Massive hydraulic simulation of extreme hydrological scenarios through dams and flood plains for dam safety analysis

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ABSTRACT

For extreme flood estimation in dam safety studies, hydrologists from EDF generate, thanks to the SCHADEX method, hundreds of thousands of synthetic floods, having a wide range of intensities and dynamics. This paper presents two efficient tools recently developed, allowing to process the hydraulic modeling of all these hydrological scenarios. A first software, called MELχOR, can simulate the routing of such massive sets of hydrographs through one or several reservoirs. It provides a complete distribution of maximum reservoir levels during floods. A second software, called AutoMaT, processes the same hydrographs through a 1D hydraulic model with storage cells for flood plains. MELχOR and AutoMaT allow then to provide a better hydraulic modeling of extreme floods in large and heterogeneous catchments with complex hydraulic behaviour. Hydrological dam safety analysis is finally assessed in a more robust way than with classical methods, accounting for numerous and diverse flood scenarios. This approach is currently under application on the French basin of the Durance River.

Keywords: Flood, Dam, Safety, Hydrograph.

1 INTRODUCTION

1.1 *SCHADEX Method*

The SCHADEX probabilistic method for extreme flood estimation described by Paquet & al. (2013) has been developed and applied since 2006 at Electricité de France (EDF) for dam spillway design. SCHADEX is based on a semi-continuous rainfall–runoff simulation process: a continuous hydrological simulation provides an exhaustive description of the possible pre-flood hydrological states of the catchment, while floods are generated on an event basis. The method has been developed around two models: the Multi-Exponential Weather Pattern (MEWP) distribution for rainfall probability estimation, and the MORDOR hydrological model. The simulation process allows to compute an estimated distribution of flood volumes at the study's time step (often daily), as well as a distribution of flood peaks based on a peak-to-volume ratio computed from observed hydrographs of significant floods. A wide range of rainy events are simulated on each hydrological state, generating an exhaustive set of crossings between precipitation and soil saturation hazards. Therefore, SCHADEX stands clearly apart from the "N-years flood is generated by a N-years rainfall" paradigm, as a great diversity of hydrological scenarios can generate a flood of a given return period, with many variables taken into account. Since its introduction, SCHADEX has been widely applied in France for industrial studies, to catchments from several square kilometers to several thousand square kilometers. This, and applications abroad under various climatic conditions, allowed the continuous testing and improvement of the method.

1.2 *French Durance River*

The French Durance River is a Mediterranean river located in the South-Est of France. From it source to its confluence with the Rhone River, it is 324 km long with a catchment of 14 225 square kilometers. The Durance main tributary is Verdon River, 166 km long.

EDF operates fifteen dams and 180 kilometers of power canals in Durance catchment for electricity production, irrigation and flood mitigation.

Two major dams, Serre-Ponçon on Durance, and Sainte Croix on Verdon, affect significantly the hydrological behavior of Durance, in particular during floods.

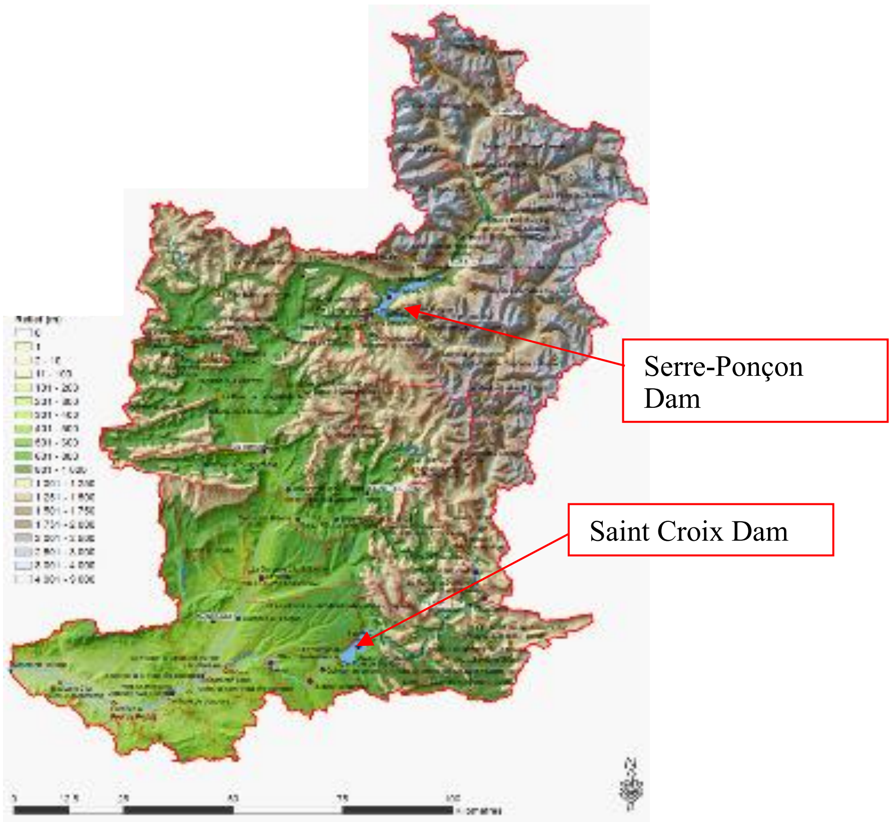


Figure 1. Durance River catchment at Mallemort dam

1.3 *Need for new methods for extreme flood estimation*

The hydrological studies of dams and canal are currently being updated, but the regular application of the SCHADEX method faces some limits in the context of the Durance study:

- The catchment is large with a high hydrological variability;
- The Serre-Ponçon and Sainte Croix dams (about 2.10^9 m^3 of total capacity) have a major influence on floods, up to extremes;
- The effects of large flood plains are not explicitly modeled in the standard SCHADEX Method.

This paper introduces some developments aimed at dealing with those issues:

- SCHADEX-SD (a semi-distributed version of SCHADEX) generates hundreds of thousands hydrological scenarios at the daily time-step, accounting for the spatial variability of the flood-generating processes within such a large catchment;
- SHYDONHY builds the corresponding hourly hydrographs for the Durance river and its tributaries in order to feed the hydraulic modeling;
- Melχor simulates the routing of such massive sets of hydrographs through one or several reservoirs;
- AutoMaT processes the same sets hydrographs through a 1D hydraulic model with storage cells for flood plains modeling.

2 BUILDING HYDROLOGICAL SCENARIOS

2.1 *Simulation of flood events with SCHADEX-SD*

The hydrological model used within SCHADEX, the MORDOR model (Garavaglia et al., 2017), is a lumped model, which implies that hydrological processes, e.g. rainfall and soil saturation, are supposed to be homogeneous throughout the modeled catchment. Snow processes are nevertheless represented in relation with altitude. This homogeneity is questionable for large catchments (from several thousands of square kilometers), or in areas of highly contrasted climatology (like the Durance catchment, in which the altitudes range from 250 to 4100 m ASL, and where the climate evolves from mountainous to Mediterranean). Modeling the catchment with a fully distributed approach is not an easy task, in particular distributing the rainfall-runoff model parameters trough space, and within the SCHADEX stochastic framework, generating extreme rain fields with relevant spatio-temporal features.

An intermediate solution is applied here, providing a better representation of the hydro-climatic diversity of the studied catchment, while keeping at the same time the SCHADEX simulation framework. The catchment is divided into several, more homogeneous sub-catchments, including also all the upstream catchments of the significant reservoirs. Rainfall-runoff models are parameterized individually for each sub-catchment, using local discharge data for calibration if available. A first SCHADEX simulation is done at the global scale (i.e. for the whole catchment), which allows assigning a probability to each simulated event, mainly based on the global areal rainfall drawn for the event (see Paquet et al., 2013 for details). Then the rainfall of each event is distributed through the different sub-catchments using the spatial patterns calculated thanks to the SPAZM precipitation reanalysis (Gottardi et al., 2012), using comparable situations of the 1948-2012 period (in terms of season and intensity). The simulated rainfall events are thus disaggregated on the domain in a realistic way, ensuring that for the simulated floods, the contributions of each sub-catchment are relevant. Corresponding daily discharge sequences are then calculated with the hydrological models at the outlet of each sub-catchment.

2.2 *Hydrographs generation with SHYDONHY*

The SHYDONHY method (Paquet, 2019), used to build synthetic hydrographs for each simulated event, is based on 1300 gauging stations in France and Switzerland, covering a wide range of size and climatology. For each station, an average of two floods per year are selected by a peak-over-threshold method, providing an extensive database of about 69 000 hydrographs in total. For a given catchment, some "donor stations" are selected with criteria of proximity in space, size and runoff production. These donors provide hundreds of hydrographs which can complement the ones recorded locally, or replace them if no hydrograph is available. For a given daily discharge sequence (simulated thanks to SCHADEX-SD), a relevant synthetic hydrograph is generated by combining appropriate hydrographs of this subset.

(a) Target and donor catchments (b) Simulated daily sequence and candidate hydrographs (c) Synthetic and observed hydrographs

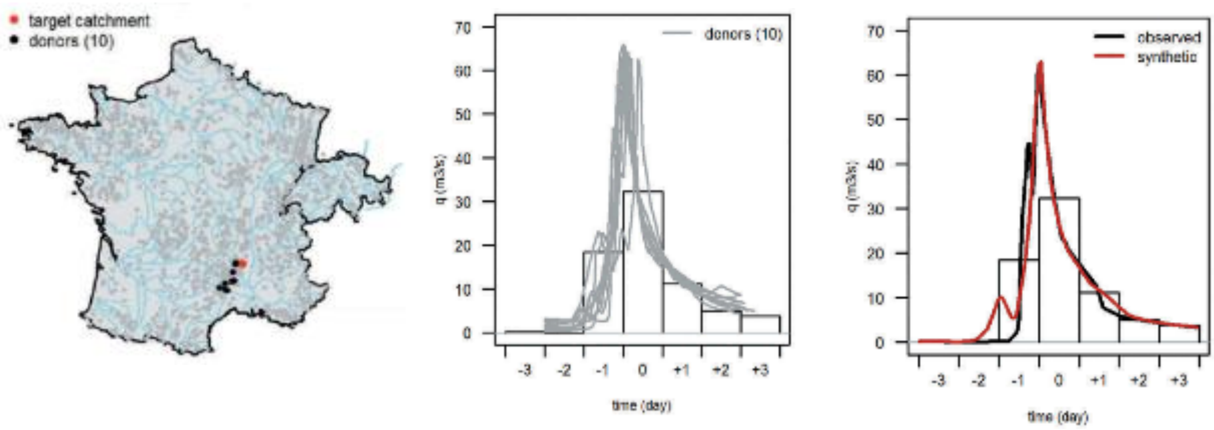


Figure 2. Example of synthetic hydrograph generation (from Paquet, 2019)
(a) Location of centroids of target and donors catchments; (b) simulated daily sequence and candidate hydrographs from the donors; (c) Synthetic and observed hydrographs.

3 HYDRAULIC MODELING OF FLOODS

3.1 *The Melχor software: routing through reservoirs and rivers*

The Melχor software is based on the PyCATSHOO library developed in C++ language by EDF R&D, and described by Chraibi (2013 and 2016). This library is used to ease the statistical studies of hybrid systems, including:
- Time located random state changes;
- Continuous state variables described by differential or explicit equations.

Three levels of tools can be chosen in the PyCATSHOO library:
- Knowledge base including classes (as in object-oriented programming);
- Tools to build a system by classes instantiation - i.e. to create a model of a valley - , and to parameterize and to launch simulations;
- Analysis and results processing tools.

The Melχor knowledge base (described by Lassus et al., 2017) includes five classes:

- The flood class is used to bundle hydrographs generated by SHYDONHY in the system.
- The Reservoir class models the reservoir behavior during floods by solving first order differential equations (1) where V is reservoir volume, y is reservoir level, Q_E and Q_S are upstream and downstream discharge and t is time.

$$\frac{\partial V(y(t),t)}{\partial t} = Q_E(t) - Q_S(y(t),t) \qquad (1)$$

- The Spillway class simulates a weir or a gate, in order to:
  - Estimate maximal downstream discharge for each spillway for a given level in reservoir;
  - Estimate if this discharge can be controlled (gate) or not (weir);

– Calculate opening speed for gates.

- The Regulation class models dam flood management by calculating actual downstream discharge for each time step. Two approaches are implemented:
  – The simplified regulation, where gate opening is instantaneous, can be modulated at each time step and downstream flow gradient is not limited. Within this approach, if water level is under full supply level (FSL), there is no discharge downstream. When water level reaches FSL, gates are opened instantaneously to balance upstream and downstream flows. If water level is above FSL, gates are opened at maximal capacity with a limitation to avoid a downstream discharge higher than already observed maximal upstream discharge during the flood.
  – The complex regulation simulates the "linear trajectory" flood management method described by Antunes-Vallery (2016), an approach inspired from automation using integral plus derivate driving. Flood management is based on water level trajectory depending only on water level, Δy=f(y). Set points are used for water level and increasing speed is controlled. Contrary to simplified approach, gate opening speed, observation periods and gate opening periods are taken into account.

- The Hayami class models the diffusion and propagation of hydrographs in the bed of river (not flood plains) for instance between two dams. A discharge 1D propagation library was developed by EDF R&D based on Hayami equations (1951). This library is based on a robust calculation module which can easily be parameterized (without bathymetry) with fast calculation time.

A Melχor model is built in two steps. Objects are created by knowledge classes instantiation (i.e. each flood, reservoir, spillway, regulation and Hayami object is created and parameterized), initializing states and attributes. Then, objects are linked together. Figure 3 shows, for instance, a model of two dams with Hayami propagation between them. Two gates and a crest weir are used for flood management on each dam.

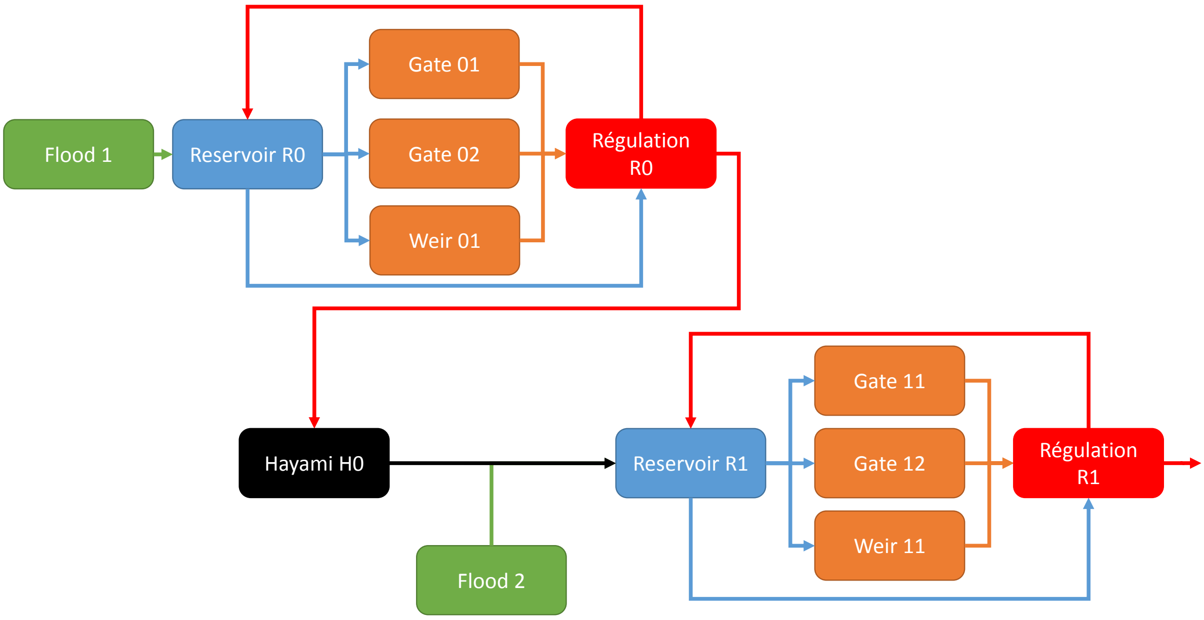


Figure 3. Example of Melχor model with two dams and Hayami propagation

Few parameters are necessary to generate a Melχor model. Hydrographs are needed for each flood object. For each reservoir object, FSL, Maximal Authorized Flood Level, Safety Level, Initial level (FSL in general, but it is possible to use historic or seasonal water level), bathymetry (or capacity curve) are used. For spillway objects, discharge curves and gate speed opening are needed. For regulation objects, parameters of the "linear trajectory" must be known if the complex regulation is chosen. And for Hayami objects, length, width, slope, and Strickler friction coefficient of the river are required.

3.2 *AutoMaT: modeling flood plains*

AutoMaT, for Automatic Mascaret Treatment, is based on Mascaret API in SALOME environment. SALOME is an open source software (www.salome-platform.org) which is a platform for pre and post processing for numerical simulation and where it is possible to define a chain or a coupling of computer codes. It is based on an open and flexible architecture with reusable components. SALOME is developed by EDF, the CEA and OPENCASCADE S.A.S. with the GNU LGPL license as the source code can be downloaded and modify from the website. All the components within SALOME can be used together in a computation scheme. SALOME call each module and make them communicate.

Mascaret is an open source hydraulic modelling software (www.opentelemac.org) dedicated to one-dimensional free-surface flow, based on the Saint Venant equations. Mascaret includes, with its subcritical unsteady kernel, a floodplain storage module in order to represent quasi-2D model. To create AutoMaT, API version of Mascaret in SALOME is used.

AutoMaT architecture has two levels. First level sub-program simulates one scenario with Mascaret API and second level manages cluster use for many simulations.

First level includes a knowledge base and few functions. The knowledge base is composed of only one class: Mascaret class used to generate one-dimensional hydraulic models, with subcritical steady or unsteady kernels. To simulate one hydrological scenario, AutoMaT first reads in data generated by SHYDONHY hydrographs of the river and of all its tributaries and generates for each hydrograph two law files for Mascaret: one with first value of hydrograph and one with complete hydrograph. Then, with the first set of law files, it runs a steady flow simulation to generate initial condition (water levels and velocities) for unsteady flow model. With the second set of law files and initial condition, it simulates all the flood with floodplain storage module and unsteady kernel.

To improve numerical stability, AutoMaT manages errors (using try and except method) on steady and unsteady runs modifying initial discharge, time step or vertical discretization of the cross sections.

AutoMaT model needs only few data: a Mascaret model of the river and hydrological scenarios.

4 FIRST APPLICATIONS TO THE DURANCE CATCHMENT

4.1 *Durance river catchment*

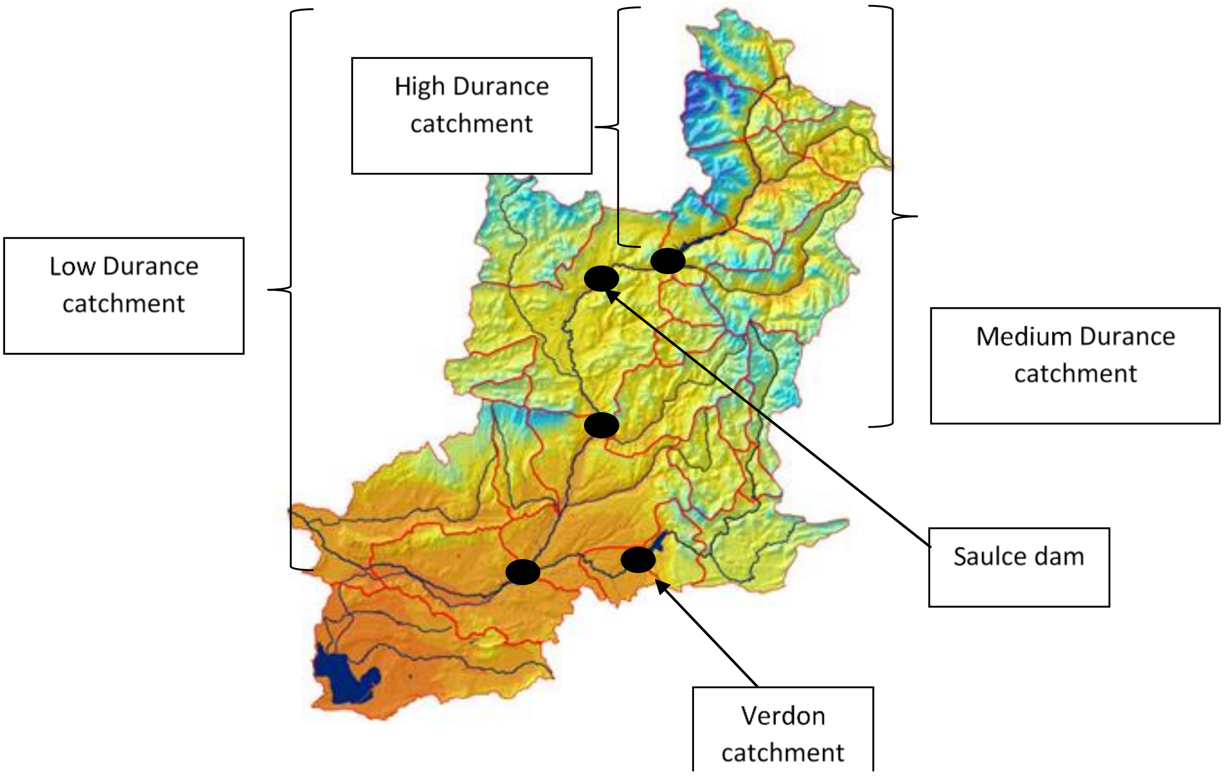


Figure 4. Durance sub-catchments

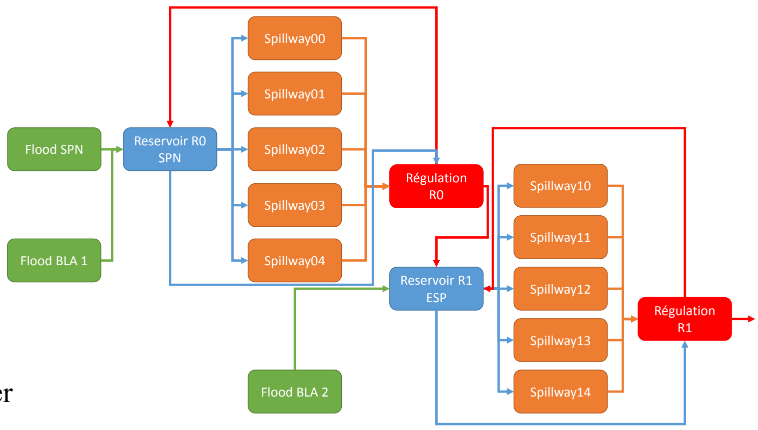
As shown on the Figure 3, from upstream to downstream, four points of Durance river catchment are studied (each study including all the necessary upstream catchment studies):

- High Durance, including Serre-Ponçon and Espinasses dams;
- Saulce dam catchment;
- Medium Durance for St Lazare and Escale dams;
- Low Durance for Cadarache and Mallemort dam.

The Verdon River is also studied for Sainte Croix, Quinson and Gréoux dams and is necessary for Low Durance catchment study. For those five studies, a SCHADEX-SD simulation of floods, followed by a hydrograph generation by SHYDONHY, is carried out, thus providing a set of around 200 000 hydrological scenarios for each sub-set of catchments, covering a wide range of floods intensities and dynamics.

4.2 *Head Dams simulation*

A first step in the global study is the safety assessment of the two larger head dams (Serre-Ponçon on Durance river, and Saint Croix on Verdon river), modeled along with their smaller downstream dams (respectively Espinasse for Durance, Quinson and Gréoux for Verdon). The Melχor models of the corresponding catchments (named High-Durance and Verdon respectively) are presented in the Figure 5.



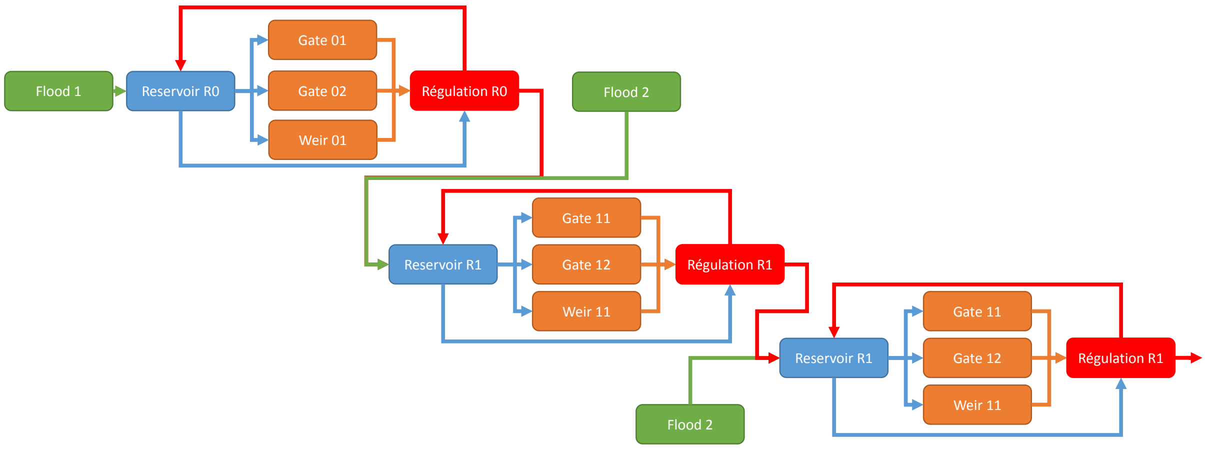


Figure 5. Melχor models of High Durance (up) and Verdon (down)

Around 200 000 hydrological scenarios were simulated (in few hours on 4 processors) for each catchment. For each hydraulic simulation, the following data are stored:

- Date of event (associated to initial state of the catchment and reservoirs);
- Event probability, as affected by the SCHADEX-SD stochastic simulation;
- Upstream and downstream discharge (hour step $Q_E(t)$ and $Q_S(t)$ and maximal values Q_{Ept} and Q_{Spt}) and water level (hour step y(t) and maximal value y_{pt}) for each reservoir.

The main processing performed on the simulated data is computing the cumulative distribution function (CDF) for discharges and levels. Figure 6 shows the CDF of reservoir level, as well as input and output discharges CDFs for Sainte-Croix dam. Such a comprehensive hydraulic simulation provides useful results: an important one is that, for return periods between 30 and 3000 years, the downstream discharge remains almost the same, the Sainte-Croix reservoirs "filters" completely those floods. Furthermore, even with intermediate catchments between dams, input discharges in Quinson and Greoux reservoirs are mainly conditioned by the Sainte-Croix output discharge.

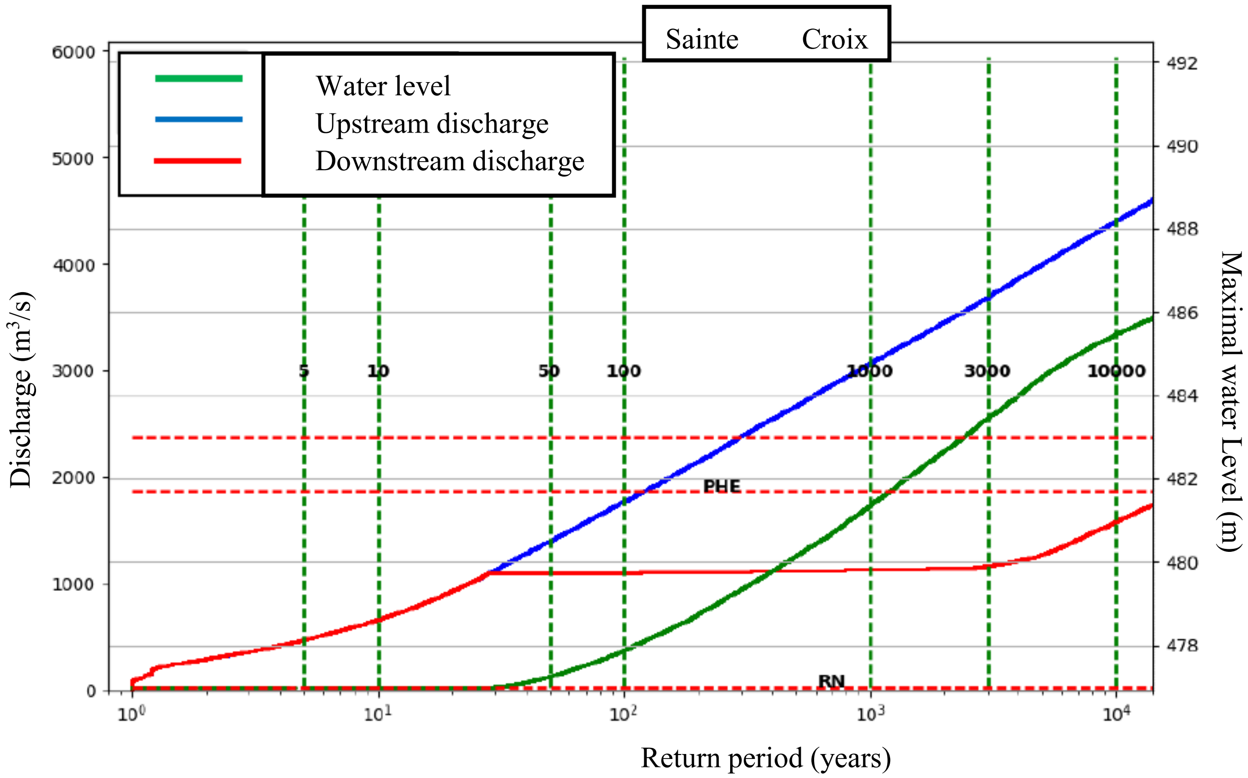


Figure 6. Water level (green), input discharge (blue) and output discharge (red) CDF for Sainte-Croix reservoir

To have a closer look at events of a given return period, it is possible to zoom at any particular simulation within the reservoir level CDF, thus easily retrieving and plotting its return period, reservoir level and event number, as shown on Figure 7.

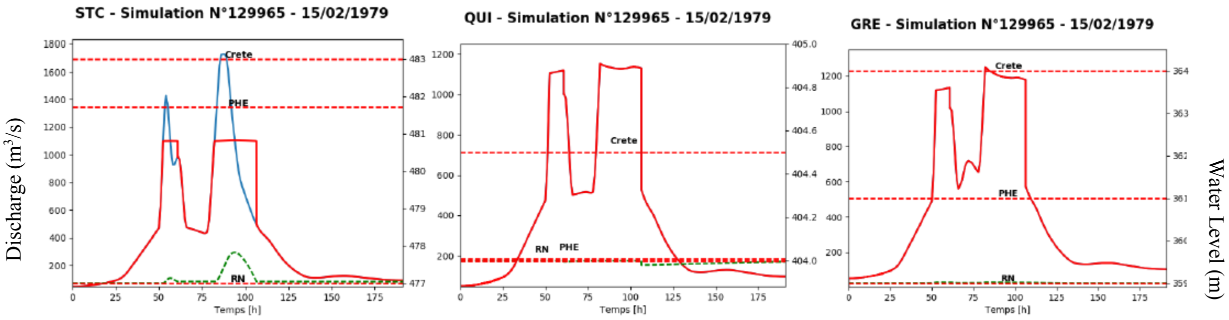


Figure 7. Reservoir level (green), input discharge (blue) and output discharge (red) for a specific event at Sainte-Croix (left), Quinson (middle) and Gréoux (right) reservoirs (RN = FSL, PHE = Maximum flood level and Crete = dam crest)

4.3 *Flood plains simulation*

For the downstream parts of the Durance River catchment (Saulce dam, Medium and Low Durance), AutoMaT will be used (study is still in progress) for flood propagation downstream of the Espinasses dam (after simulating influence of Serre-Ponçon and Sainte Croix dams with Melχor model).
A Mascaret Model of Durance from downstream of the Espinasses dam to the Mallemort dam (around 180 kilometers long) has been created. The geometry of this model is based (Figure 8) on a Lidar and cross section topography (every 500 m) done in 2016: 47 flood plain storages (with floodplains storage module) are included with links between river and storages and between storages. The distance between calculation points is 50 meters. Five run-of-river dams (Saulce, St Lazare, Escale, Cadarache and Mallemort dams) with low storage capacity are included as stage discharge relation. Confluence with tributaries (Verdon, Bleone, Buech…) are not modeled, only hydrographs from tributaries are included as discharge addition.

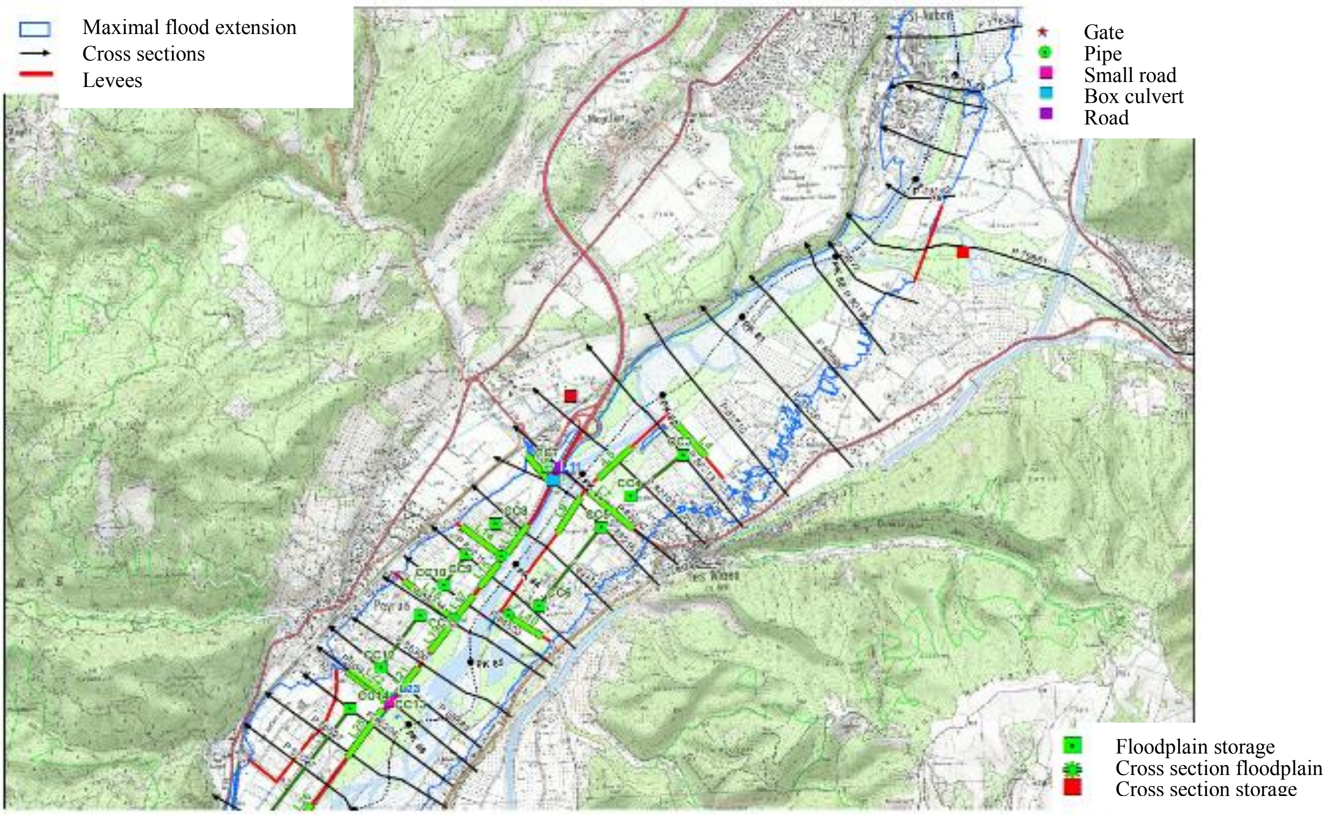


Figure 8. Scheme used to model Durance River with Mascaret

The model calibration is done on the historical flood of 1994 (Figure 9) and also for more recent floods of 2008 and 2014. The Durance River is a moving river with a lot of sediment transport. Therefore the calibration focuses on flood diffusion and propagation more than water levels. It has been done in two steps: first with steady flow simulation (with maximal discharge) to calibrate the Strickler coefficient in the river bed. Then with unsteady flow simulation to adjust the Strickler coefficient and calibrate flood plain storage links focusing on flood propagation and diffusion.

Dams included in AutoMaT are Run-of-river dams with low storage capacity and possible floodplain bypass of a part of discharge. Dams are modeled in the Mascaret model with simplified stage discharge relation and calibration focused on flood propagation and diffusion more than water level. Uncertainties on water level just upstream of dams is considered high. Therefore, contrary to Melχor, AutoMaT will only focus on discharge at each dam.

The Mascaret model of the Durance River is now well calibrated and AutoMaT is operational. The studies aiming at building the hydrological scenarios are still ongoing. Around 200 000 of them will be simulated with AutoMaT (in 10 days on 420 processors) for the Saulce dam, for Medium Durance and for Low Durance. For each simulation, recorded data are:

- Date of event (associated to initial state of the catchment);
- Event probability;
- Output discharge for each dam (hourly time step Q(t) and maximal values Q_{pt}) .

A similar processing of the computed discharges (Figure 10) will be done with AutoMaT and Melχor. The CDFs of each variable will be built and it will be possible to zoom at any particular event.

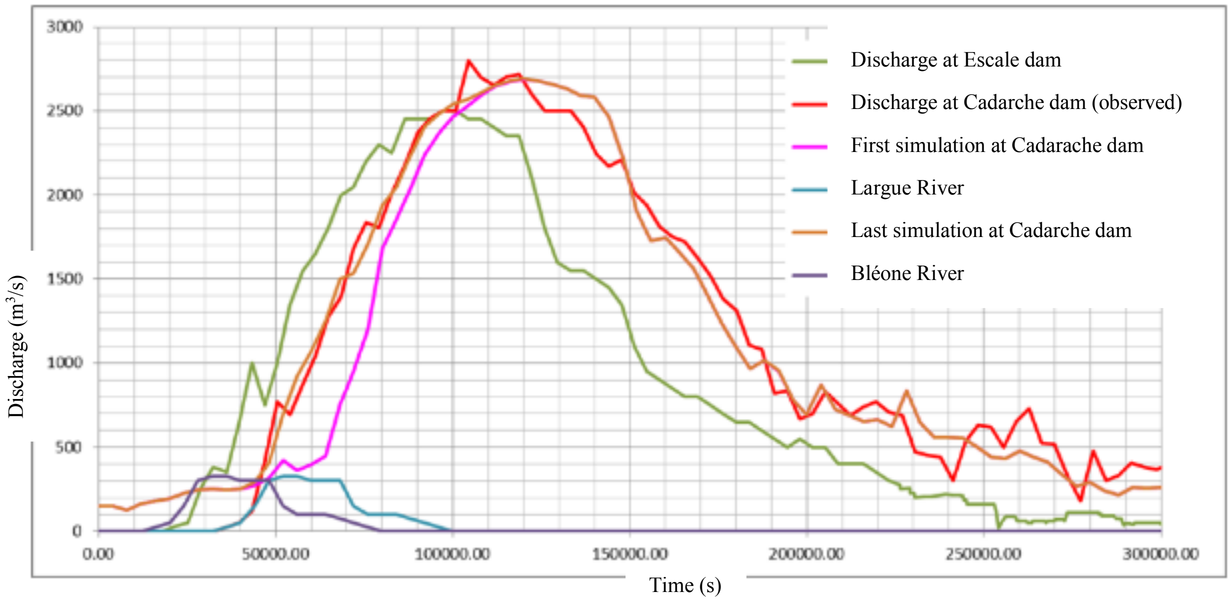


Figure 9. Model calibration of river section between Escale dam (green hydrograph) and Cadarache dam (red hydrogrph) for historical flood of 1994 – Main tributaries: Largue and Bléone River

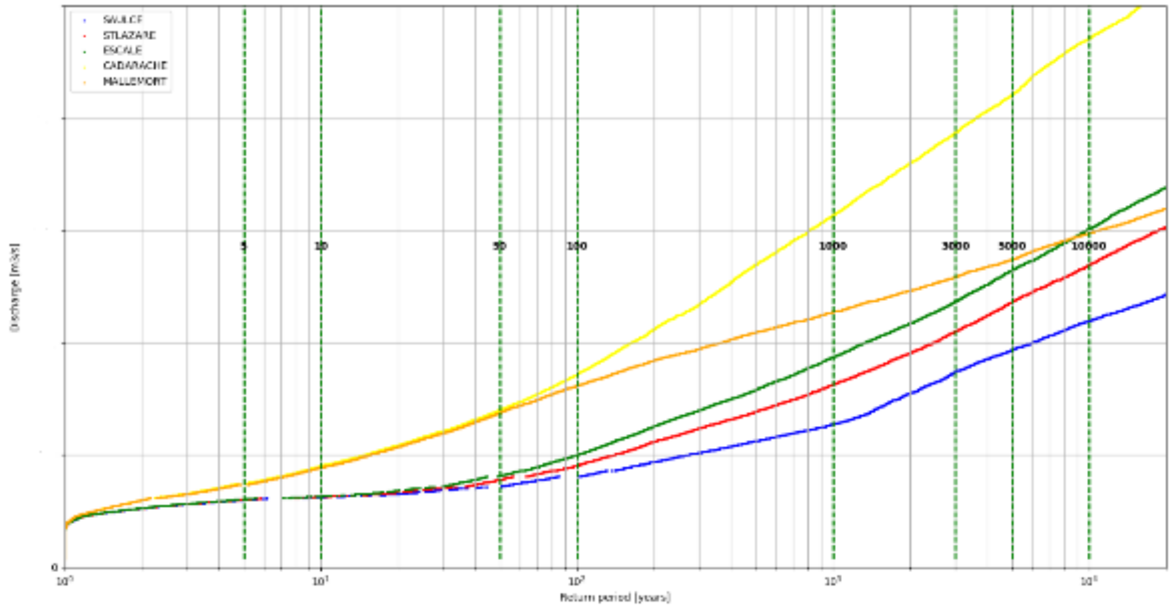


Figure 10. Discharge CDFs computed with AutoMaT and Durance River Mascaret model (with a test set of hydrographs) – blue: Saulce Dam, red: St Lazare Dam, green: Escale Dam, yellow: Cadrache Dam, orange: Mallemort Dam

5 CONCLUSION AND PERSPECTIVES

The presented methods and tools draw a new technical perspective for the hydrological dam safety assessment in large and complex catchments. They allow an extensive modeling of reservoirs, rivers and floodplains and account for upstream reservoir management. This hydraulic modeling is fed by a sophisticated stochastic rainfall-runoff simulation which provides a complete set of flood hydrographs, describing the complete range of flood magnitudes and sub-catchment contributions. Overall, the dam safety assessment in performed on a much more robust basis than using a limited number of reference hydrographs or scenarios. The complete application to the Durance River is still in progress but the first results obtained on the Verdon River are reliable and useful, with all the computational tools now fully operational.

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