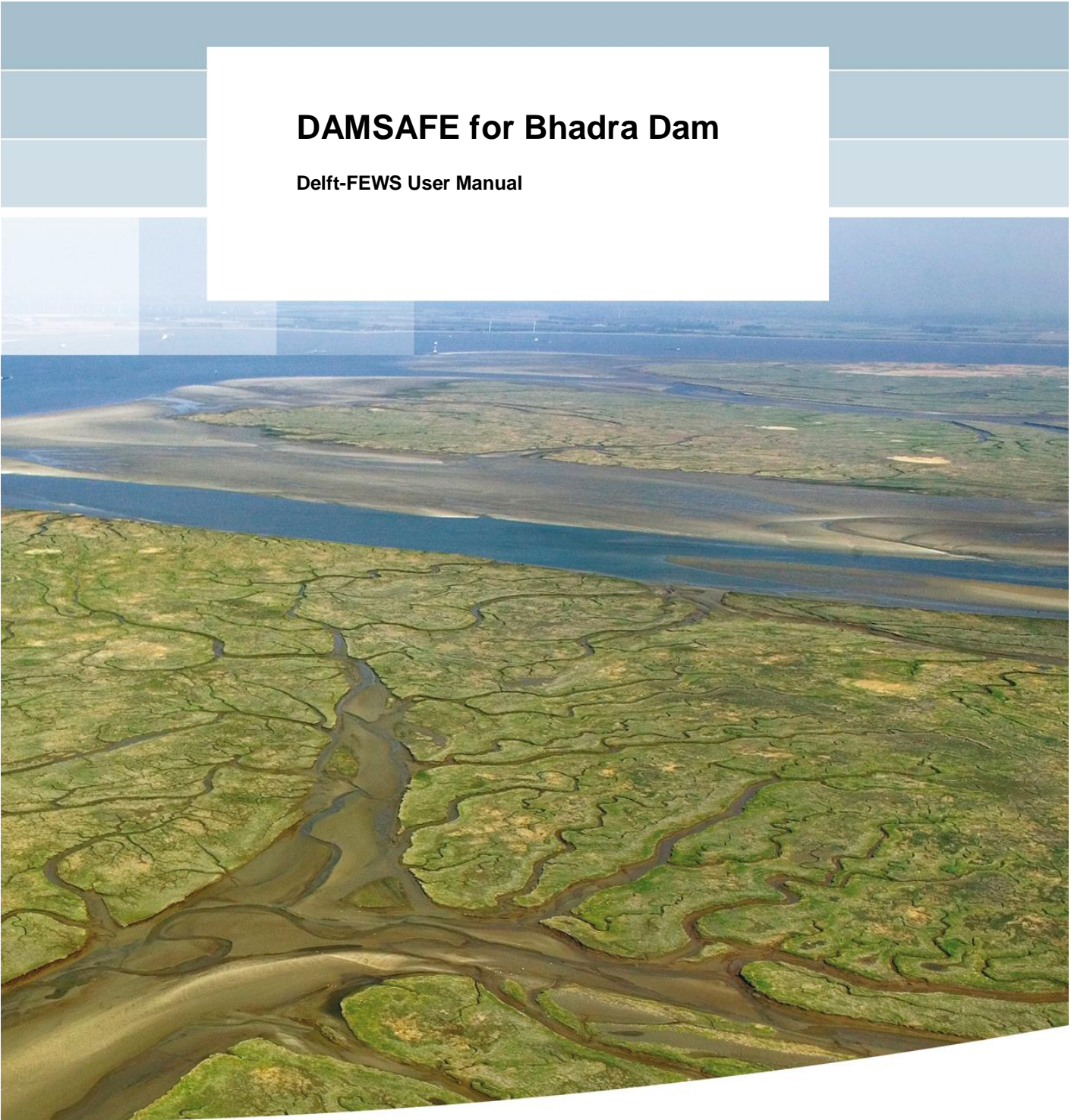


DAMSAFE for Bhadra Dam

Delft-FEWS User Manual



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Delft-FEWS User Manual

Min Xu
Frans van den Berg



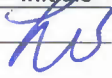
11200775-005

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DAMSAFE for Bhadra Dam

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Summary
DAMSAFE is a pilot project to demonstrate a number of innovative technologies that contribute to the main project goal: enhancing dam safety and water reservoir management

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1 Introduction

1.1 The project

DAMSAFE is a pilot project to demonstrate a number of innovative technologies that contribute to the main project goal: **enhancing dam safety and water reservoir management**. The project is co-funded by the Dutch Partners for Water program. The key end-user of the project outcome is the Karnataka Water Resources Department (KaWRD), one of the major departments in the Government of Karnataka responsible for management of 230 large dams and reservoirs. The Deltares led DAMSAFE consortium consists further of the Dutch companies SkyGeo and Royal Eijkelpark and the Spanish company iPresas. These companies provide specialist (measurement) technologies. The role of Deltares is to integrate this measurement data into information using the Delft-FEWS platform and numerical modeling. The DAMSAFE project activities are:

- Online monitoring and Delft-FEWS software to forecast reservoir inflow and water levels, thus increasing reservoir performance.
- PS-InSAR satellite measurements and risk-informed safety assessment software for monitoring of the dam condition, resulting in optimization of Operation and Maintenance (O&M).
- Online monitoring and FEWS-DAM software for rapid assessment of dam stability in order to provide information for emergency response.

The pilot case of the DAMSAFE project is the Bhadra dam-reservoir system. The Bhadra dam is located across Bhadra River in the Chikkamagalore District of Karnataka State at an elevation of 601 m above Mean Sea Level. This is a multi-purpose dam, including irrigation, water supply and hydropower generation. Here, an online monitoring system has been installed to monitor the water reservoir and identified dam failure mechanism. All measurement stations are equipped with a battery and solar panel for energy supply and a wireless connection for real time data transmission.

Persistent Scatterer Interferometric Synthetic Aperture Radar (PS-InSAR) is a radar technique used to generate maps of surface deformation, using differences in the phase of the waves returning to the satellite. The technique is applied here to measure millimeter-precision changes in deformation of the dam. In combination with dam safety modeling, this provides information to prioritize O&M efforts and can be used to detect anomalies that need short term in-situ inspections.

Delft-FEWS is an operational platform developed by Deltares that is used at Bhadra to integrate data from different sources and to perform computations automatically using different numerical models, i.e. HEC-HMS, SOBEK and DAM. The platform uses HEC-HMS and SOBEK to forecast water levels in the Bhadra reservoir. With DAM the stability of the Bhadra dam is calculated real time for different failure mechanisms.

More (actual) information can be found on: <http://damsafe.eu/>.

1.2 Goal and scope

This user manual is intended for use only for this specific project and will give a description how to use the FEWS-DAM software for the monitoring of the stability of the main dam and saddle dams

2 Project Description

2.1 Location

The Bhadra reservoir dam is located in the province of Karnataka and has a catchment area of 1968 km². The exact location of the main dam is 130 42' 0" N, 750 38' 20" E.

2.2 Bhadra dam

The Bhadra dam (see figures below) is a composite dam, having a length of 1708 [m] and a height of 59.13 [m]. There are 3 saddles on the left bank and one saddle on the right bank consisting of an earthen embankment. The central spillway has a length of 83.3 [m] and having four vertical lift type gates of size 18.29 [m] x 7.62 [m] (60'x25') with a maximum flood discharge capacity of 1,06,700 [m³/s] over the spillway.



A front sight of the Bhadra dam

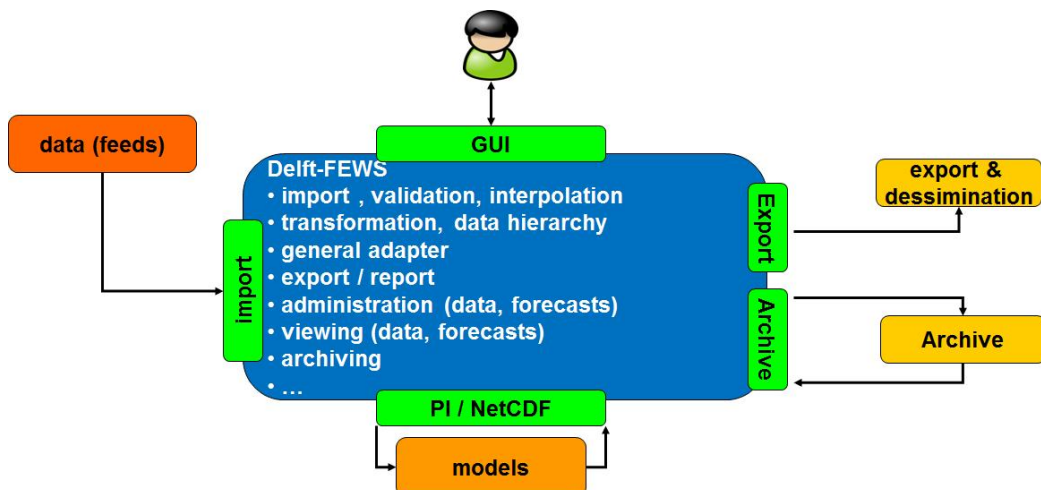


Top sight from the Bhadra dam

3 Delft-FEWS Introduction in DAMSAFE Application

3.1 Delft-FEWS

Delft-FEWS is a platform for real-time forecasting and water resources management. The main feature of Delft-FEWS is efficient data management, including data importing and processing, model execution, results dissemination, and data exporting and archiving. It is an open platform that can import many different data format and integrate multiple numerical models. The concept of Delft-FEWS can be illustrated in the figure below.



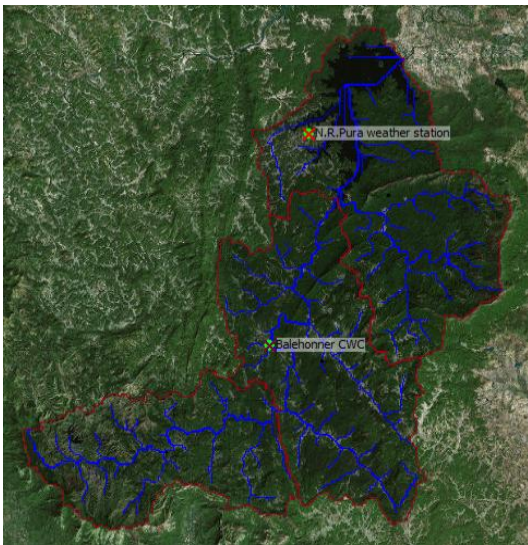
Delft-FEWS was designed to support the flood forecasting process, but due to its flexible modular structure, it is also very well suited to support day-to-day operational management, real-time control and forecasting and warning in other disciplines, like water quality, reservoir management, hydropower, navigation, groundwater, drought and dike strength monitoring.

For the DAMSAFE project, Delft-FEWS is used as a platform to facilitate reservoir management and dam strength analysis.

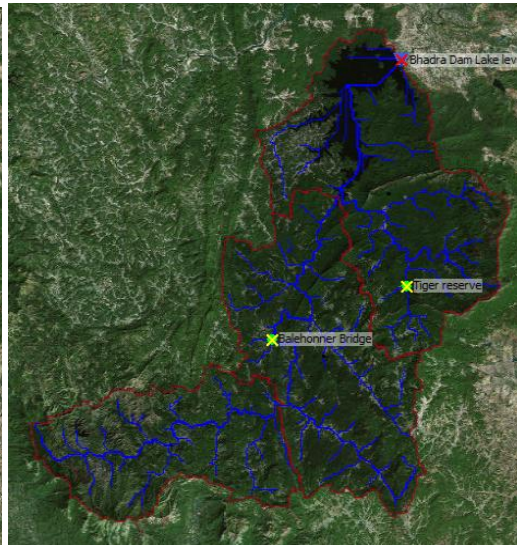
For detailed introduction of Delft-FEWS, please refer to the attached Delft-FEWS brochure.

3.2 Monitoring

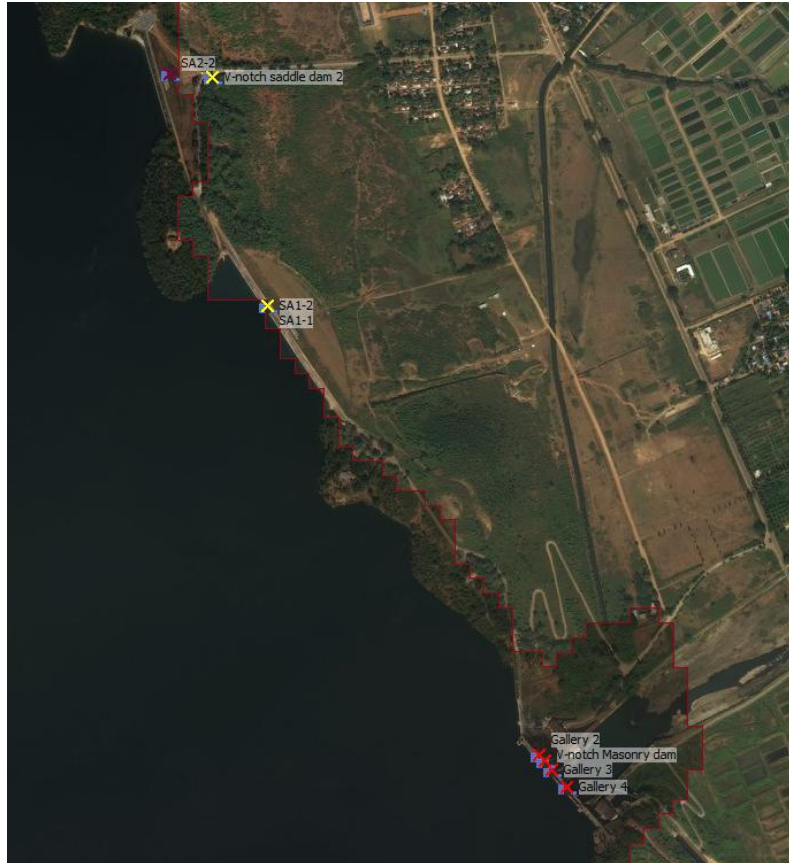
Data is the basis for any study. Real time data is necessary for daily operation. Karnataka Water Resources Department (KaWRD) can only provide offline data for hydrological study, which is not sufficient to setup an operational system. Moreover, there is no measurement for dam conditions, e.g. ground water level in the dam. In DAMSAFE project, Eijkelkamp installed several sensors to measure different parameters in real time. Based on the modeling requirement, two meteorological stations were installed to measure for example, precipitation, temperature, relative humidity, wind, global radiation. Three hydrological stations were installed to measure water levels, which can be converted to discharge with rating curves provided by KaWRD. For the dam monitoring, four sensors are installed for the main dam and two sensors for each of the saddle dam, which measure ground water level in the dam. This information is necessary for the dam module calculation. In addition, two sensors were installed at the V-notches downstream of the dam to measure discharge. The figure below shows the locations of Eijkelkamp sensors.



Meteorological stations



Hydrological stations



Dam stations

3.3 Models

Delft-FEWS can integrate many models. In the DAMSAFE project, we try to integrate the existing models that are already developed by KaWRD. The types of model needed for this study are hydrological model, hydraulic model and dam/dike model. It contains the entire process from precipitation to reservoir management.

Currently, the reservoir operation is based on the observed discharge at Balehonner and the estimated traveling time of 6-8 hours. Therefore, the maximal lead time is 8 hours. In this project we intend to use the meteorological forecasting information (GFS forecast) as model inputs, so that we can increase the leading time and provide more buffers for reservoir operation. The models used here is intended to provide better streamflow forecasting to improve reservoir management.

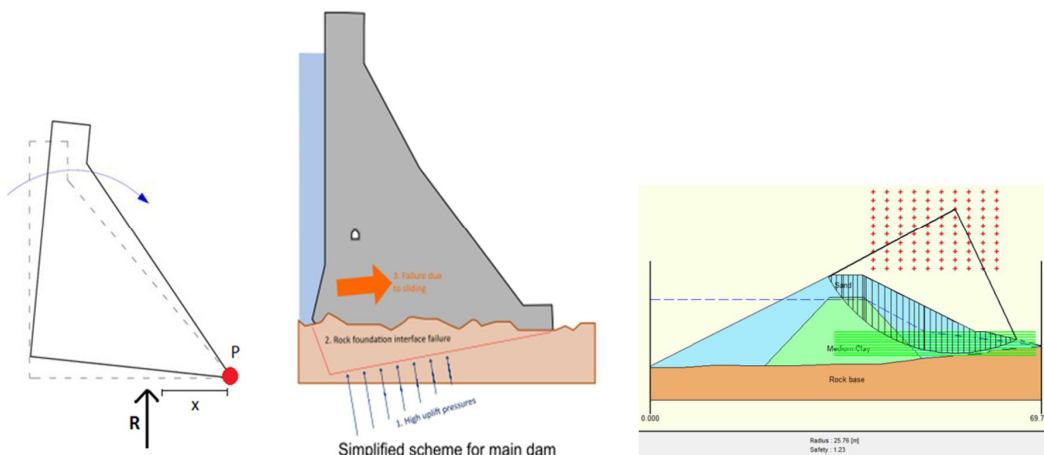
KaWRD provided an existing calibrated hydrological model (HEC-HMS version 4.2), which generates the reservoir inflow. For detailed information HEC-HMS, please refer to the software website: <http://www.hec.usace.army.mil/software/hec-hms/>. This inflow is then used as boundary input for the hydraulic model. KaWRD developed a hydraulic model in HEC-RAS, version 4.1.0. For detailed information of HEC-RAS, please refer to the software website: <http://www.hec.usace.army.mil/software/hec-ras/>. Please note that HRC-RAS 5.0 is not fully supported by Delft-FEWS. This model doesn't cover the upstream of the river due to

the availability of geometric data. However, the flow at Balehonner is still used as upstream boundary of the model. Downstream boundary uses the user defined release. The purpose of this model is to be used in operational system for different release scenario selections. Deltares developed a SOBEK model (hydraulic model) with dummy geometric data. SOBEK is a modeling software package developed by Deltares. It contains several modules that can be coupled each other: hydrology, 1D2D hydraulics, water quality and real-time control. For detailed information over SOBEK, please refer to the software manual: <https://publicwiki.deltares.nl/display/DSM/SOBEK>. The model starts from the upstream of the river. Please note that this model should not be used in operational system for decision making. The purpose of this model is to provide another model option. If geometric data is corrected and model is validated, the workflow configured in Delft-FEWS for SOBEK model can be used for daily operation, similar as the HEC-RAS model.

Based on the results and conclusions from the working session conducted on February 22, 2017 carried out by iPresas (iPresas, 2017) different possible failure mechanisms has been identified. For this project the following failure mechanism have been taken into account:

- Overturning stability of the main dam
- Horizontal sliding of the main dam
- Macro instability of the saddle dams

Graphical pictures of these three failure mechanisms are illustrated below.



Failure mechanisms: Overturning stability, Horizontal stability and macro stability

For dam strength analysis, two models are applied. The saddle dams are models in Dam-Live model developed by Deltares. The main concrete dam is model by iPresas (Excel) and converted into a python script by Deltares for the integration into Delft-FEWS. The Dam-Live model analyses the macro-stability of the saddle dams and the Python script analyses the sliding stability and overturning stability. In Appendix - Dam The background of the models and the monitoring is described.

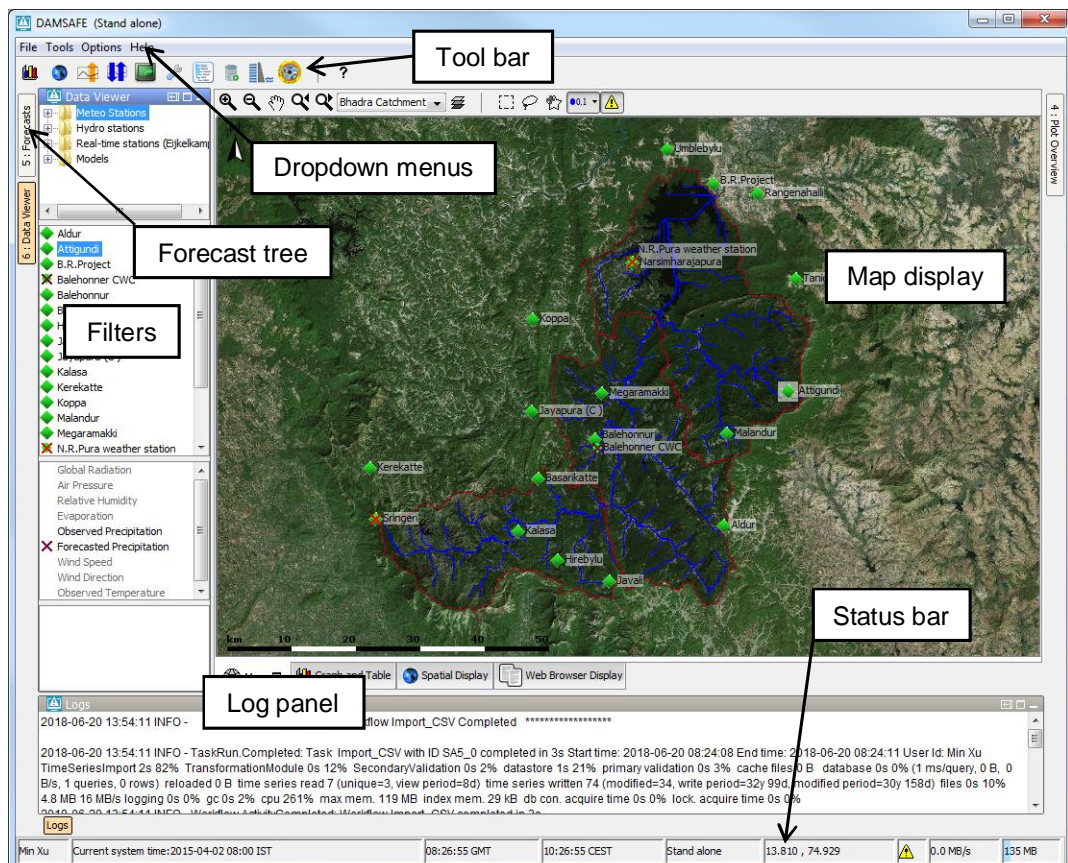
4 Delft-FEWS Functions in DAMSAFE Application

This user manual describes the function and the use of DAMSAFE application. For general user guide of Delft-FEWS application, please refer to the Help.pdf file in the root folder of DAMSAFE application. The DAMSAFE application is configured using the Delft-FEWS build number 76124, patched from build number 76073. It requires a 64bit windows operating system. The application is setup in a Stand Alone system, but can be upgraded to a client server system with limited amount of effort.

The delivered system contains three components:


- bin: binary files for Delft-FEWS application
- jre: java runtime environment
- DAMSAFE: application configurations

Delft-FEWS explorer is the principal window. The main components of the explorer are highlighted in the figure below.



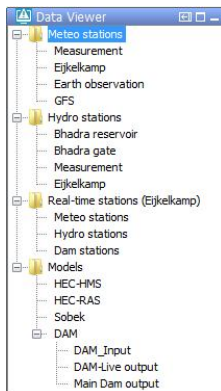
4.1 Map display, filter and time series display

All locations are displayed on top of the background map in map display. Users can zoom in or out the map with scroll wheel. Four map extends are configured: Bhadra Catchment;

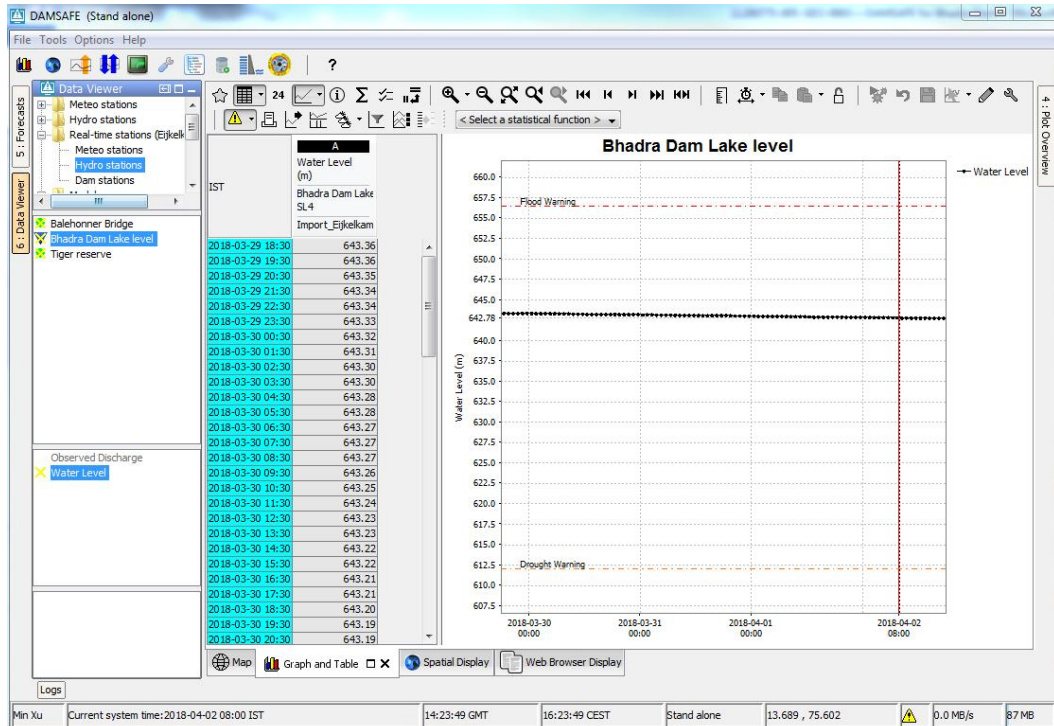
Bhadra_dam; Karnataka and India. Map layers can be enabled or disabled via the Layer button  on the Button bar. Tooltip will be displayed when pointing the mouse on a location. Multiple locations can be selected by holding down the CTRL key while selecting.

Time series groups are designed with the structure shown in figure below. “Meteo stations” contains all meteorological data. “Measurement” includes the stations from India (this displays historical data converted into csv files); “Eijkelkamp” contains the stations installed by Eijkelkamp; “Earth observation” and “GFS” contain data from the two open data service for observation and forecast and then interpolated to the meteorological stations from India.

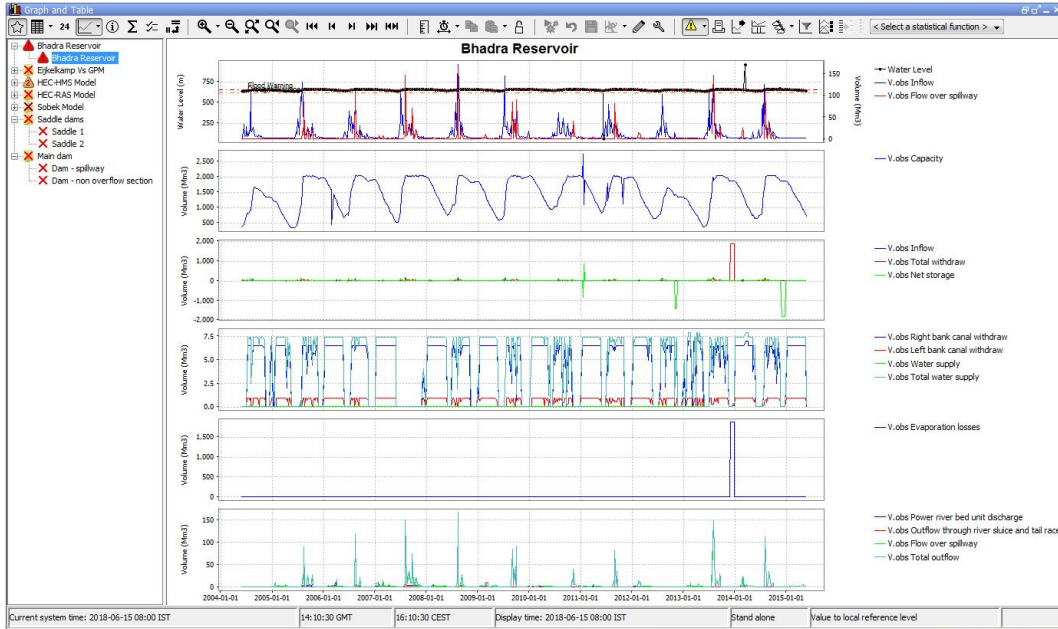
“Hydro stations” contains all hydrological data for reservoir catchments and dam, including both manual data from India and the real-time data from Eijkelkamp. “Real-time stations (Eijkelkamp)” contains all the data from Eijkelkamp sensors installed within this project. Is is separated into Meteo stations, Hydro stations and Dam stations. “Models” contain all model results, including HEC-HMS, HEC-RAS, Sobek (Dummy data), and DAM. The DAM models contain both the DAM-Live model from Deltares and Main Dam model which is converted from an iPresas model.



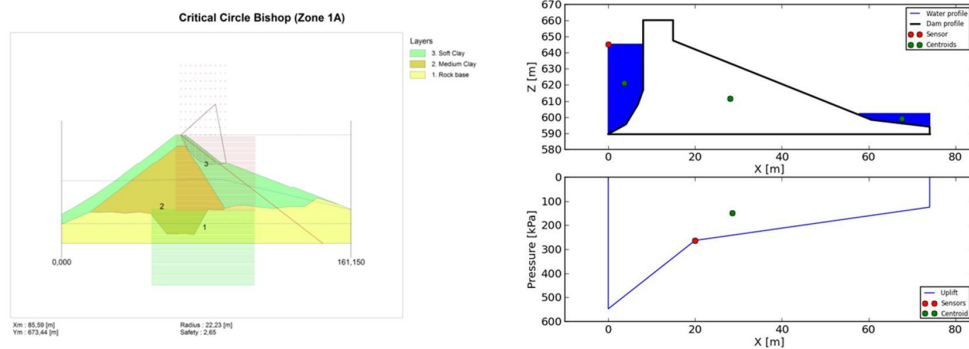
Multiple locations and parameters can be selected in the filters when holding on the CTRL key and mouse selecting. The selected locations will be highlighted in the map display. The time series will be displayed in the Graph and Table tab. See example below. Thresholds will be displayed if defined. The function of buttons on the Graph and Table tab can be found in the Help.pdf file.



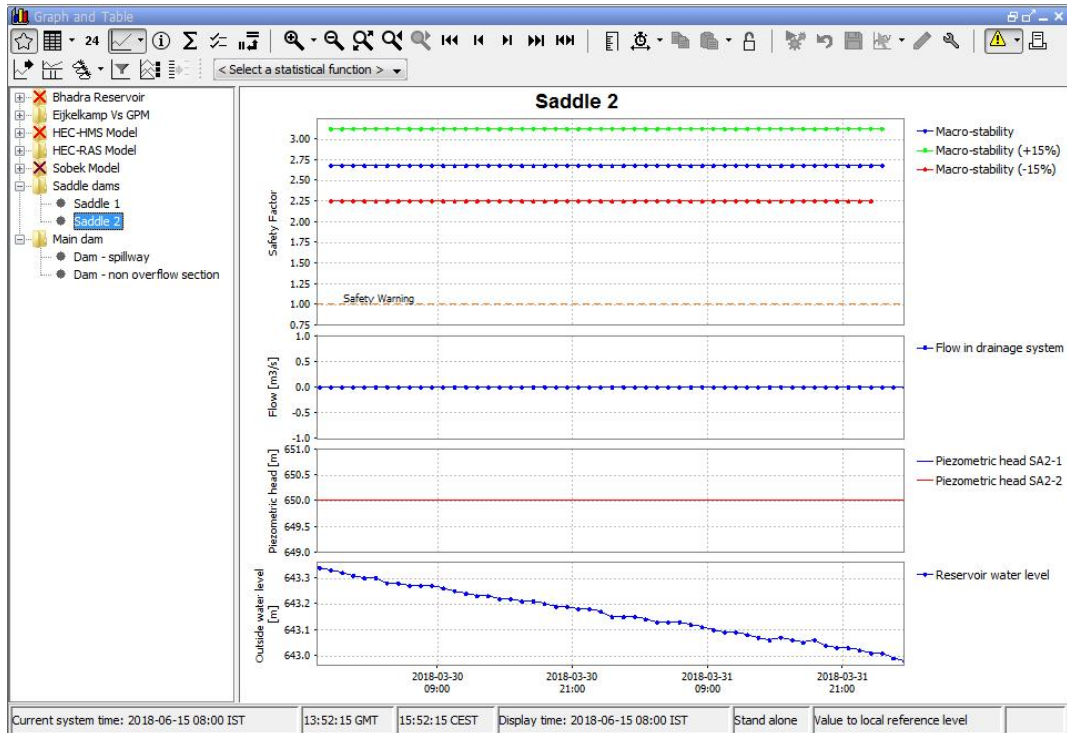
One function linked to Graph and Table tab for time series display is so called Shortcuts as indicated by the icon ☆. In the DAMSAFE application, the time series configured for the shortcuts are illustrated in the figure below. The results displayed in the figure is the offline reservoir data provided by KaWRD. The data is restructured into csv format and import into the application through Import CSV workflow. Validation rules are applied to the data. It is clearly see from the figure that certain data is out of the normal range which is apparently wrong. By this display, it is very convenient to track the wrong data in the original file, which is manually edited by the local staff.



For the outputs of Dam-Live model and the main dam model, the slip surface and uplift results can be visualized in graphs. This can be done by selecting Models->Dam->Dam-Live output or Models->Dam->Main Dam output and putting the mouse over the locations either in the filter or on the map. Examples of the slip surface and uplift are illustrated below. Please note that the slip surface and uplift figure only show the most latest model simulation.

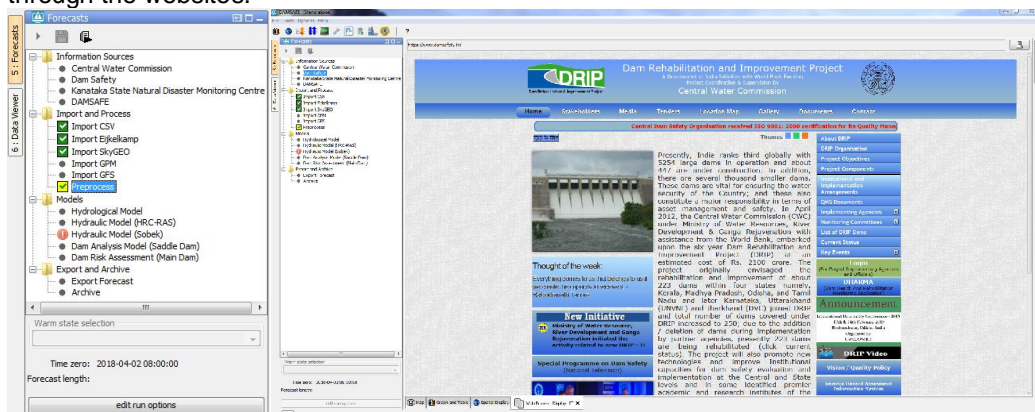


Another way of visualizing the three stabilities are in shortcuts of the Graph and Table tab. The stabilities factors are displayed together with the reservoir water level and piezometric head in the dam. Example of the results are illustrated below. For macro stability, three model results are displayed. The middle line in the first subplot shows the model results with the best parameter estimation. The upper and lower lines are the results with +15% and -15% of the strength, which give users confidence over the stability.





4.2 Forecast tree (Iterative Forecast Display (IFD))

Forecast tree tab is used to organize different workflows that execute tasks in sequences. The configuration follows certain operation logics. Figure below shows the operational nodes in the forecast tree. The Information Sources contain links to four websites. After clicking the docked tab Web Browser Display and selecting the information source, users can browse through the websites.




The second node in the forecast tree is called Import and Process. As the name indicates, the sub-nodes here are linked to different import workflows and data process workflows. Import CSV will import the offline data from Inida that contains historical meteorological data and historical reservoir data. Import Eijkelkamp imports data from the Eijkelkamp sensors installed







within this project. Import SkyGEO imports satellite measurement of dam deformation data from SkyGEO. Import GPM and Import GFS are linked to workflows that import observed and forecasted meteorological data. The most important meteorological parameter is precipitation. For detailed introduction of GPM and GFS, please refer to the following website: <https://pmm.nasa.gov/category/keywords/imerg>; <https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/global-forecast-system-gfs>

The last sub-node is Preprocess that processes all imported data. The preprocessed data will be used later as different model inputs. Once a certain node is selected, clicking either  (local run) or  (server run) icon on the forecast tree will execute the task. Please note that Preprocess node needs to be executed after the import nodes are completed that makes sure all imported data is preprocessed for later usage.

The node Models contains 5 sub-nodes. The name indicates the linkage to different model. Please be aware the hydrological model provides inputs for hydraulic models and needs to be executed before running the hydraulic modes. The two dam models for saddle dams and main dam can be executed independently. But all models can be executed before the Preprocess node is conducted successfully.

Different icons can be displayed for the workflow nodes at different situations, which is shown in the figure below.

- A grey box with either a green or blue check mark. A grey box means the T0 of the approved run in the database is different than the one in the IFD. The check mark indicates whether the approved run is a local or a server run.
- A yellow box with either a green or blue check mark. A yellow box means the state settings of the approved run in the database are different than the settings in the IFD. For example you might have a different warm state, warm state search interval, or forecast length. The check mark indicates whether the approved run is a local or a server run.
- The red circle with exclamation mark  means the run is failed due to some reasons. Investigation is needed to find out the root cause of the problem, by checking the log file (log.txt) in the region home directory of the DAMSAFE application.

	Local	Server
Normal		
T0 diff		
State diff		

The last node in the forecast tree is Export and Archive. It exports forecasting results to the Export folder in pi-xml file format and archives the observed data from Eijkelkam measurements and GPM (Eearth Observation precipitation) in netcdf format.

4.3 Tool bar

The tool bar provides quick access to frequently used tools. Tools are plug-ins to FEWS explorer. The tool bar can be configured with icons or text. In the application of DAMSAFE,

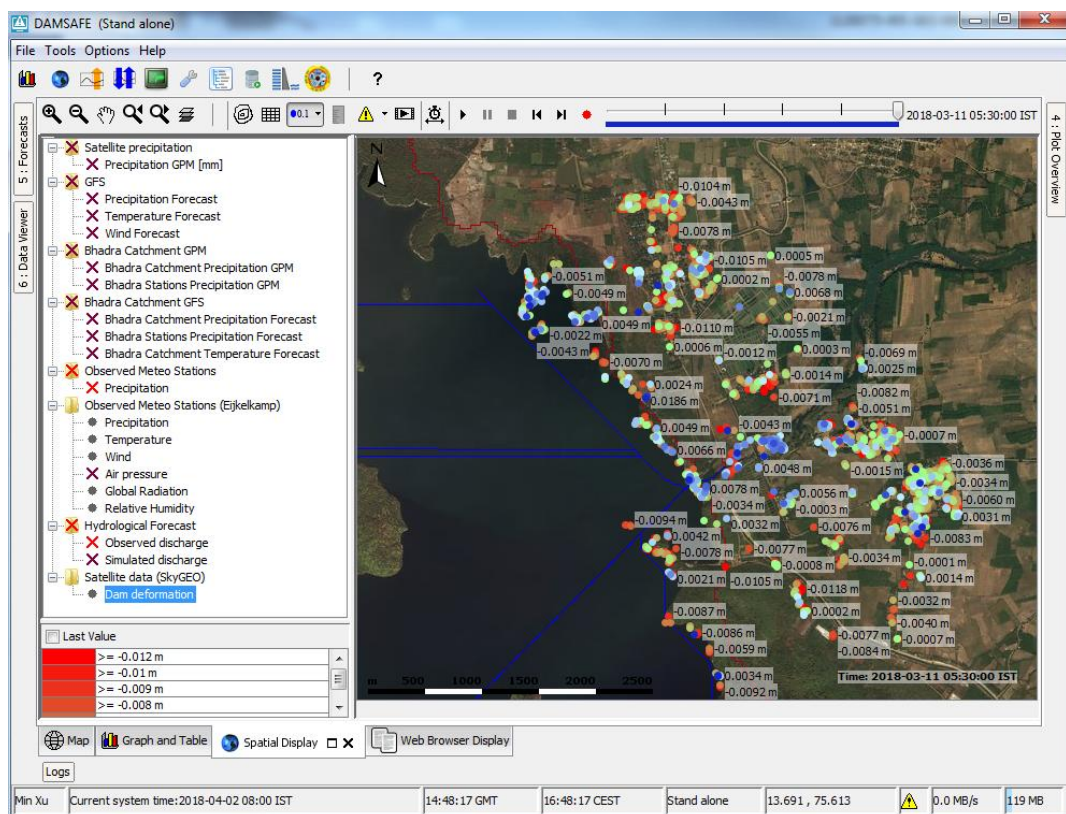
the tool bar contains: Graph and table; Spatial Display; Manual Forecast; Forecast Manager; System Monitor; Modifier; Workflow Navigator; Database Viewer; Schematic Status Display; External URL Link. There is no specialty for Manual Forecast, Forecast Manager, System Monitor and they can be referred to the User Guider. Below we introduce the rest of tool bar.

4.3.1 Spatial display

In DAMSAFE application, the Spatial Display is structured as shown in the figure below. Satellite precipitation displays the spatial precipitation data of GMP (grid, observed); GFS displays the forecasted spatial precipitation, temperature and wind (grid). The above data is displayed for the whole India. Bhadra Catchment GPM and Bhadra Catchment GFS are the data cut for the Bhadra catchment from GPM and GFS. Moreover, spatial interpolation is applied to the GPM and GFS data for the meteorological stations from India and the results are displayed here as well.

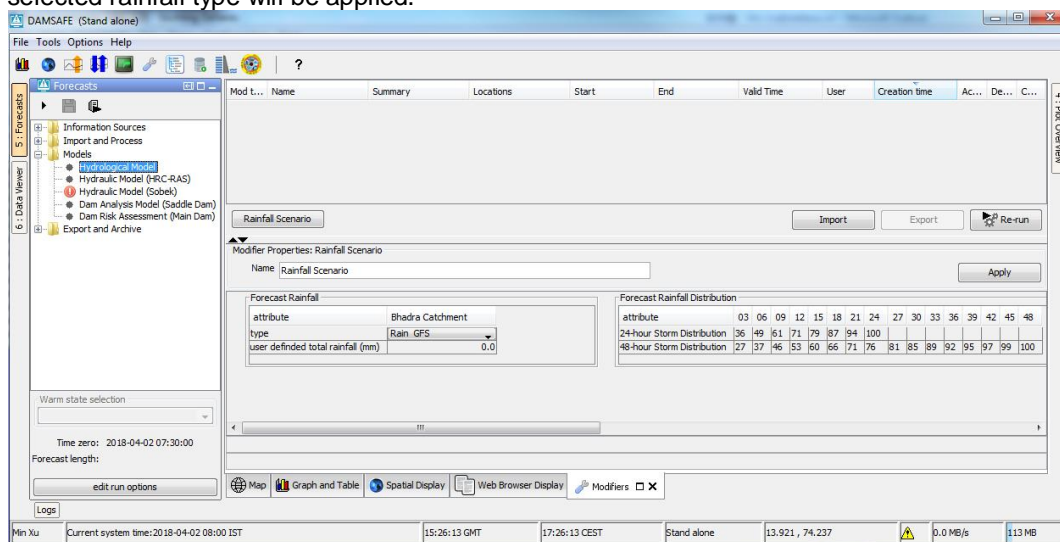
Observed Meteo Stations and Observed Meteo Stations (Eijkelpamp) spatially displays the meteorological stations from India (Offline data) and Eijkelpamp (Online data). Double clicking each location, the corresponding time series will be displayed through Graph and Table tab.

Hydrological Forecast displays the simulated discharges from the hydrological model (HEC-HMS). For comparison, the observed discharge is also displayed (only at Balehonnur). The last display is Satellite data (SkyGEO). It displays the dam deformation data from SkyGEO. Red indicates elevation decrease and blue for level increase. The recent data is updated till 2018-03-11

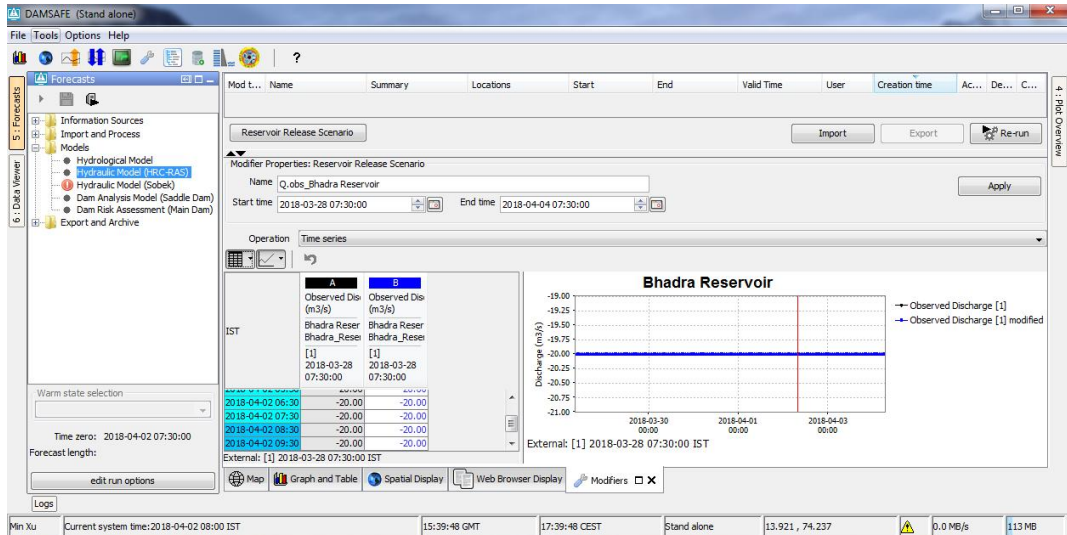


4.3.2 Modifier

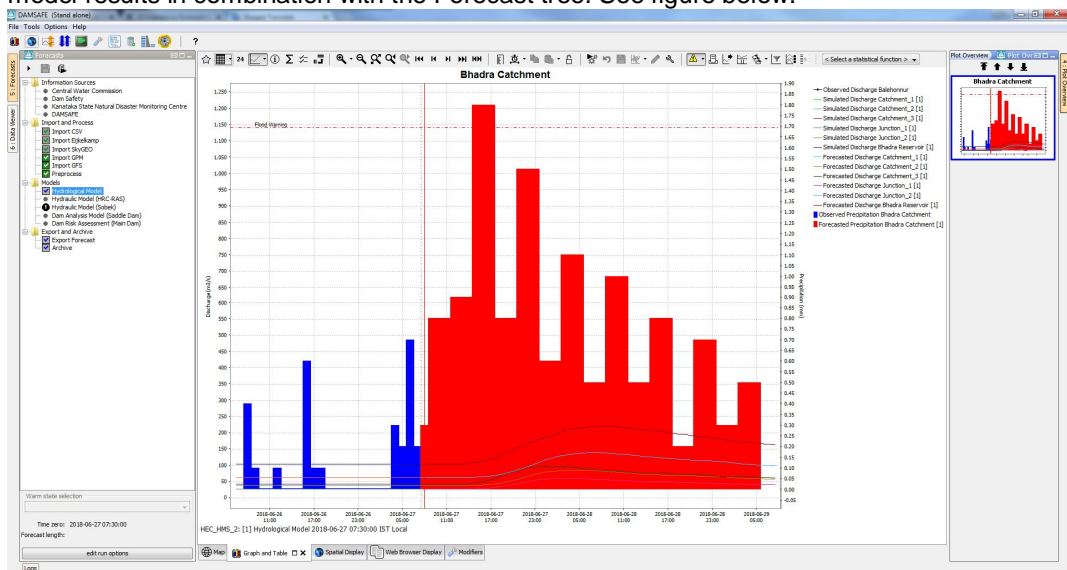
Modifier plays an important role in DAMSAFE application. It is used together with the Forecast tree and is only coupled with the Hydrological Model and Hydraulic Model. After the Modifier display is opened and the Hydrological Model node is selected, the following display shows. By default, GFS precipitation (forecasted) is used as the input of the hydrological model. The default forecasting length is 48 hours. It is possible to select other rainfalls by double clicking the Forecast Rainfall type, such PMP_24h_269mm, PMP_48h_359mm, SPS_24h_222mm, SPS_48h_297mm, User_Defined_24h, User_Defined_48h. The first four scenarios are provided by Karnataka as design storms for 24 hours and 48 hours. The rainfall distributions are described in the table beside. Users can define their own storm with the last two options. But the user defined storms also follow rainfall distribution in the table beside. After a rainfall type is selected, click the “Apply” button and rerun the hydrological model. The selected rainfall type will be applied.



After the Modifier display is opened and the Hydraulic Model (HEC-RAS) node is selected, the following display shows. The reservoir release scenario is possible for editing. By default the reservoir releases -20 m³/s (minus indicates outflow for the model), as displayed in the table and the graph beside. Users can edit the table with a proper release strategy. The graph will be changed accordingly. After editing, click the “Apply” button and rerun the hydraulically model. The new release strategy will be applied.

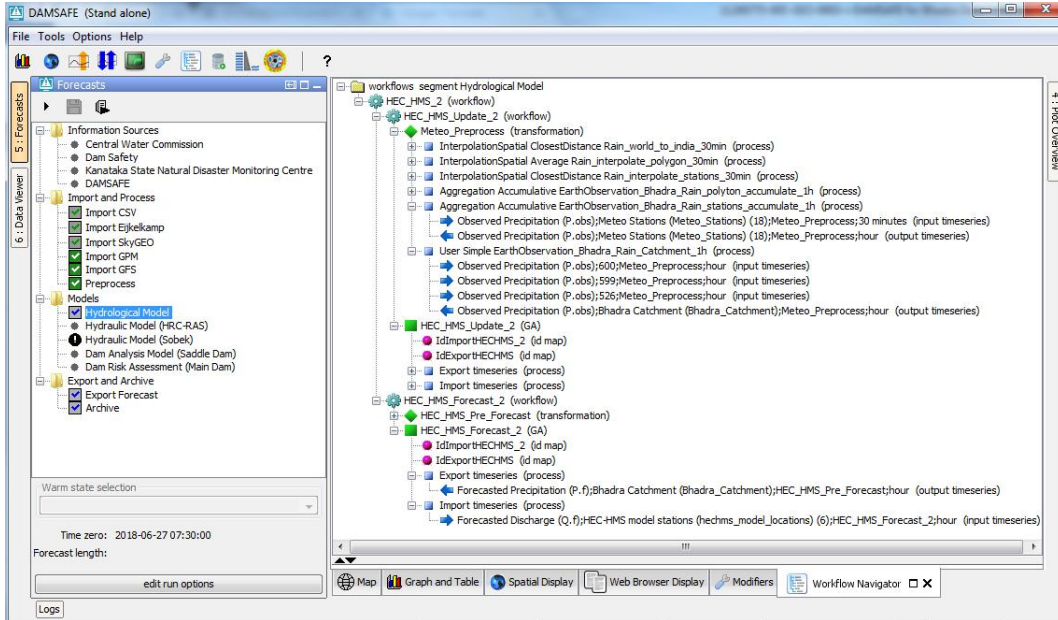


After model simulation is completed, a plot overview can be used to quickly visualize the model results in combination with the Forecast tree. See figure below.



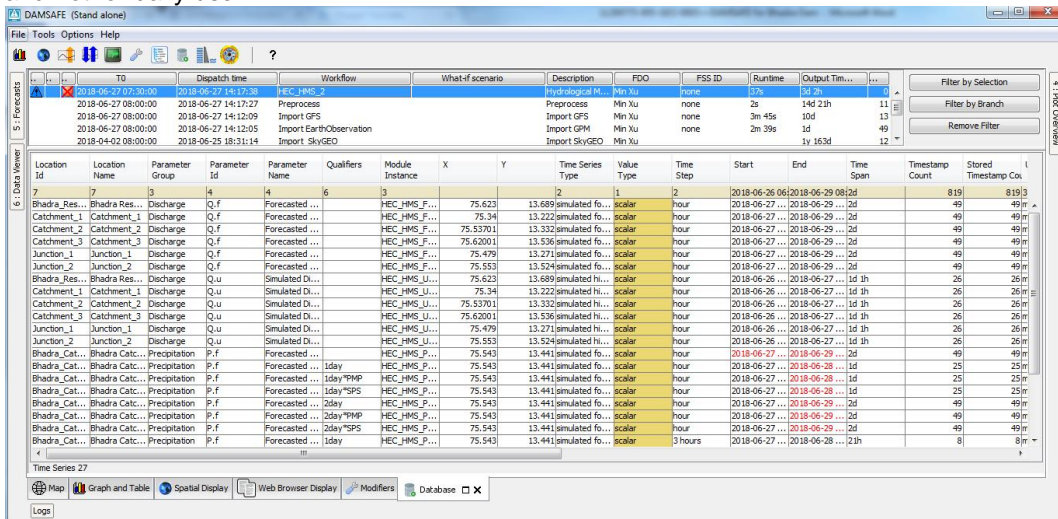
4.3.3 Workflow Navigator

Workflow Navigator provides possibility of checking the modules in each workflow. It can be linked with the forecast tree. After opening the Workflow Navigator display and selecting a node in forecast tree, user can see the modules in this workflow. Expanding the modules, user can see the input and out variables of the modules. By right mouse clicking, users can view each time series in graphs. Please note that this function is meant for system debug and not for daily use.



4.3.4 Database viewer

Database viewer displays all data processed in DAMSAFE application. Data is associated with each workflow execution. Please note that this function is also meant for system debug and not for daily use.



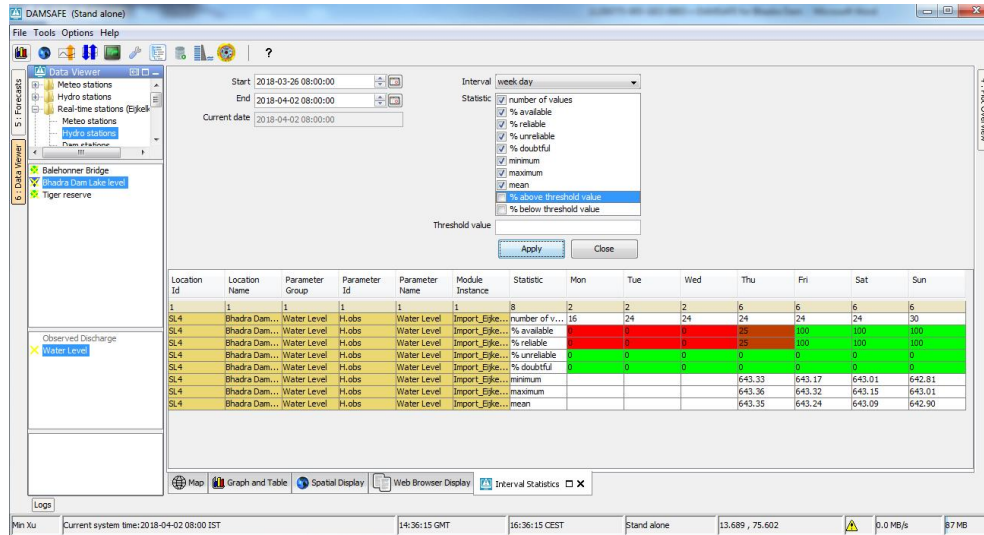
4.4 Dropdown menu

In the dropdown menus, besides the functions listed in the tool bar, several other functions are defined, such as: Tabular Config Display, Interval Statistics, and Topology. Below we provide description of these displays.

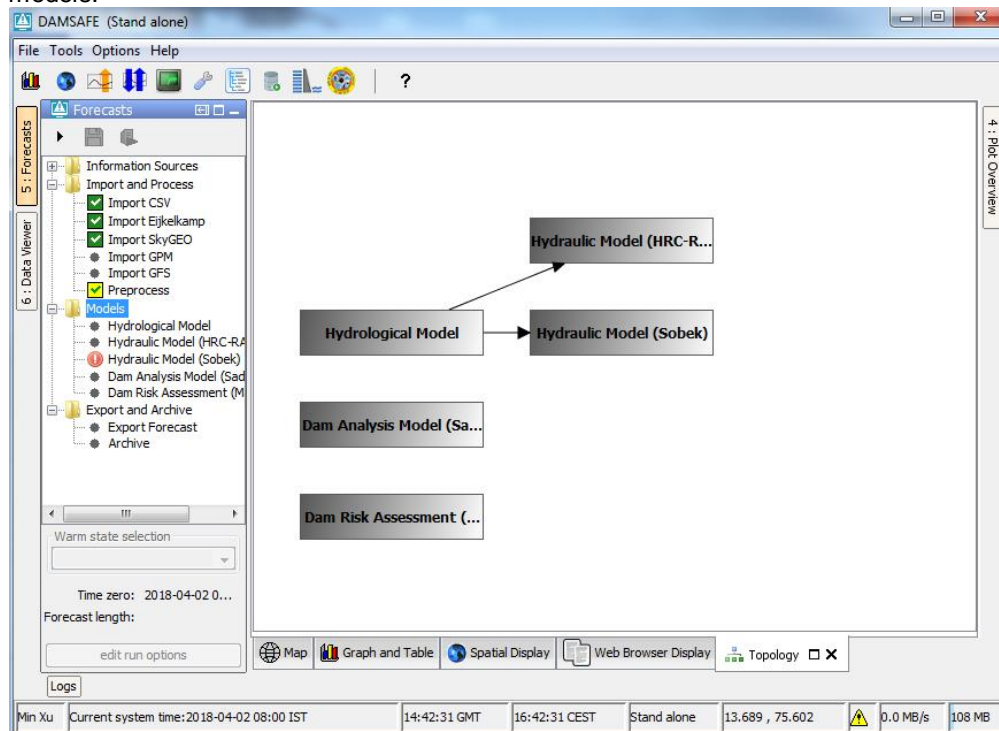
- Tabular Config Display**
 This is used to display the map layer tables (CSV table) which are used to manage locations in the Delft-FEWS system. The file is stored in the MapLayerFiles folder of the application. This table can only be visualized in Tabular Config Display, but not edited within Delft-FEWS. After opening this display, selecting a location will display the corresponding csv table. See example below. Double clicking any cell of the table can filter out unwanted information. Clicking table header can sort the table.

ID	Name	X	Y	EXTID	Type	EXTPARID	Instal_Location	PARENT	VERSIE
WS-2	N.R.Pura weather station	75.51983	13.61068	WS-2	meteo		Narasimharajapura		
WS-1	Balehonner CWC	75.4706	13.35178	WS-1	meteo		Balehonner		
WA1	Gallery 4	75.63671	13.70115	WA-4	hydro	PiezoMetricHead	MasonryDam	main_dam1	v3
WA2	Gallery 3	75.63644	13.70146	WA-3	hydro	PiezoMetricHead	MasonryDam	main_dam1	v3
WB1	Gallery 2	75.63621	13.70174	WA-2	hydro	PiezoMetricHead	MasonryDam	main_dam2	v3
WB2	Gallery 1	75.6363	13.70162	WA-1	hydro	PiezoMetricHead	MasonryDam	main_dam2	v3
WD2	V-notch Masonry dam	75.6363	13.70162	VD-2	hydro	DrainageFlow	MasonryDam	main_dam1	main_dam2
WD1	V-notch saddle dam 2	75.6301	13.71404	VD-1	hydro	DrainageFlow	Saddle2	saddle2	
SL4	Bhadra Dam Lake level	75.6363	13.70162	SL-3	hydro	Waterlevel	MasonryDam		
SL-2	Tiger reserve	75.64327	13.41933	SL-2	hydro	Waterlevel	TigerReserve		
SL-1	Balehonner Bridge	75.4706	13.35194	SL-1	hydro	Waterlevel	Balehonner		
SB1 (PL1)	SA2-1	75.62932	13.71409	SA2-1	hydro	PiezoMetricHead	Saddle2	saddle2	v3
SB2 (PL2)	SA2-2	75.62932	13.71409	SA2-2	hydro	PiezoMetricHead	Saddle2	saddle2	v3
SA1 (PL1)	SA1-1	75.63114	13.70988	SA1-1	hydro	PiezoMetricHead	Saddle1	saddle1	v3
SA2 (PL2)	SA1-2	75.63114	13.70988	SA1-2	hydro	PiezoMetricHead	Saddle1	saddle1	v3
SA	Saddle 1	75.62932	13.71409		stability			saddle1	
SB	Saddle 2	75.63114	13.70988		stability			saddle2	
WA	Dam-spillway	75.63671	13.70115		mandam			main_dam1	
WB	Dam-non over flow section	75.63621	13.70174		mandam			main_dam2	

- Interval Statistics**
 This function is used to display statistics of selected location at selected time interval. After opening this display, by selecting the required location, users can select time interval and parameters for statistics. The statistics of the time series are colored based on the data availability.



- **Topology**
The tab is used together with the Forecast tree. It displays the structure of selected nodes. Below shows an example of the structure of “Models” node. It indicates that the outputs of the hydrological model is the input for both hydraulic models of HEC-RAS and Sobek, Dam analysis model and Dam risk assessment are two independent models.



4.5 Log panel

The log panel displays high level messages generated by active system components. It provides information about the status of tasks run by the system. Additionally, detailed messages are available in the Log Browser. The following types of system messages are identified:

- Fatal (Severe errors that cause premature termination)
- Error (Other runtime errors or unexpected conditions)
- Warn (Events that are undesirable or unexpected, but not necessarily wrong)
- Info (Runtime events that allows tracking the progress of the system)

4.6 Status bar

The status bar provides information about the status of the forecasting system. From left to right, it contains: user account; current system time; GMT; local time; Delft-FEWS type; mouse coordinates; system status icon; speed; memory.

5 Recommendations

After the discussion with the staff from KaWRD during their visit at Deltares, we conclude that the DAMSAFE application integrates the current practice of Bhadra dam and can be applied to daily use as a pilot. During the testing period, further improvements can be made. For future improvement and upgrade of the system, following recommendations are suggested:

- During testing, real-time data was continuously broken for certain reasons. The sensors should be better maintained.
- Validate the GPM data with ground measurement and correct biases in both GPM observations and GFS forecasts
- Improve the SOBEK model with real data, conduct model calibration and validation
- Implement reservoir optimization technique to improve reservoir operation, such as flood control, water usage. RTC-Tools developed from Deltares can be fulfil the requirement
- Forecast ground water level in the dams in order to forecast dam strength
- Setup an operator server system to automate the work processes

A Appendix - DAM

A.1 Introduction

Dike-strength Analysis Module (DAM) is a software platform for automated levee/dam strength calculations. In this software platform several levee failure mechanisms can be analysed with customary software programs, tools or models. These calculation programs, tools or models are implemented in the platform for batch processing of the calculation. Also implemented in the platform are the adjustable algorithms to schematize the levee by the available information for the different failure mechanisms. (Van den Berg, 2017).

The possibilities of DAM are suitable for operational purposes in monitoring the actual stability of levees with installation of water pressure sensors in the dam. This application of DAM is called DAM-Live and for this project it is implemented in the operational system FEWS.

In this chapter the monitoring system will be described as well as the different models used for describing the failure mechanism.

A.2 Monitoring

For all the three failure mechanisms the phreatic line inside main-/ saddle dams' body and the water pressures in foundations are inputs needed in order to determine the pore water pressures inside the dams and the uplift pressures acting on the base of dams. The latter destabilizes and directly influences the safety of the dam. The analyses of these failure mechanisms and the evaluation of their safety are therefore linked to a monitoring system for evaluating interstitial pressures in dams' body and foundations. In particular, the monitoring system gathers data from one reservoir water level sensor and two water pressure sensors for each dam studied. In case of a saddle dam one piezometer is placed in dam's body in order to get information about the phreatic line inside the dam while the second sensor is placed beneath the dam, in the foundation, for detecting the uplift force acting on the dam base. Regarding the masonry dam both piezometers are located in the foundation near the drains' line to accurately detect the behaviour of uplift force in correspondence of the drainage system.

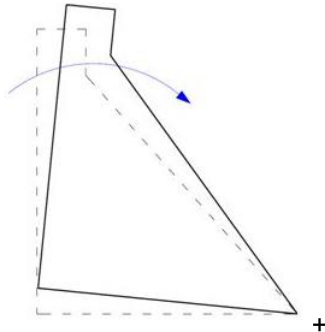
The monitoring system is also composed of sensors for the measurement of water discharge through the drainage system both for saddle dams and main dam. Information deriving from these sensors is useful for detecting anomalies of the drainage system or in the impervious zones inside dams' body.

In the latter case stability calculations can give the dam's owner indication if something is going wrong and if additional actions (e.g. visual inspections, checks on monitoring instrumentations or more detailed analyses) are needed, especially from a forecasting point of view.

A.3 Overturning stability

A.3.1 Model

Generally overturning occurs when the dam is subjected to a rotational movement of the entire body around a pole, usually located at the downstream toe of the dam.



Overturning failure mechanism

The safety of the masonry dam against overturning is assessed by evaluating the forces acting in the system dam-foundation-reservoir and by calculating their moments with respect to the pole around which the rotation is supposed to happen. The safety factor is then calculated as ratio between total stabilizing and total destabilizing moments.

$$FS = \frac{\sum M_{stab}}{\sum M_{destab}}$$

High reservoir's water level and high uplift pressure beneath dam's base could enhance the risk of failure due to overturning. Also for this failure mechanism the safety is considered satisfied if the safety factor is higher than 1

A.3.2 Monitoring

For the calculation of overturning stability and horizontal sliding stability, iPresas has created their own model. This model which is an elaborated version of the model as described in paragraph A.3.1 is built into FEWS (as a Python script).

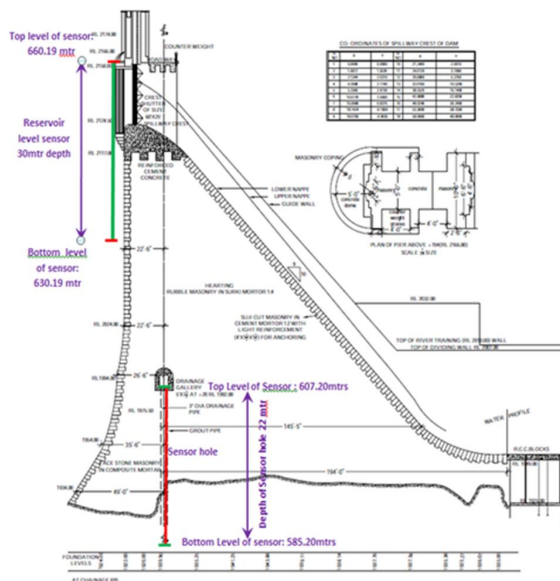
The input for this calculation consists out of the fixed input as given in the figure below and the variable input from the four sensors which are installed in the rock foundation of the main dam to measure the uplift water pressure. The following sensors are placed in the main dam:

- WA 1 at a depth of 584,51 [m] MSL
- WA 2 at a depth of 585,34 [m] MSL
- WA 3 at a depth of 584,55 [m] MSL
- WA 4 at a depth of 584,70 [m] MSL

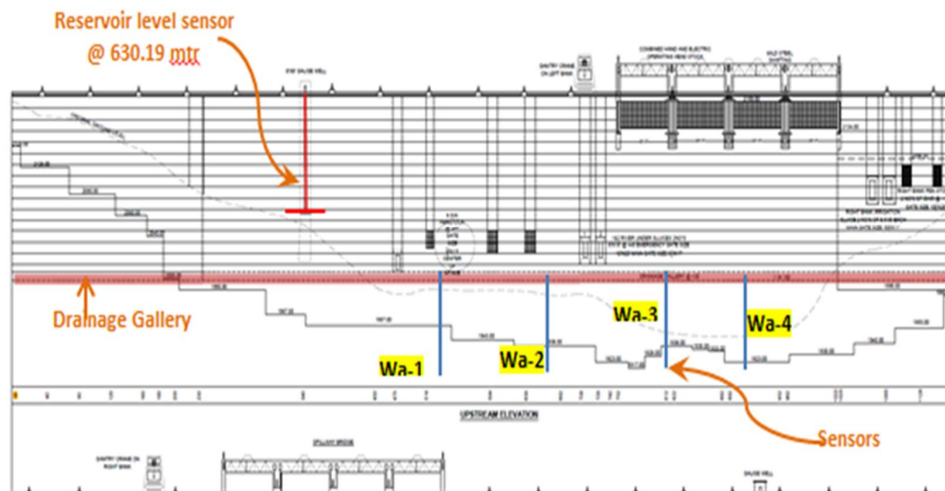
Density of concrete ρ_c [kg/m ³]	2338
Density of water ρ_w [kg/m ³]	1000
water level on the upstream face H_{up} [m]	657.76
water level on the downstream face H_{down} [m]	605.37
Friction angle at the contact dam-foundation ϕ [°]	36
Cohesion at the contact dam-foundation c [Pa]	350000
Coefficient of lateral earth pressure k [-]	0.4
The z coordinate of sediments' layer z_{sed} [m]	601.98
Immersed unit weight of sediments γ_{sed} [N/m ³]	15500

Input for the overturning/ horizontal stability (based upon the calculation method of iPresas)

The locations of the sensors, which are installed in the main dam, are illustrated in the figures below.



Locations of the sensors in a cross section (sensors were installed from the gallery)



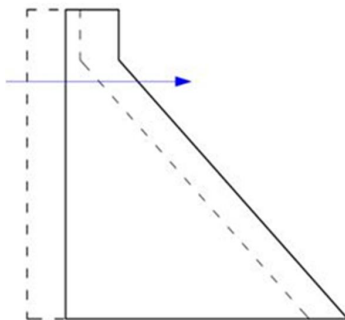
Location of the sensors from the frontside of the main dam

More detail about the installation of the sensors are given in (Eijkelkamp, 2018)

A.4 Horizontal stability

A.4.1 Model

The sliding failure mechanisms have been studied in relation to the interface at the dam-foundation contact. That interface is considered as weak surface since two layers with different materials face each other. The difference between the mechanical properties of the materials in foundations and in dams' body and the possibility of high seepage at the interface can make that surface particularly weak and eventually subject to horizontal sliding.



Sliding failure mechanism

The safety against sliding at this interface is assessed through a limit equilibrium analysis in which the shear strength is computed by integrating the resisting shear stresses (τ) deriving from the Mohr-Coulomb formula, reported in the following expression:

$$\tau = \sigma' \tan(\varphi) + c l$$

The safety against this failure mechanism is expressed in terms of safety factor as the ratio between the maximum total resisting shear strength (T_F) and the total mobilized shear forces (T).

$$FS = \frac{T_F}{T} = \frac{(N - U) \tan(\varphi) + c L}{T}$$

where N is the sum of normal forces acting on the dam's base and U is the uplift beneath the base, L is the length of the base in compression, φ and c are respectively friction angle and the cohesion that characterize the dam-foundation contact.

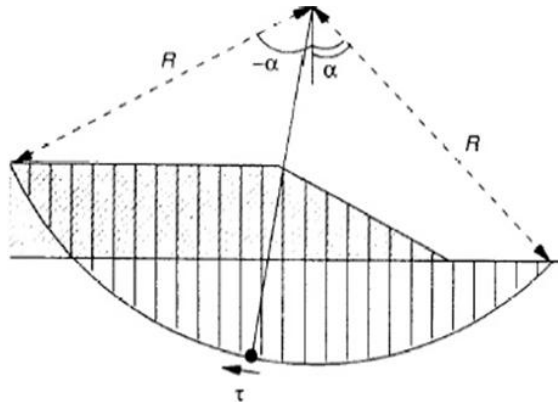
The safety is considered satisfied if the safety factor is higher than 1.

A.4.2 Monitoring

For the calculation of overturning stability and horizontal sliding stability, iPresas has created their own model. The input for this model are given in paragraph A.3.2

A.4.3 Model

The macro stability failure model is based upon the Bishop model (Bishop, 1955). In the figure below, a possible slip circle is depicted. The stability is depended on the equilibrium between the active force and the passive force.



Bishop sliding model with lamels

The safety against sliding at the slip circle is assessed through a limit equilibrium analysis in which the shear strength (τ) is computed in every lamel.

The shear stress is calculated as follows:

$$\tau = \sigma' \tan(\varphi) + c l$$

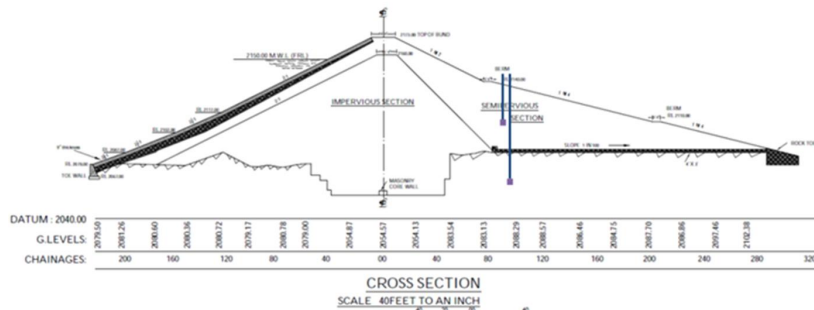
The safety against this failure mechanism is expressed in terms of safety factor as the ratio between the active force and the passive force.

$$FS = \frac{F_{active}}{F_{passive}}$$

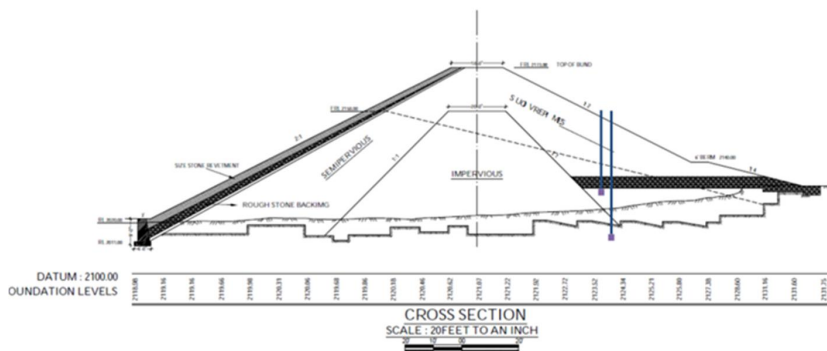
The safety is considered satisfied if the safety factor is higher than 1.3 as the parameters are based upon average values.

A.4.4 Monitoring

The macrostability calculation is carried out for two cross sections at saddle dam 1 and saddle dam 2. The cross sections are derived from (Shankarappa, 2016). In 2017 two sensors are placed in each cross section. See for more information the monitoring report (Eijkelkamp, 2018). The cross sections with the location of the installed sensors are illustrated in the following figures.



Cross section saddle dam 1 with installed sensors



Cross section saddle dam 2 with installed sensors

For the saddle dam 1 there are two sensors installed:

SA1-1 depth: 645.8 [+m MSL]

SA1-2 depth: 636.7 [+m MSL]

For the saddle dam 2 there are two sensors installed:

SA2-1 depth: 649.43 [+m MSL]

SA2-2 depth: 640.38 [+m MSL]

The height of the reservoir will be measured by the sensor SL4, which is located at the maindam at a height of 630,19 [+m MSL]

B Literature

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