

# POST-EVENT FLOOD DOCUMENTATION AND COMMUNICATION USING A HYDROLOGICAL MAP INFORMATION SYSTEM

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## ABSTRACT:

In order to support authorities in performing their mandates to protect the population from floods and minimize damages, additional documentation methods are needed. Before and during a flood event, the use of appropriate real time hydrological maps for improved early warning and monitoring activities is undisputed. After an event, however, the gained knowledge and expertise (i.e. the “lessons learned”) must be retained and fostered. This should preferably take place in a formalized way and the storage in a spatiotemporal database is one promising way to achieve this goal. However, such data-base driven map information systems used as repositories for hydrological knowledge have so far gained little attention. The added values of these kinds of systems are: a more profound understanding of flood processes; a better basis for decision-making; and improved means of post-event documentation and communication to peers and to the public.

The usefulness of interactive map information systems for flood documentation and communication purposes is shown, using an implementation of the main following concepts: the integration of quantitative, qualitative, and multimedia data; combination of these data types for cartographic visualization; retrieval of historical maps in an easy, time-saving way; user-defined customization of map content to explore the interplay of flood-causing hydrological factors, during every flood phase; toggling of map symbols to represent data on different temporal aggregation levels; and the animation of both maps and connected map elements (e.g. time series graphs).

## 1. INTRODUCTION

### 1.1 Motivation

Floods and other natural hazards may leave tremendous damages which need be avoided, or minimized, using different methods and approaches. To name a few, these approaches comprise the adjustment of operational, project, and planning levels in flood risk management (e.g. Plate, 2002); the increase of lead times to event peaks by coupling several stochastic meteorological forecasts with hydrological models (e.g. Cloke and Pappenberger, 2009); or facilitating integrated hydrological information collection, access and visualization by applying real time visual methods (e.g. Lienert *et al.*, 2010).

This work is primarily motivated by the increased information demand after disastrous flooding. Different stakeholders require processed and visualized information to cope with the situation. In this article, we focus on interactive visualization instruments appropriate for the use by officials in administration responsible for flood management, who have to inform the population and take measures to better handle the next flood. After several disastrous events in Switzerland during the past decade, flood management has moved high on the official agenda. Beside the optimization in warning and alerting issues, facilitating the post-event documentation process with

visual methods is advantageous for different reasons: (1) it improves the post-event analysis process, thereby improving the reconstruction process, which means that the vulnerability of involved stakeholders to the next flooding is reduced; (2) it acts as a basis for experts to gain new insights into flood processes and exchange results of analysis; (3) makes the results of analysis much more accessible for non-experts, i.e., as a means of communication to external parties such as the media; (4) it offers a comparable reference in order to assess possible evolutions of current floods.

### 1.2 Aims

Visual methods bear the potential of accelerating the information retrieval and decision-making process in flood management, provided that data is presented to the user in an unambiguous, captivating and interactive form, ideally in one single graphical user interface. These requirements call for an infrastructure that can store and large amounts, and different kinds, of spatial data at different temporal resolutions. Automatic workflows are needed for the sorting, filtering, aggregation, linking, classification, and cartographic visualization of data. In addition, these operations must be performed very quickly, preferably on-demand by the user.

The overall aim of the presented work is to provide a cartographic documentation and communication instrument for flood managers to meet the information needs of possibly all involved stakeholders (internal staff and external parties). The instrument aims at improving post-event flood analysis with maps and should be able to simulate and reveal the spatial distribution and response times of flood-causing hydrological factors in retrospect. The data structure that has to be prepared in advance should be valorized with this instrument so that knowledge can be gained, retained and fostered.

More specifically, the subordinate aims of the work are the following ones: (1) Finding ways of spatiotemporal data integration so as to store and retrieve combined sets of historical hydrological data; (2) providing dynamically generated maps in a (carto-)graphic user interface which contains interactive maps which are the result of a fully-automated cartographic production process; (3) making available interactive tools for customized modification of map content and map layout; and (4) offering animated maps with user-defined content.

### 1.3 Overview of Related Work

Generally, the need for detailed flood documentation and communication originates from the increased demand for hydrological information and data in administration, private industry, education, and research. Water-related domains, such as long-term spatial planning, flood protection and water resources management face enormous challenges which are emerging from altered global or regional boundary conditions, such as climate change or population growth.

Historical hydrological information was, and still is, primarily stored in national hydrological atlas systems, both printed and digital. Such works can be looked at as a repository of expert knowledge that mirrors the advances of hydrological methodologies over time. Focusing more specifically on historical hydrological data and events, Black and Law (2004) present a database-driven chronology of flood events back to several centuries ago. Although no cartographic outputs can be generated from it, the database stores a variety of qualitative data, such as eye witness accounts, or source information. It allows the historical studying of individual events, the preparing of teaching activities, or the modeling and documentation of flood risks. Flood documentation plays a vital role when past hydrological situations have to be re-modeled. Such activities might be necessary in order to determine, or to adjust, statistical probabilities of flood occurrences or drought periods, which may influence decision-making on the policy-level (Brázdil *et al.*, 2006; Kidson *et al.*, 2005; Llasat *et al.*, 2005; Pfister *et al.*, 2006). Different hydrology-oriented decision support systems aim at facilitating policy-relevant activities, such as land-use planning, river management, or to stakeholder conflict mitigation (e.g. de Kort and Booij, 2007; Salewicz and Nakayama, 2004).

Usability and data visualization in cartographic applications are intimately connected. The importance of unambiguous, captivating spatial visualizations of hydrological events, be they referring to actual or historical situations, is emphasized in several studies. Ishikawa *et al.* (2005), use climate change maps to discuss maps as general means for communication. They conclude that the quality of the map design greatly influences decision making. Discrepancies between the information intended to be conveyed by the map maker, and the information actually perceived by the user have to be avoided as far as possible. On the one hand, map making should start with user-centered interface and map design in order to anticipate the various user needs (e.g. Jankowski *et al.*, 2006; Soh *et al.*, 2006). On the other hand, various tools must be provided in systems which make all sorts of models more accessible to non-modelers. The need for automatic or user-defined information filtering is another feature that most notably non-technical users miss in many decision-support systems. The information conveyed to the user often lack conciseness and usability, particularly in emergency situation (e.g. Cutter, 2003).

Visualization of hydrological information is, as mentioned, traditionally found in 2D maps of national hydrological atlases (e.g. HADES, 1992-2010). Existing computer-based, interactive hydrological visualization systems include multimedia content and animations (e.g. Fuhrmann, 2000), or handle real time data (Lienert *et al.*, 2010). Animated spatiotemporal maps – a prominent feature presented in this paper – allow users to perceive information faster than static ones, even when they contain the same content (Koussoulakou and Kraak, 1992). Further striking hydrological visualization examples comprise 3D representation. Slocum *et al.* (2003) developed a 3D tool that helps decision makers to better understand uncertainties associated with water resources problems. Drogue *et al.* (2002) present a similar 3D application to visualize the output of rainfall-runoff modelling.

In all, it can be stated that there are several interesting hydrological visualization instruments and tools available. The range from traditional atlases to advanced multi-dimensional softwares. The aspect of using cartographic visualization – or rather a cartographic visualization instrument – to document historical flood events has not yet been scrutinized, albeit the availability of long high-resolution data time series. On the one hand, this might be due to the complex harmonization and integration of hydrological data which is imperative for the consecutive visualization. On the other hand, this might be due to the time-consuming data collection, since data are usually stored at differently located departments.

## 2. CONCEPTS AND IMPLEMENTATION OF A HYDROLOGICAL MAP INFORMATION SYSTEM

In this work, the maps used for flood documentation and communication are 2D and interactive, and they may be

animated. Moreover, we define a hydrological map information system as a system that consists of a central spatiotemporal database, a graphical user interface, and a variety of interactive tools available on this interface. Latter are supposed to facilitate data exploration and analysis. The graphical user interface is more specifically termed a cartographic user interface in which maps are automatically generated and where maps are the central means to access hydrological data in the database.

Data workflows for the integration and storage of historical data are vitally important and will be discussed next. The workflow, however, are not directly relevant to the user in the documentation and communication process. From a hydrologist's perspective, it is more important to have the possibility to visualize and analyze a variety of archive data in one single system that integrates all relevant data and tools. In this section, selected innovative aspects of of historical data storage, automated visualization, and hydrological analysis are discussed.

## 2.1 Historical Data Integration

A large set of data variables were collected and stored in a database. They were measured by official network operators and research institutes at a temporal resolution of 10 minutes or even less. For some variables, the time series reach back to the 1970s. They cover the entire area of Switzerland and originate from several hundred ground gauges, plus three different precipitation radar stations. Table 1 provides an overview.

Variable	Time series from	Temporal resolution
streamflow	1974	10-60 minutes
lake levels	1974	10 minutes
precipitation	1981	10 minutes
air temperature	1981	10 minutes
air humidity	1981	10 minutes
air pressure	1981	10 minutes
precipitation radar	1991	5 minutes
snow depths	1993	30 minutes
groundwater level	2000	10 minutes

Table 1. Overview of available hydrological variables

Data values are stored in an database that can also handle spatial data (i.e., geometry data). It is updated once a year, when official quality-checks have been performed by the data supplier. Descriptive statistics and aggregated data (averages, maxima, minima, sums) are calculated directly out of the high-resolution data using database-internal calculation routines. Particularly for streamflow, users may be interested in maximum values of a specific year. Or as to precipitation, in turn, users may want to learn about the hourly, daily or even weekly sums to better classify the respective 10 minute values. For this reason, aggregation functions and respective cartographic symbolizations for different aggregation levels were required (see below).

**2.1.1 Modelling the time of occurrence of hydrological events:** In this work, special emphasis is laid on time and how time, during which events have occurred, is stored. A qualified data model for this purpose is able to manage large amounts of spatiotemporal information, and allows for fast and concurrent manipulation of data. For this reason, a data model in form of object-relational database was set up.

In the database, hydrological variables, time, space, and attributes (e.g., descriptive statistics, metadata) are held separate. Each gauge is represented by an individual table to which new observation values are appended. Observation data records consist of the observation value and the observation time. Latter acts as a unique identifier in the database. The relationships between each single hydrological variable, its spatial, temporal, and attributive property, are explicitly modelled. Thereby, additional gauge identifiers are used as linking objects.

Each table with temporal data contains two columns for timestamp data types: one is called "from", the other is called "to", indicating the valid time of the respective record (Ott and Swiaczny, 2001). On each "from" and "to" column, a unique time constraint is applied. Such an approach is required to avoid data duplicates at the same gauge and to keep the database free from errors when updating it every year. It is also very useful when data has to be sorted or queried by their observation times.

**2.1.2 Extending the database** The set up of the database, and particularly its extension by further historical hydrological variables, calls for an additional web-based user interface (beside the cartographic). Its aim is to facilitate these rather technical operations. The so called database installation interface implements both the temporal, spatial, and attributive parts of the database in a step-wise process. After any step, the (administrator) user gets a status message on the screen. Due to its complexity and also because of security reasons, the database installation interface is confined to technically adept users.

Generally, data is organized in different database schemas. Within such schemas, individual tables are inheriting their table structure and manipulation functionality from superior parent tables. The main idea behind this concept is to facilitate and accelerate data management by carrying out operations at one parent table, which are then automatically carried out at several hundred child tables. The database installation interface implements this inheritance structure and applies insertion and update rules on parent tables (Lienert *et al.*, 2010).

## 2.2 Customizing the Visual Reproduction of Flood Events

Once the database is set up and filled with the historical data, hydrologists are gathering their information by means of different tools on the cartographic user interface (selection of data layers, use of tooltips, display of time

series graphs, modification of map layout, switching of time points, controlling of animation). Maps are then generated according to the interactions made with these tools.

In the following, a procedure and connected cartographic visualizations are proposed to illustrate how to document and communicate the flooding in Switzerland during Ascension Day 1999. According to official statements (see FOEN, 2006), winter and spring 1999 were characterized by extraordinary snowfalls. The melting of the snow was contributing decisively to the streamflow, and thus to the floods. Antecedent conditions in April 1999 indicated that the soil moisture was high and soils were therefore already saturated, favoring fast surface runoff. By the end of April, a pronounced warm period set in.

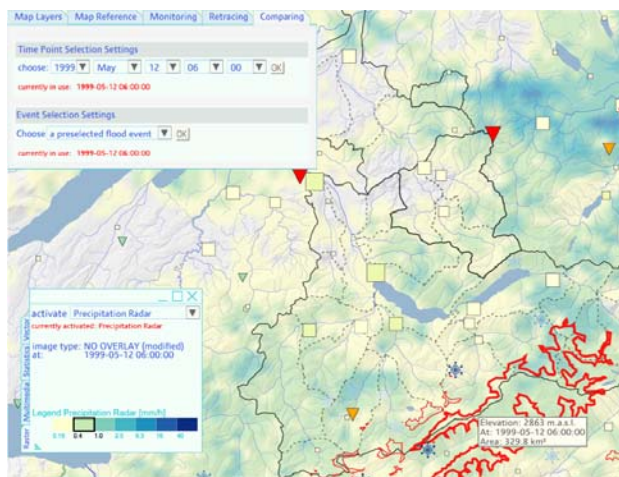


Figure 1. Map of 1999-05-12, at 6 a.m.

Maps are retrieved by choosing a historical date on the cartographic user interface (Figure 1, top left). Additional legend, graphical or tooltip information is displayed when map symbols are being moved over or clicked on. In the map shown in Figure 1, the snow cover situation (snowflakes symbols) and the antecedent soil moisture conditions (triangles) are shown in combination with the 0°-Celsius isotherm (red polylines), the precipitation radar (area symbolization on top of the relief), and the streamflow quantities (squares). Generally, the darker the colors, or the larger the sizes, of the map symbols are, the higher are the represented quantities.

Interplaying with each other, the mentioned visualized variables may intensify or attenuate flood processes. The altitude of the 0°-Celsius isotherm, for example, determines on what area precipitation falls in liquid or solid form, thus how fast precipitation may contribute to surface runoff. In the morning of May 12<sup>th</sup> 1999, the 0°-Celsius limit is at an altitude of 2863 meters a.s.l. (Figure 1). Since the hydrological basin under examination is mountainous, an area of more than 300 km<sup>2</sup> is above the freezing point. An

extensive precipitation field is situated over the basin, while snow depths amount to over 3.5 meters at some locations.

Due to the increase of air temperatures at noon time, the 0°-Celsius limit rises to over 3000 meters a.s.l.. As shown in the map in Figure 2, the area above that limit has decreased, meaning that precipitation in liquid form falls on a much larger area. The core of the precipitation cell has moved towards the east, but some local showers are still occurring. In order to explore the evolution of individual hydrological variables, time series graphs can be displayed in an auxiliary window. These graphs are automatically generated out of the database.

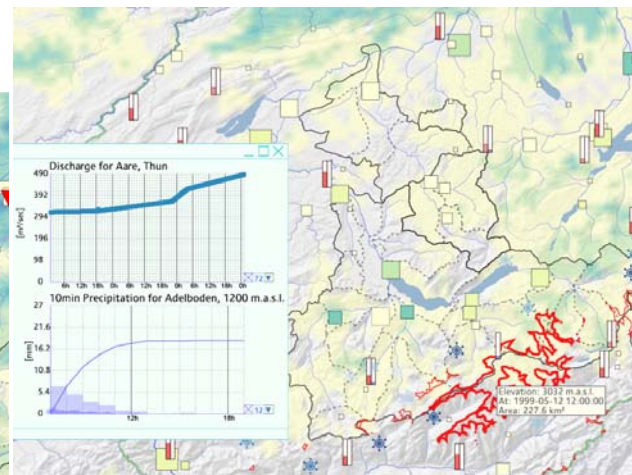


Figure 2. Map of 1999-05-12, at noon.

The center of the graphs shown in Figure 2 represents the time to which the map refers. The part left of the graph's center therefore shows how the variable has evolved, and the part right shows what course the variable will take. In the upper time series graphs, the streamflow at one gauge is shown. The 10 and 60 minutes precipitation amounts together with the cumulative curve over 24 hours are displayed in the lower graph. While the curve is stagnating at around 20 mm, the streamflow time series suggests that the peak is not yet reached.

The interplay between temperature and snow melt exacerbates the situation noticeably the next day, as shown in the map in Figure 3. The 0°-Celsius limit has moved up to above 3500 meters a.s.l. which implies that precipitation – on almost all areas in the hydrological basin – falls in liquid form and that snow melt itself is not only accelerating, but also most intensely contributing to runoff and streamflows.

In addition to the three framed rectangle symbols which represent temperature, air pressure, and air humidity, the map in Figure 3 also shows the overall temperature distribution which was each time interpolated from point gauges (Lienert *et al.*, 2009). The upper time series graphs in the auxiliary window markedly show that lake levels

have exceeded the officially defined damage threshold (red line in the graph). The lower time series graph indicates, for a snow gauge at an altitude of 2360 meters a.s.l., a melt rate of 10cm in 24 hours.

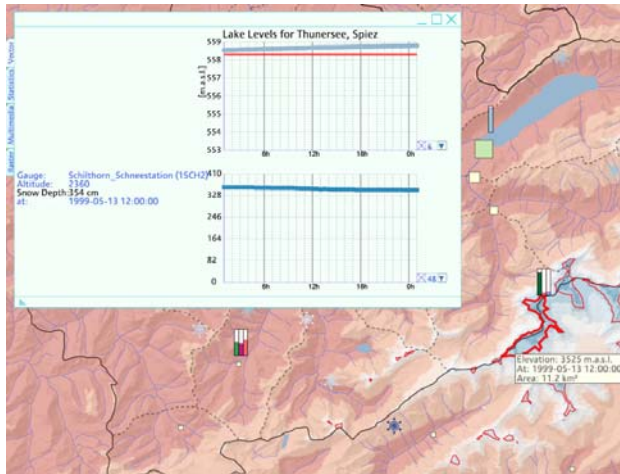


Figure 3. Map of 1999-05-13, at noon

When zooming on the cartographic interface, a bigger picture can be documented. One day later on May 14<sup>th</sup> 1999, it can be seen that the hourly precipitation sums (circles) are still high and that yet another precipitation front is moving from the west towards the Alps. Most of the lakes (framed rectangles) have already exceeded their critical levels. As shown in the time series graph, the river Aare in the Swiss Capital of Berne – with a streamflow quantity of over 500m<sup>3</sup>/sec – has yet not reached its peak.

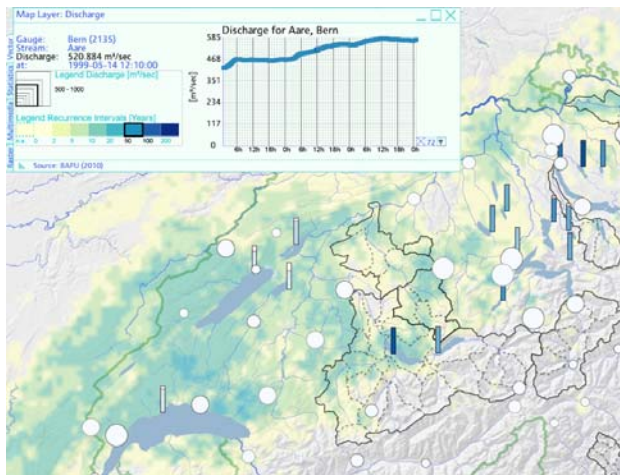


Figure 4. Map of 1999-05-14, at noon

This said peak is reached two days later on 16<sup>th</sup> of May, when observed streamflow amounts to over 600m<sup>3</sup>/sec. This quantity can be assigned a recurrence interval of over 200 years, meaning that such an observation value is very

rare. The Berne gauge is located in the center of the map in Figure 5. The connected time series graph and the legend are displayed in the auxiliary window.

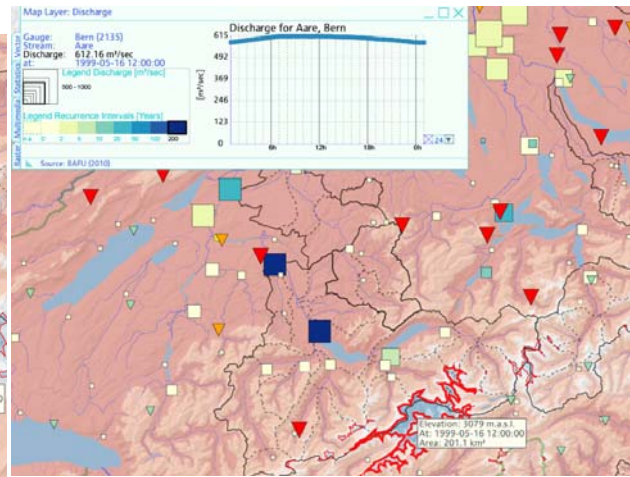


Figure 5. Map of 1999-05-16, at noon

Also displayed in the map in Figure 5 are the triangular soil moisture symbols. Most of them are large and marked red, indicating that soil moisture has reached alarmingly high values. Further precipitation is likely to run off at the surface since soils are saturated. Also, the 0°-Celsius limit remains high at around 3000 meters a.s.l. This indicates that the hydrological situation is still very critical as it remains vulnerable and susceptible to floods in case further precipitation falls. As a matter of fact, another flood had occurred in late May 1999, when large amounts of precipitation fell in a short space of time.

### 2.3 Animations to Gain Insights into Flood Processes

The maps shown above for documentation can be viewed as time slices on the time axis, representing one time point. They give some indication of the situation at that very moment. Temporal animation, in turn, may reveal even more of the spatiotemporal characteristics of floods. Animation is an established method in cartography. The innovative approach to animation in this work consists of three aspects: (1) users interact with the database and freely compile their data before the animation is released; (2) graphical elements in the auxiliary window are animated conjointly with the map; and (3) animations are automatically recorded in form of an established movie format.

At the beginning, the map animation approach is similar to retrieving single historical maps: a historical starting point is first chosen by the user; then the animation may be released for a sequence of 24, 48, or 72 hours on a navigation panel. In the cartographic user interface, animation controls are available. The automatic export from the interface in form of movies (a feature not yet fully automatic provided) aims at enhancing the exchange

and communication of results of post-flood analysis. Once the findings are internally approved by flood experts, the administration may use these movies as a communication instrument with the public. It may also be ideal for insurers, researchers, or professionals in the education sector to raise general awareness of floods and their consequences.

Available online at <http://reticah.ethz.ch/watch.php?v=R01>), the first animation highlights the spatial distribution and the response times of streamflow in a specific hydrological basin. For this purpose, a flow map was created in which the observed streamflow was interpolated and visualized as a proportional band along the river courses. The map is animated together with the time series graphs of three gauges, situated at the upper, middle and lower reach of the river. The spatiotemporal shift of the flood wave is nicely visible, both on the map and in the graphs. The band thickens at the location of the peak, therefore heading downstream. In the time series graph of the gauge located at the upper reach, the peak of the curve arrives first, followed by the graph of the middle and lower gauge.

Available online at <http://reticah.ethz.ch/watch.php?v=R02>), the second animation intends to reveal the large-scale spatiotemporal dynamics of the flooding, as it happened in August 2005 in Switzerland. For this purpose, national maps are required in order to display large scale precipitation flow patterns in combination with observations made at ground gauges. The animation shows – particularly from a meteorological perspective – much of what happened during the once-in-a-century flood between 21<sup>st</sup> and 24<sup>th</sup> of August 2005. The weather situation during these days was characterized by an extensive and enduring precipitation field over the Alps. Together with the radar image, a time series graph representing the 24 hours precipitation total at an alpine gauge in central Switzerland is animated. On the map, the totals are represented by a quantitative circle symbol. The larger and darker the circles, the greater the totals and the higher are the recurrence intervals for those totals. The severity of the August 2005 event becomes clearly evident in this animation, even only when precipitation data is visualized by time series graphs, plus area and point map symbols.

### 3. CONCLUSIONS

Well-structured historical data, interactive cartographic visualization, and additional data exploration tools have the potential to improve current flood management. Creating, and maintaining, a high-resolution spatiotemporal database is worth the effort, since such a database can be used by hydrologists – and other experts in the natural hazard management domain – as an extendable knowledge repository.

By offering a cartographic user interface to visualize historical data for documentation and communication

purposes, users are not exposed to technical or modeling procedures. Instead, they are provided with straightforward customization tools which interface them to the high-resolution spatiotemporal database. Through the generation of interactive, dynamic, and animated maps, the structured data in the database becomes useful information. When interactive functionalities allow experts conducting data analysis and exploration themselves, according to their own expertise, information becomes visualized knowledge which can be shared among experts and non-experts alike – over several decades.

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