-General’s Department 2009). The case study illustrates the advantages of having such a system installed. The system allows the production of up-to-date flood maps based on actual precipitation events that occur, including the spatial and temporal variations associated with such events. The system allows more targeted actions to be taken in communication and safety precautions. Moreover, it gives the local authorities and residents more time to take action.

With the Flash Flood Guidance System of Oman, a countrywide installed network was presented. The hydrometric network has proven to be an appropriate tool for monitoring flash floods. With the existing network, it is possible to project flood events. Thus, the described system may form a convenient foundation for the development and use of an efficient FEWS.

A recent review of the United Nations University (Perera et al. 2019) names technical, financial, institutional, and social challenges concerning the implementation of FEWSs in general. Flash flood management responses require a set of multidisciplinary collaborative efforts in the fields of meteorology, hydrology, and emergency management. In many countries, national meteorological services and national hydrological services do not coordinate closely to improve flash flood forecasting services (WMO 2007).

The case of the FEWS, installed in Parrametta, demonstrates how most technical issues associated with flood warning systems can be addressed and resolved. However, on the technical side, such an implementation also depends on a sufficiently vast and reliable sensor network being installed and being in operation.

Moreover, non-technical issues may be crucial, such as the availability of funds for hardware and software, maintenance, communication, and cooperation between various authorities, the availability of trained competent personnel, and the proactive involvement of the public within the community.

References

3Di (2020) https://docs.3di.lizard.net/. Accessed July 2020

Al-Hinai HY, Abdalla R (2020) Spatial prediction of coastal flood-susceptible areas in Muscat Governorate using an entropy weighted method. WIT Trans Eng Sci 129:121–133

Attorney-General's Department (2009) Manual 21 flood warning. Australian emergency manuals series, Commonwealth of Australia, 2009. Available at http://www.em.gov.au/Documents/Manual%2021-Flood%20Warning(2).PDF

Casulli VA (2009) High-resolution wetting and drying algorithm for free-surface hydrodynamics. Int J Numer Meth Fluids. https://doi.org/10.1002/fld.1896,60,391-408

Casulli V, Stelling GS (2013) A semi-implicit numerical model for urban drainage systems. Int J Numer Meth Fluids 67:441–449

de Risi R, Jalayer F, de Paola F, Lindley S (2018) Delineation of flooding risk hotspots based on digital elevation model, calculated and historical flooding extents: the case of Ouagadougou, Stoch Environ Res Risk Assess. https://doi.org/10.1007/s00477-017-1450-8

Flash® (2020) https://3diwatermanagement.com/blog/flood-resilience-in-action-flash/. Accessed July 2020

Holzbecher E, Barghash H, Hadidi A, Al Balushi K (2019) Application of big data and technologies for integrated water resources management—a survey. In: 5th international conference on social network analysis, management and security (SNAMS 2019). IEEE Proceedings, Granada

ITU-T (2014) Focus group on smart sustainable smart cities, smart water management in cities. https://www.itu.int. Accessed June 2019

Lizard (2020) https://lizard.net/. Accessed July 2020

Mileti DS (1999) Disasters by design: a reassessment of natural hazards in the United States. Joseph Henry Press, Washington D.C.

Morrison T, Molino S (2016) Floodplain management innovation to facilitate city growth. In: Floodplain Management Australia Conference

Perera D, Seidou O, Agnihotri J, Rasmy M, Smakhtin V, Coulibaly P, Mehmood H (2019) Flood early warning systems: a review of benefits, challenges and prospects. UNU-INWEH report series, issue 08, United Nations University, Institute for Water, Environment and Health, Hamilton, Canada

QGIS (2020) https://qgis.org/en/site/. Accessed July 2020

Tingsanchali T (2012) Urban flood disaster management. Proc Eng 32:25–37. https://doi.org/10.1016/j.proeng.2012.01.1233

Umakhanthan K, Ball J (2002) Importance of rainfall models in catchment simulation. In: 13th congress APD-IAHR, Singapore

Volp ND, Prooijen BC, Stelling GS (2013) A finite volume approach for shallow water flow accounting for high-resolution bathymetry and roughness data. Water Resour Res. https://doi.org/10.1002/wrcr.20324C,49,4126-4135

Webber JL, Gibson MJ, Chen AS, Savic D, Fu G, Butler D (2018) Rapid assessment of surface-water flood-management options in urban catchments. Urban Water J 15(3):210–217

Wicht M, Osinska-Skotak K (2016) Identifying urban areas prone to flash floods using GIS—preliminary results. Hydrol Earth Syst Sci Diss 1–22

WMO (2007) Fifteenth world meteorological congress: abridged final report with resolutions. WMO-No. 1026, pp 204–207. ISBN 92–63–11026–3