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Hydrological models and datasets to support flood flow estimation at river-bridge intersections

Ganora D.[a]*, Evangelista G. [a], Mazzoglio P. [a], Claps P. [a]

[a]*Politecnico di Torino, corso Duca degli Abruzzi 24, 10129 Torino, Italy*

Abstract

A working group on the "Hydraulic Compatibility of Bridges" (sites.google.com/view/gii-ponti) has been recently established in the hydraulic engineering academic community aiming at reviewing methodologies, studying good practices, and suggesting guidelines for assessing the bridge hydraulic compatibility. In this initiative, a subgroup is focusing on the hydrological aspects as in Italy there are not standard procedures to estimate design flood values requested by the Italian technical standards of constructions (NTC 2018) over the whole country as, for example, in the UK where the Flood Estimation Handbook provides standard data and methods. Some models are available at the regional scale but are often based on not up-to-date data; moreover, while in large rivers flood discharge values, defined according to the European Flood Directive have been computed and mapped, in small river catchments they are not available.

In this context, the unit of Politecnico di Torino working on hydrology is going to release some country-wide hydrological datasets, including all the available official information on discharge and rainfall extremes updated to recent years, that can be used as a common reference for bridge analyses. These include high-resolution maps of extreme precipitation statistics, a database of flood flow extremes recorded at more than 600 river sections, and a catalogue of river catchments characteristics (morphology, climate, land use, etc).

Nation-wide datasets can support the application of standardized hydrological analyses, needed for flood hazard assessment, especially in small basins. Operational products will be made available within the PNRR RETURN project in order to be easily available and referable for any hydrological analysis in Italy.

* Corresponding author. Tel.: +39 011 090 5644.
E-mail address: daniele.ganora@polito.it

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1. Introduction

Hydraulic safety of bridges is a relevant issue as most of the bridges' collapses are due to hydraulic triggers. Failure can be related to different processes: excessive force on the bridge structure (with or without overtop); pier or abutment scour and bed erosion; damages to road embankments or protection elements due to channel migration. These processes can be enhanced by wood and debris accumulation on bridge deck and piers. Therefore, an adequate analysis of hydraulic forcings, both for design and verification, requires knowing several elements, in particular the hydraulic behavior of the river close to the bridge, i.e., water level and velocities, in order to evaluate direct forces on the structure and local scour effects, but also the hydraulic behavior of the river reach upstream the bridge. This second point is related to the evolution of the river geomorphology (both planimetric and vertical geometry) and strongly affects the direct and indirect erosion-based impacts.

To properly understand the hydraulic and morphological behavior of the river it is fundamental to study the hydrologic forcing and the subsequent hydraulic and morphological effects, other than possible wood and debris effects. Despite this complexity, the Italian technical standards of constructions (NTC2018) provide only basic rules to treat this issue; for this reason, a working group on the "Hydraulic Compatibility of Bridges" (sites.google.com/view/gii-ponti) has been recently established in the hydraulic engineering academic community aiming at reviewing methodologies, studying good practices, and suggesting guidelines for assessing the bridge hydraulic compatibility. In this initiative, a subgroup is focusing on the hydrological aspects as in Italy there are not standard procedures to estimate design flood values requested by NTC2018 over the whole country. This point is even more relevant after the Ministry of Infrastructures issued inspection guidelines (LLGG 2020) to perform a fast assessment of bridge risk and identify those requiring urgent actions.

2. Bridge inspection guidelines in Italy

Bridge inspection guidelines have been issued by the Italian Ministry of Infrastructures in 2019 and updated in 2020 and are developed to allow a quick evaluation of the risk associated to the bridge. As this evaluation is based on simplified indicators, which can be evaluated through inspections and analysis of available documentation, the "risk" is thus referred to as "class of attention". Guidelines are organized in sections regarding structural, seismic, landslide and hydraulic classes of attention. Here, we focus on the hydraulic part of the guidelines which requires to define the hazard level associated to:

- water level causing possible reduced freeboard or overtopping;
- erosion due to section reduction (changes in flow velocity);
- local scour (expected scour depth with respect to foundation base).

These indicators are then combined to obtain a unique hazard class. The vulnerability of the bridge is also evaluated for the three possible hazards and depends on simple indicators (basin area, presence of wood deposits, evidence of erosion, etc), while exposure depends on the level of service of the bridge and is not directly related to its hydraulic characteristics. Erosion and local scour hazards are evaluated using only geometric data of river and bridge, while the water level under flood conditions is more articulated: as the evaluation must be fast, it is not requested a full hydrological analysis, but the required data are expected to be easily obtained from available documentation. Unfortunately, this is not the case for many bridge-river intersections, especially for small river basins.

Official documentation of the River Basin Authority, compliant with the European Directive 2007/60/CE, can provide direct or indirect information about flood water elevation; typical data that can be obtained are reported in Table 1 for the case study of the Piemonte Region (Po River Basin Authority, Italy). However, there are many cases where such information is not available; in these cases, the guidelines suggest adopting one of the following methods:

- Flood hazard maps available:
  - No levee: joint use of flood maps + DTM
  - Levee: consider levee elevation + 20 cm
- No flood hazard maps available:
  - River with possible lateral expansion: consider bank elevation + 50 cm
  - River with no possible lateral expansion: evaluate max discharge + hydraulic model

Table 1. Method to evaluate flood water elevation: example for the Piemonte Region (Italy).

Type of data	Availability	Applicability to estimate water elev.
Maps of accurate water depth/elevation estimates	Currently only at some hot spots (main cities and high-risk areas)	Applicable as the water level is reported at the section of interest
Water elevation at different sections along the river	Available for major rivers	Depending on the proximity of the bridge to the section; bridge deck elevation may require topographic survey and not only quick evaluation
Use of hazard inundation maps	Major rivers and some minor rivers	Maps can be compared with high-resolution DTM and reliability of water elevation estimate strongly depends on the quality of topographic data

The latter case is the most critical as it requires to evaluate: i) the flood discharge for a return period of 200 years and ii) to compute the water elevation corresponding to the design discharge. Both the steps are expected to be done in a simplified way. The guidelines provide non-compulsory suggestions: i) the discharge can be evaluated with "commonly used" formulas from the literature and ii) water level can be estimated as the normal depth of the flow.

Focusing on point i), many empirical equations are available in hydrological handbooks, but with several disadvantages: first, they are usually derived as envelope curves or recorded floods, thus they are not probability-based; second, they are not up-to-date (some have been developed in the 1930's); finally, they are "valid" over very large areas and are not able to account for different catchment characteristics (area, elevation, land use, …). Moreover, such equations lead to very variable results, depending on the chosen parameterization.

Another option is to use regional models, which are statistically-based relations allowing to estimate the design flood discharge in ungauged basins (e.g., Laio et al, 2011), as for example the models included in the Italian "Va.Pi" initiative. This class of model is much more reliable than empirical equations, but usually the application in small and very small catchments is not recommended because they are calibrated mainly on large ones. Moreover, their use may require some non-standard GIS applications.

A further option and largely used approach for small catchments is the well-known rational formula (e.g., Maidment, 1992), that reads:

$$Q(T) = c \cdot ARF \cdot i(t_c, T) \cdot A \tag{1}$$

where c is the runoff coefficient that accounts for the permeability of the soil, ARF is the areal reduction factor that accounts for the extent of the precipitation event with respect to catchment size, i is the average intensity of precipitation for to the critical duration t_c, given the return period T, and A is the catchment area. The rational formula, widely used in the engineering practice, has been criticized due to the subjectivity of its parameters (in particular c and t_c, see e.g. Grimaldi et al., 2012) and for the strong assumption that the return period of discharge and precipitation are assumed equal. Despite this, it is a valid tool for this kind of fast assessment thanks to its ease of use that make comparable the results and thus allows to define priorities. Moreover, in contrast to the empirical curves like those of the "traditional" Italian formulae, the rational formula can represent the different characteristics of catchments.

3. Examples of application

Fourteen bridges with potential hydraulic risk (Table 2) have been recently investigated within the FABRE activities over the Piemonte region, their list and minimal information can be found in Table 2. The river catchments closed at the bridge sections are generally very small, with 6 catchments smaller than 10 km^2, 5 larger than 100 km^2 and only one larger than 1.000 km^2. As expected, only in two cases water elevation was directly available from official documents of the River Basin Authority, while in other 7 cases flood maps were available, but in some cases they were not useful for water level determination. Finally, in 6 cases flood discharge was calculated with the rational formula of eq. (1), and the water level computed under hypotheses of uniform flow with the Chezy equation.

Table 2. Summary of the bridges with hydraulic risk investigated in the Piemonte region and synthetic description of the methods used to evaluate the water level.

River	Road	City	Basin area (km^2)	Method used for water level estimation
Torrente Stura di Demonte	SS 28	Fossano	1320	Flood elevation available from River Basin Authority
Fiume Dora Riparia	SS 335	Oulx	258	Flood elevation available from River Basin Authority
Fiume Tanaro	SS 28	Nucetto	375	Flood hazard maps available but deep channel: Q from regional model + normal depth
Fiume Tanaro	SS 28	Ponte di Nava	149	Flood hazard maps NOT available: Q from regional model + normal depth
Torrente Dora di Bardonecchia	SS 335	Oulx	240	Flood hazard maps + DTM (5m)
Rio Predasso	SS 35	Cassano Spinola	25	Flood hazard maps + DTM (5m) + CTR
Rio Castellania	SS 35	Villavernia	20.2	Flood hazard maps + levee elevation
Torrente Branzola	SS 704	Mondovì	6.3	NO flood hazard maps available (river bank elev. + 50 cm)
Torrente Branzola	SS 704	Mondovì	3.8	NO flood hazard maps available (river bank elev. + 50 cm)
Naviglio di Bra	SS 702	Bra	4.5 approx.	flood hazard maps available BUT not clearly related to the river (river bank elev. + 50 cm)
Rio Gironda	SS 24	Salbertrand	3.8	Q from rational formula + normal depth. Flood hazard maps available but not useful as over the whole alluvial fan
Rio Perilleux	SS 335	Oulx - Reyeres	3.7	Q from rational formula + normal depth. Flood hazard maps available but not useful as over the whole alluvial fan
Rio Merieto	SS 35	Cassano Spinola	3.5	Q from rational formula + normal depth. Flood hazard maps NOT available
Diversion of torrente Ossona	SS 35	Tortona	33	Q from rational formula + normal depth. Diversion channel without flow control gates

We report in Figure 1 one example, referred to the rio Gironda catchment, whose perimeter has been extracted with commonly available GIS procedures (in this case with QGIS-GRASS commands “r.watershed” and “r.water.outlet”). The GIS allows to compute simple catchment characteristics (area, river slope) that can be used to characterize t_c and c, although with significant uncertainty. In this application the Ventura’s formula (Rossi and Salvi, 2007) has been used to calculate $t_c = 0.127\sqrt{A/i}$ (with A being the catchment area and i the average river slope). Note that common equations (Evangelista et al., 2023) for t_c calculations account for catchment area, slope of the river/watershed, drainage path length, etc., thus allowing to differentiate between fast-responding basins (e.g., steep mountain environments) from slow-responding ones (e.g., smooth hilly areas). The runoff coefficient c was assumed equal to 1 for mountain basins and 0.8 for low-elevation ones. Yet, the most robust information is the precipitation intensity that can be easily calculated from the intensity-duration-frequency (IDF) functions, nowadays commonly available in many regions. In the example of Figure 1, panel b, the web-gis portal of the ARPA Piemonte (regional environmental agency of Piemonte) provides the IDF parameters over the whole regional territory with a 250 m grid.

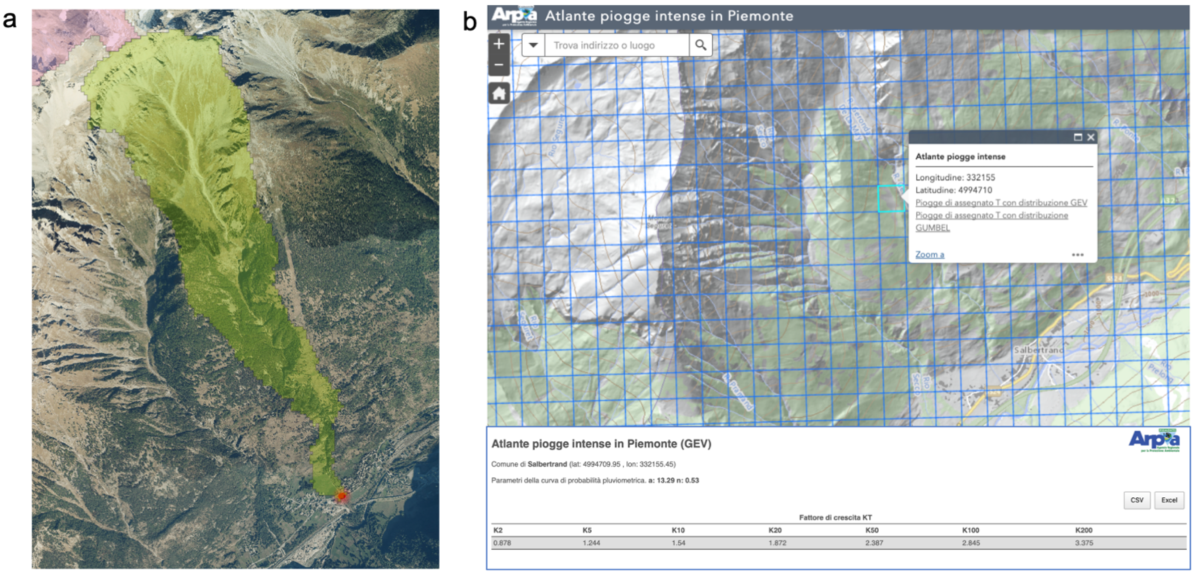

Fig. 1. (a) catchment area obtained from DTM processing; (b) a map of extreme precipitation parameters available through a Web-GIS portal.

4. New opportunities for Italian hydrological datasets

Application of systematic hydrological analyses at the national level as for instance, but not limited to, bridge analysis requires a common base of hydrological information. In Italy, the collection and management of hydrological data has been carried out at the national level by the National Hydrological Service (SIMN) up to about 40 years ago. The dismantling of the SIMN resulted in the transfer of data collection and management tasks to the regional level, i.e., to the agencies of 19 regions and 2 autonomous provinces. Once the regional services had been set up, the local authorities adopted different policies for distributing the data. This extreme data fragmentation, combined with a complex data policy, has always resulted in difficulties in performing national-scale studies.

This situation does not facilitate the implementation of standard procedures at the national level based on accurate and accessible data. In this direction, the authors of this paper recently developed country-wide hydrological dataset that can be used to support systematic hydrological investigations. Datasets are currently partially available, but will become of full public domain within the framework of the PNRR RETURN (Multi- Risk sciEnce for resilienT commUnities underR a changiNg climate) project (https://www.fondazionereturn.it); they are described in the following sections.

4.1. Maps of extreme precipitation statistics

To ensure the availability of comprehensive and consistent data of extreme precipitation across the entire country, the Improved Italian - Rainfall Extreme Dataset (I^2-RED) has recently been established, aiming to facilitate studies with a uniform dataset on a national scale (Mazzoglio et al., 2020). Covering annual maxima rainfall depths registered over 1, 3, 6, 12, and 24 consecutive hours from 1916 up to the present, the database incorporates data from more than 5000 rain gauges.

The dataset was used to obtain updated maps at the national scale related to rainfall statistics and parameters of the IDF (Intensity-Duration-Frequency) curves in the form:

$$h_{d,T} = a \cdot d^n \cdot K_T \tag{1}$$

where $a \cdot d^n$ is the average IDF and K_T is the growth factor (i.e., a dimensionless probability distribution) that represents the dependence with the return period T (Claps et al., 2022). Statistics of rainfall extremes were computed at-station and then interpolated at 250 m resolution with the autokrige R function (Hiemstra and Skoien, 2023). In this application, we used an automatic ordinary kriging that accounts for the variogram that better fits the data, automatically generated by the autofitVariogram R function. More specifically, the rainfall statistics that we provide are:

- the scale factor a and the scaling exponent n, calculated on time series with at least 10 years of data;
- the coefficient of L-variation (or L-CV), calculated on time series with at least 20 years of data;
- the coefficient of L-skewness (or L-CA), calculated on time series with at least 30 years of data.

The L-CV and L-CA represent the variability and skewness of the sample according to the L-moments theory (Hosking and Wallis, 1997) and are defined as the average value of those obtained from the 1- to 24-hour durations. L-CV and L-CA can be used to compute several probability distribution functions (e.g., Gumbel, GEV, lognormal, etc.) to relate the precipitation for a given duration to the return period.

These maps represent the first attempt to reconstruct updated information related to rainfall extremes over the entire Italy, following what has been released e.g. in Switzerland (i.e., the Hydrological Atlas of Switzerland, available at https://hydrologicalatlas.ch/), Austria (i.e., the Hydrological Atlas of Austria), Germany (i.e., the KOSTRA-DWD, or "Coordinated heavy precipitation regionalization and evaluation of the DWD", available on https://www.dwd.de/DE/leistungen/kostra_dwd_rasterwerte/kostra_dwd_rasterwerte.html).

4.2. River flow extremes database

A systematic collection of country-wide flood flow data has been released as "Catalogo delle Piene dei Corsi d'acqua Italiani" (Claps et al., 2020a, 2020b, 2020c) and currently under updating and extension, including 631 Italian catchments for which historical time series of peak flows and/or maximum daily flows are available. This catalogue provides a comprehensive overview of what has been collected by the SIMN since the 1920s and formerly included in the CUBIST project database (Claps et al., 2008). Until the 1970s the data largely reflect what was reported in the Publications n°17 of the SIMN. In the following years, the data were collected by regional services; also, entities managing dams and hydropower plants provided observations recorded at their stations.

This information was collected from the different sources, carefully revised and republished systematically by the research unit of the Politecnico di Torino with the collaboration of several Italian universities and the support of regional environmental agencies and river basin authorities.

4.3. Catalogue of river catchments characteristics

In recent years, several national databases of hydrological information and geomorphoclimatic catchment attributes have been established all over the world, such as the CAMELS datasets developed for the United Kingdom, Switzerland, France, Germany, the United States, Australia, Chile and Brazil (now integrated in Caravan) and LamaH-CE. In Italy, the FOCA (Italian FlOod and Catchment Atlas; Claps et al., 2023) dataset represents a systematic collection of data that integrates the hydrometric information of the Italian flood catalog (see sect. 3.2) with a comprehensive set of more than 100 descriptors related to geomorphology, soil and land cover, vegetation indexes, climate and extreme precipitation. These descriptors have been calculated using sources that meet the following three criteria: i) national spatial coverage; ii) absence of regional or local bias; iii) adequate spatial resolution. For each variable, the best available dataset was selected, giving priority to local information and relying on global data only in a few cases.

One of the strengths of FOCA, compared to several other national datasets, is the inclusion of a rich set of quality-controlled geomorphological descriptors. The second relevant aspect is the inclusion of extreme precipitation characteristics calculated using station data rather than reanalysis data, an approach often used in the development of CAMELS datasets. In particular, maps described in sect. 3.1 were used to compute the precipitation statistics at the catchment scale.

5. Conclusions

Methods to perform a fast but reliable assessment of discharge to study bridge safety (but also for other design and verification purposes) at the national level should rely on a robust and up-to-date set of hydrological data. This is even more relevant for small catchments; in fact, most of the Italian bridges are located in small catchments (Ballio (2023) estimates ~50% of the bridges have catchments of 10 km^2 or less), but on the other hand small catchments are less represented in databases of observations. Simple models like the rational formula or other rainfall-runoff models can be used to this aim, but should be based on standardized dataset in order to:

- make fast assessment easy to apply, with minimal GIS operations;
- make applications standardized and comparable;
- use up-to-data hydrological data;
- be able to represent the variability of basin characteristics.

Three hydrological datasets have been recently developed in this perspective to provide maps of extreme precipitation parameters, discharge data, and catchment characteristics. Operational products will be made available soon within the PNRR RETURN project in order to be easily available and referable for any hydrological analysis in Italy.

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