Integrated Flood Studies in Sicily: An Hydro-Geomorphological Approach

Silvia Di Francesco
Unicusano: Universita degli Studi Niccolo Cusano
martina carlino (martinacarlino1991@gmail.com)
Unicusano: Universita degli Studi Niccolo Cusano https://orcid.org/0000-0003-0038-3059

Research Article

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INTEGRATED FLOOD STUDIES IN SICILY: AN HYDRO-GEOMORPHOLOGICAL APPROACH

Silvia Di Francesco[1], Martina Carlino[1*]

[1]Niccolò Cusano University, Via Don Carlo Gnocchi 3, 00166 Rome

*Correspondence: martinacarlino1991@gmail.com

Abstract

The present study originates from the need to investigate and monitor rivers in order to manage and mitigate fluvial dynamics and prevent flood adverse effects. The aim is to develop an integrated flood risk management procedure that properly incorporates safety and quality issues, in accordance respectively with Flood Directive and Water Framework Directive (WFD). Flood inundation models (2-D) were used to develop flood inundation maps that takes into account uncertainty related to modeling process and hazards related to channel dynamics were investigated. Two survey and classification tools, recently developed in the IDRAIM methodology, were tested: the

Morphological Dynamics Index (MDI) and the Event's Dynamics Classification (*EDC*). These latter tools are required for integrating the standard hydraulic analyses used for flood mapping and, therefore, for obtaining an overall more robust and reliable flood risk assessment.

Hydraulic simulations and applications of morphological indexes were applied on two different rivers located in Sicily: a highly controlled river, Arena river, and a more dynamic gravel-bed river, Tempio river. Specifically, the indexes were used to identify portions of river interested by morphologic variability. Based on obtained results, interventions addressed to mitigate fluvial dynamics and prevent flood adverse effects were designed.

Keywords: Channel dynamics, Flood, Mitigation, IDRAIM

1 Introduction

The coming decades are likely to see a higher flood risk in Europe and greater economic damage: severe floods with devastating effects happen every year, and such flood events are likely to become more frequent with climate change. Reducing human casualties and damage to economic activity and the environment are key objectives shared by all EU countries; the implementation of the 2007 Floods Directive [1] has an important role in making this happen.

According to Floods Directive (FD), for inland waters as well as all coastal waters across the whole territory of the EU, flooding assessment must be carried out in order to identify the river basins and associated coastal areas at risk of flooding.

For such zones, flood risk maps must be produced and flood risk management plans focused on prevention and protection must be established.

Traditional measures to reduce negative impacts of floods include constructing new or reinforcing existing flood defense-infrastructure such as dykes and dams. There are, however, other and potentially very cost-effective ways of achieving flood protection which profit from nature's own capacity to absorb excess waters.

EU environmental legislation asks for the evaluation of better, feasible environmental options to the proposed structural changes to rivers, lakes and coasts, if these changes could lead to a deterioration of the status of these waters.

The EU Water Framework Directive (WFD) [2], Habitats Directive [3], Environmental Impact Assessment (EIA) and Strategic Environmental Assessment Directive (SEA) [4] set out such requirements, and strive to balance maintaining human needs whilst protecting the environment with the ultimate goal of achieving a sustainable approach to water management.

As a consequence, flood risk management must go hand in hand with nature protection and restoration, and deliver benefits for both people and nature.

During recent decades, increasing effort has been dedicated to the development of conceptual frameworks and methodologies aimed at supporting river management by introducing the use of fluvial geomorphology as a key component, and integrating geo-morphological tools in ecological studies and river engineering applications.

Existing frameworks based on a geo-morphological approach [5] [6] are primarily focused on river restoration objectives, while there is a lack of integrated methodologies including explicit consideration of both river quality and fluvial hazards [7] [8].

In Italy the National Institute for Environmental Protection and Research (ISPRA) promoted the development of a methodological framework IDRAIM [9] that aims to support the management of geo-morphological processes, in order to integrate both WFD and FD objectives and promote effective river management by considering several aspects and priorities (i.e. flood risk, environmental quality, natural resources, societal needs).

A specific goal of IDRAIM was the development of tools required for a harmonized implementation of the two Directives, including a method for morphological quality assessment [10] and additional tools to assess fluvial dynamics and their related hazards. These latter tools are required for integrating the standard hydraulic analyses used for flood mapping and, therefore, for obtaining an overall more robust and reliable flood risk assessment.

IDRAIM tools, the Morphological Dynamics Index (MDI) and the Event's Dynamics Classification (*EDC*), based on indicators examining rivers processes and primary attributes, protection structures, morphological variations and channel obstruction probability, were used in this study to assess fluvial dynamics and their related hazards for two different rivers located in Sicily: a highly controlled river, Arena river, and a more dynamic gravel-bed river, Tempio river.

Obtained results for these indexes helped in identifying river reaches that calls for restoration and interventions in order to mitigate hydraulic risk.

2 Materials and Methods

The integrated flood assessment procedure, was operationally composed of the following phases:

- Watercourse geo-morphological characterization.

- Watercourse Hydraulic characterization and flood mapping
- Assessment of fluvial dynamics and related hazards
- Existing structures' safety level and stability verification/ New structures design

3 Watercourse Hydraulic Characterization and Flood Mapping

The Hydrologic Engineering Center's River Analysis System (HEC-RAS 5.0.7) [11] [12] widely applied for hydraulic modeling [13] [14] [15] was used in this work.

HEC-RAS 2-D uses shallow water equations [16], which describe the motion of water in terms of depth-averaged 2-D velocity and water depth in response to the forces of gravity and friction. These equations represent the conservation of mass and momentum in a plane.

The 2-D Diffusion Wave computational method solver [17] was used adopting an Implicit Finite Volume solution algorithm that allows for larger computational time steps than explicit solution methods and provides a greater degree of stability and robustness over traditional finite difference and finite element methodologies.

We performed sensitivity analyses and evaluated how different combinations of digital elevation model (DEM) resolution and Manning's roughness affect flood maps produced from 2-D hydraulic models [18] [19].

Uncertainty associated to digital elevation models (DEMs), grid size and shape, as well as roughness data was investigated [20] [21]:

- 2-D simulations were performed using 10 m to 0.5 m resolution DEMs.
- different grid shape and size were used: uniform, hexagonal and adaptive mesh.
- different land covers were assigned to the 2-D model: manning roughness values were assigned depending on soil use type.

For a fixed return period (T), flood inundation maps resulting from 2-D simulations were produced and compared with flood maps reported in Sicily region official Hydro-geological Asset Plan, P.A.I., [22] for the same return period. The goodness of fit was assessed by the measure of relative error and F-statistics.

Relative error (RE) gives an indication of how well the inundation obtained through different models compares with respect to the inundation area reported in P.A.I.

$$RE = \frac{|A_O - A_P|}{A_O} \tag{1}$$

The fact that the compared areas of the flood inundation are similar to each other does not necessarily mean that they are “geospatially similar”: for example, two flood inundations with exactly the same areas but with no overlapping portion will yield a relative error (RE) of 0.

The use of F-statistics, used to compare the geospatial similarity of the mapped area over various studies [23] can resolve this issue. Given a reference inundation area (A_O), a predicted flood inundation area (A_P) and the overlapping portion between the two flood inundations A_{OP}, F-statistics is defined as the ratio between overlapping area (A_{OP}) to the area of both flood inundation projected on the map. High F-statistics indicates the goodness of fit between simulations and observations.

In order to estimate the uncertainty associated to a certain parameter *j*, different models were developed by varying *j* parameter and keeping all other input data unchanged.

With reference to the investigated parameter *j*, a total number of N models having different values for *j* parameter was developed: the agreement of each model with respect to the reference model was evaluated through F statistics. For each *k*-model (*k*=1,2,3…N), varying *j* parameter, flood maps were produced. For each *i*- cell point inside the model domain, a binary response f_{ik} was assigned:

- f_{ik} = 1 if the cell is flooded
- f_{ik} = 0 if the cell is not flooded.

With reference to the investigated parameter j, the probability of the cell point *i* to be flooded $P_i^{flood,j}$, is worked out weighting the binary response (flooded/not flooded)

f_{ik} of each *k*-model developed by varying *j* parameter, through the Eq. 2:

$$P_i^{flood,j} = \frac{\sum_k^N f_{ik} \cdot F_k}{\sum_k^N F_k} \quad (2)$$

where F_k is F statistics for the *k*-model:

$$F_k = \left(\frac{A_{OP,k}}{A_O + A_{P,k} - A_{OP,k}}\right) \quad (3)$$

In Eq. 3, inundation area reported in P.A.I. [22] was chosen as reference inundation A_O, $A_{P,k}$ is flood inundation area predicted through each *k*-model, while $A_{OP,k}$ is the overlapping portion between reference inundation area and flood inundation area predicted through each *k*-model.

A part from uncertainties, the present work goes further the standard approach that does not consider hazards related to channel dynamics in flood mapping [24] [25].

At this aim, IDRAIM tools [10] are useful for river dynamics definition, together with movable bottom hydraulic models.

4 Morphological Evaluation and Analysis

The definition of the stream Morphological Quality Indexes lies in a wider methodological framework named IDRAIM [9] also aimed at a subsequent analysis of the causes and the monitoring of evolution trends, further to a classification of the present morphological state.

The general procedure of classification and monitoring is based, according to the WFD [1] requirements, on evaluating the deviation of present conditions from a given reference state [26]. The reference conditions for a river reach can be identified with the following: (a) dynamic equilibrium conditions; (b) absence of artificiality; (c) absence of significant adjustments of form, size and bed elevation in a time interval of the last decades. Evaluation of present conditions and future monitoring are based on an integrated approach, making a synergic use of the two main methodologies: field survey and interpretation and GIS analyses.

The overall procedure of morphological analysis (**Errore. L'origine riferimento non è stata trovata.**) includes:

- *Initial setting and classification*: the main physical aspects, configuration and network characteristics are identified, and a first river segmentation is carried out.

- *Evaluation of the current morphological conditions*: the morphological state of the river segment is evaluated in terms of functionality, artificiality and recent channel changes.
- *Monitoring*: for some segments, selected as representative, a series of parameters are measured to evaluate if the morphological quality of the stream remains unaltered or is changing.

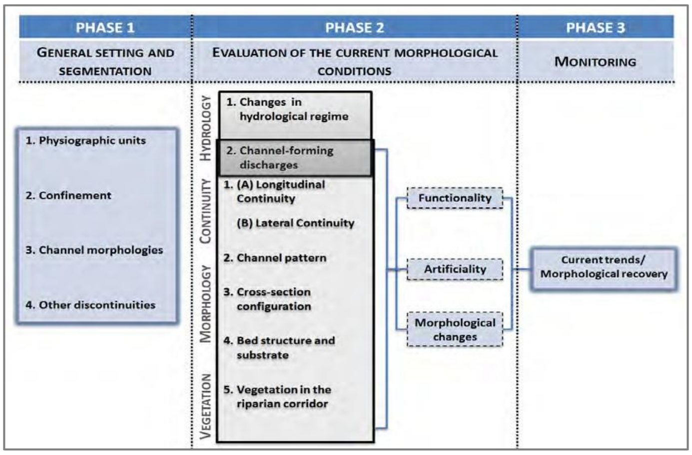

Fig. 1 General IDRAIM methodological framework.

In the morphological analysis, the entire river catchment was subdivided into physiographic units and river was divided into segments based on confinement class. For each river segment, historical and recent pictures were collected and compared to keep information regarding segment typical forms (e.g. fluvial islands, alluvional conoid, abandoned fluvial bed) as well as processes (e.g. bank retreat, lateral erosion) occurred during latest years (Fig. 2).

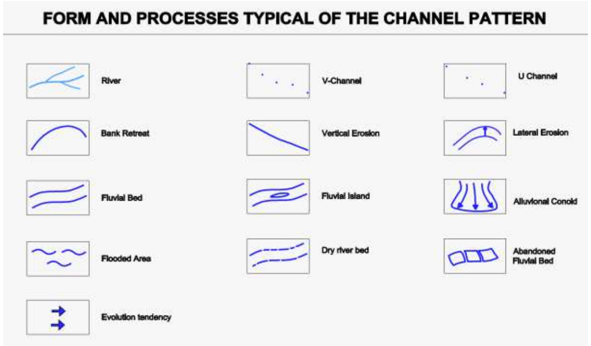

Fig. 2 Forms and processes typical of the channel pattern

A part from GIS tools, field surveys allowed recognition of on-going processes, such as vertical or lateral erosion, as well as collection of information regarding artificiality such as bank or bed protection, bridles, levees (refer to **Errore. L'origine riferimento non è stata trovata.** for symbols associated to each artificiality) to and their current status.

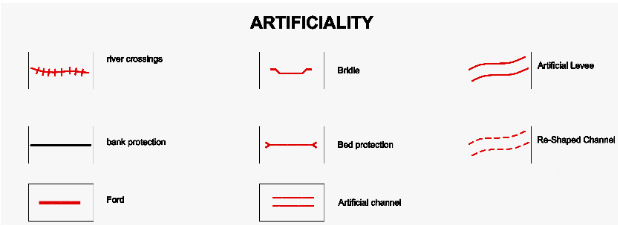

Fig. 3 River artificiality symbols

During on-site surveys, information regarding crossings occlusion status and presence of possible occlusion elements (comparing piles width and deck height with respect to wood material dimensions) and information regarding banks instability, as well as defense structure status and functionality were recorded.

In fact, not only a damaged structure could not play its defense role, but it also could induce serious risks for the surrounding area (for example in case of structure collapse). For all aforementioned reasons, hazard related to morphological processes should be properly evaluated.

In this work two IDRAIM [10] tools were tested: the Morphological Dynamics Index (MDI) and the Event’s Dynamics Classification (*EDC*). For the classification of both indexes two different forms [9], were used: the "Evaluation form of the morphological dynamics for semi-confined and non-confined river beds" for analyses related to MDI and the " Event Dynamics Evaluation sheet" for *EDC*. The Event Dynamics Evaluation sheet, is probably the most innovative part of the method, requiring information about the probability of occlusions occurring during a flood event never previously processed in the hydro-morphological field.

River subdivision into segments was necessary to concentrate the study on homogeneous areas from the point of view of various key parameters (**Errore. L'origine riferimento non è stata trovata.**), and the consequent investigations for the determination of the indicators used for determining *MDI* and *EDC* indexes on each segment.

For the GIS analysis, ArcGIS software version 10.5 developed by ESRI was used [27]. The cartographic data used include colour orthophotos and Regional Technical Map in 1: 5,000 scale and a 2m resolution DEM provided by Sicily regional Environment Department [28].

The MDI classifies the degree of channel dynamics related to progressive changes occurring over a relatively long-time scale, not including the possible answers to extreme flood events (which are addressed in the *EDC*).

MDI is highly recommended for alluvial unconfined or partly confined river reaches, but could also be applied to confined reaches if the necessary information is available. Three investigative areas are involved in MDI evaluation and a set of 11 indicators has been defined (**Errore. L'origine riferimento non è stata trovata.**):

- *Morphology and processes*, that concerns riverbed characteristics such as bottom, banks and takes into account current processes and evolutionary trends relative to the near past (last 10-15 years);
- *Artificiality,* that takes into account the defense structures involved in morphological dynamics processes;

• *Morphological variations*, that consider river variations over at least half a century, evaluated as indicators of instability.

The *EDC* is used to assess the most likely channel answers to extreme flood events (100 years return period, i.e. the most severe scenarios used in flood risk analysis according to the Floods Directive). The classification aims to assess the degree of expected change to channel boundaries that a given reach is likely to experience in response to geo-morphological processes (i.e., sediment and wood transport, mass failures) during an extreme event. The output of the classification can then be used to rank river segments into one of four classes of expected event dynamics (I: very high, II: high, III: medium, IV: low), based on the expected magnitude of morphological changes during extreme flood events, (e.g. bridge clogging by wood transport, channel avulsion by sudden bed aggradation) and to define consistent scenarios that should be analyzed further by hydrodynamic and/or morpho-dynamic modelling to predict more reliable flooding patterns. The assessment is carried out by combining two aspects: expected magnitude of morphological changes taking place during the event and clogging conditions at critical cross-sections (e.g., typically bridges) [10].

As presented, *MDI* and *EDC* tools provide information on the expected magnitude of channel dynamics in a given reach on a one-dimensional scale: this information was integrated with hydraulic analysis (2-D models) to define the areas of the fluvial corridor that will be affected by such dynamics.

Table 1 Morphological Dynamics Index (*MDI*): synthesis of indicators and assessed parameters

Indicators	**Assessed parameters**
Morphology and processes	
M1 Channel typology	Definition of channel pattern based on sinuosity, braiding, and anastomosing indices
M2 Bank erodibility	Type of banks (cohesive, non cohesive), percentage of protected banks and vegetation cover
M3B erodibility	Type of bed (alluvial, bedrock outcrops), percentage of bed revetments
M4 Bank erosion processes	Length of retreating banks and rate of retreat
M5 Channel width trend	Changes in channel width during the last 10–15 years
M6 Bed level trend	Bed level changes during the last 10–15 years
Artificiality	
A1 Bank protection	Length of protected banks
A2 Bed protection	Length of bed protected by revetments or ramps
Channel adjustments	
CA1 Adjustments in channel pattern	Changes in channel pattern from 1950s based on changes in sinuosity, braiding, anastomosing
CA2 Adjustments in channel width	Changes in channel width from 1950s
CA3 Bed level adjustments	Bed level changes over the last 100 years

5 Integrated flood assessment for a highly controlled river: Arena river case study

Arena river watershed (**Errore. L'origine riferimento non è stata trovata.**) is located in Trapani District, in the Western portion of Northern Sicily and covers a total area of 316 km^2.

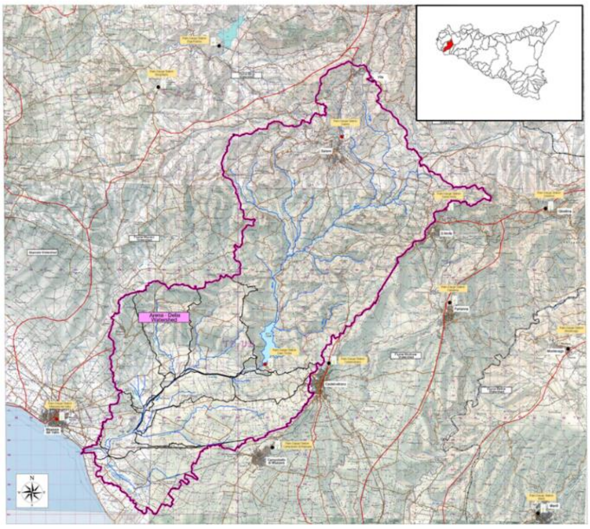

Fig. 4 Arena river's watershed location

The average altitude of the basin is equal to about 194 m, while the maximum is about 713 m. In the central portion of Arena river's watershed, an artificial reservoir was built in 1959, called Trinità Dam Reservoir, having 200 km^2 catchment area and 17.5 million of cubic capacity. The watercourse is called F. Grande in its upstream reach, F. Arena in the central and final reach. The main river, about 48 km long, has recessed meanders, with two distinct evolutionary maturity degrees: a more mature stage in the terminal part, after the dam, and a less mature stage upstream with respect to the Trinità Lake, where the river bottom is not calibrated at all. **Errore. L'origine riferimento non è stata trovata.** shows land use types and their percentage distribution within Arena River Basin, obtained from data extracted from the "Land Use Map" [29] created by the Regional Territory and Environment.

Table 2 Arena River Basin Land uses and cover percentage

Land	Citrus	Rocky	Mixed	Stain	Cultural	Olive	Simple	Urbanized	Vineyard	Wetlands
%	1.00	1.13	14.69	0.79	11.53	2.42	9.48	2.75	55.42	0.23

Arena River 2-D flow area (Fig. 5) was discretized into grid cells, where each cell uses the underlying terrain data (sub grid model): for each cell and cell face HEC-RAS generates a detailed hydraulic property table (such as elevation-volume relationship, elevation-area, etc.).

Based on given topography and resistance to the flow, that is controlled by land use type and associated Manning's coefficients, water can move to any direction among cells.

2-D boundary condition polylines (upstream inflow hydrograph and downstream n user-defined energy slope) were defined.

In order to study on 2-D model sensitivity to model terrain, different resolution DEMs were used, ranging from 10 m to 0.5 m resolution. For instance, by comparing terrain elevations extracted from 2 m and 0.5 m resolution DEM, differences in the range 0.1-1m are found, leading to difference in water surface elevation and depths (**Errore. L'origine riferimento non è stata trovata.**) in the range -1m up to 2.6 m.

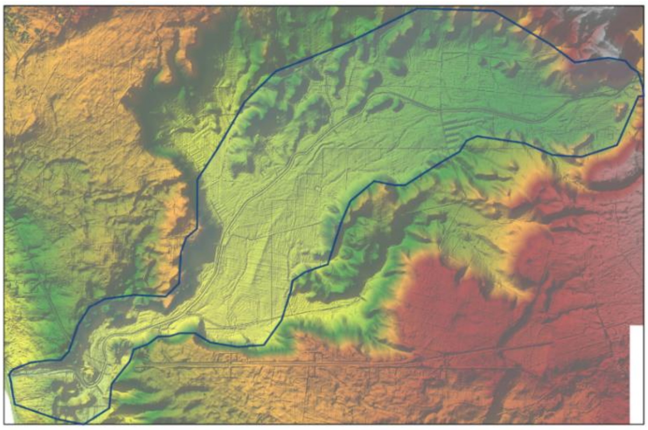

Fig. 5 Arena river 2-D Model Domain.

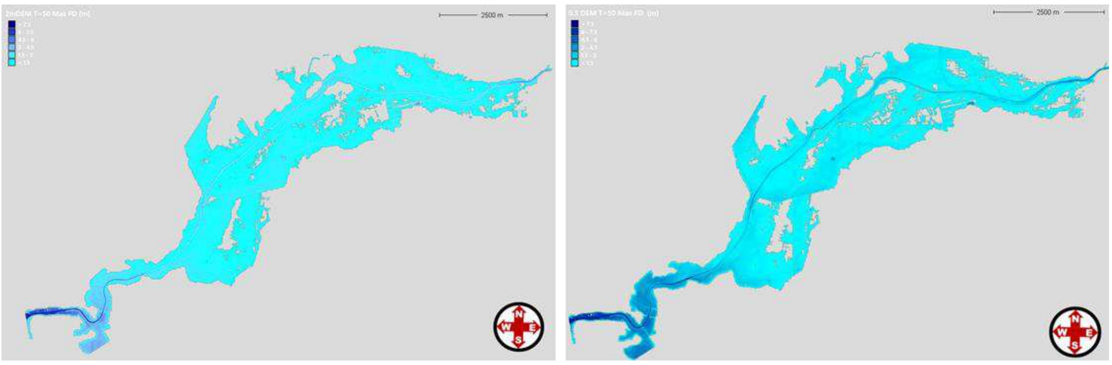

Fig. 6 DEM effect on Water depth (FD) maps: DEM 2(2 m resolution), DEM 0.5 (0.5 m resolution).

For a given return period T, flood inundation maps resulting from 2-D simulations ($A_{P,k}$), using 20 m, 2 m, 0.5 m DEMs, were tested against flood maps reported in P.A.I. (A_O), for the same return period.

With reference to T=50 years scenario, the relative error RE and F-statistics are reported at **Errore. L'origine riferimento non è stata trovata.**.

Table 3 RE and F-Statistics from 2-D Study for different DEMs

	A_O [km^2]	$A_{P,k}$ [km^2]	$A_{OP,k}$ [km^2]	RE [-]	F [-]
0.5 DEM	0.286	0.439	0.272	0.5	0.6
2 m DEM	0.286	0.396	0.267	0.4	0.6
20 m DEM	0.286	0.415	0.223	0.4	0.5

Moreover, in order to study on influence of grid shapes and sizes, uniform, hexagonal and adaptive mesh (4, 20, 50 and 100 m size), were used to simulate the same event (**Errore. L'origine riferimento non è stata trovata.**) .

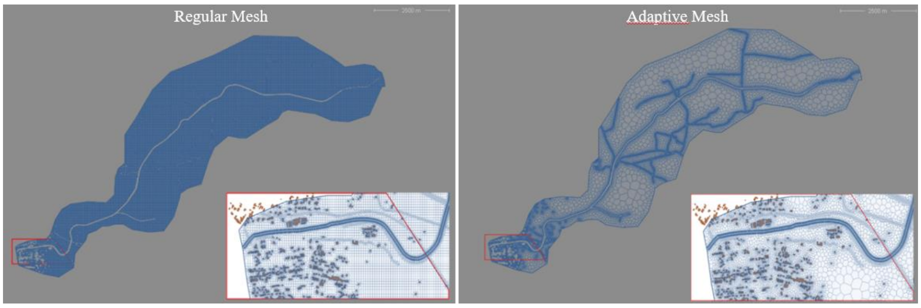

Fig. 7 Area River 2-D Flow area: Adaptive Mesh (left) and Regular Mesh (right)

Errore. L'origine riferimento non è stata trovata. shows maximum flood depth resulting from 2-D model with regular and adaptive mesh (both at 20 m size).

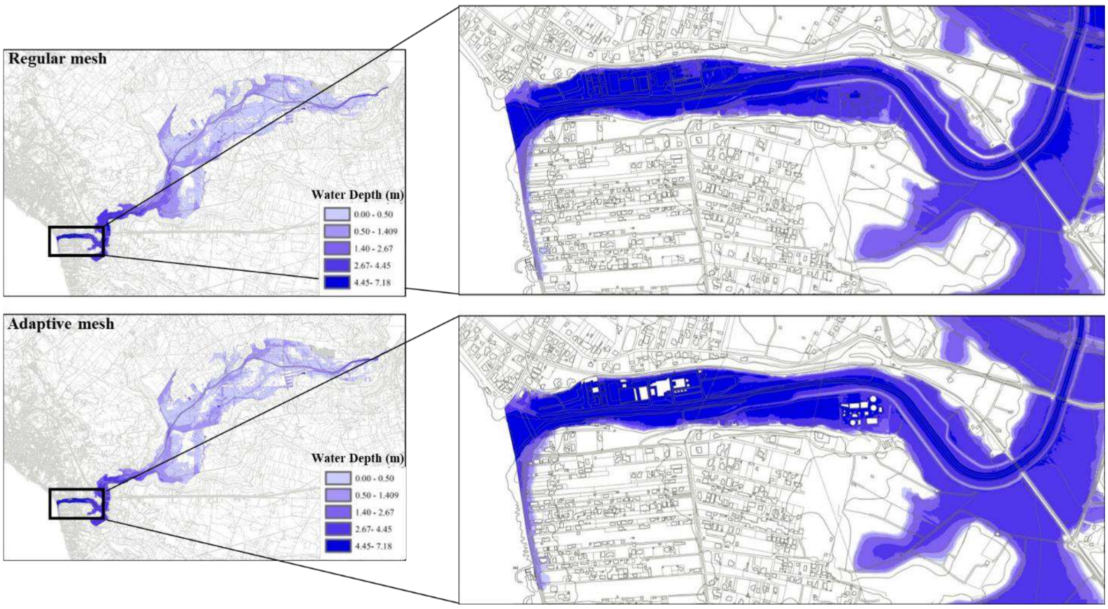

Fig. 8 Mesh Shape and Size effect on Water Depth maps.: Adaptive Mesh and Regular Mesh.

With reference to 50 years return period event (T), relative error RE and F-statistics is reported at **Errore. L'origine riferimento non è stata trovata.**.

Table 4 RE and F-Statistics from 2-D Study for different Grid Size and Shape

	AO [km^2]	$A_{P,k}$ [km^2]	$A_{OP,k}$ [km^2]	RE [-]	F [-]
Regular Mesh, 50 m	0.286	0.442	0.278	0.5	0.6
Regular Mesh, 40 m	0.286	0.455	0.276	0.6	0.6
Regular Mesh, 20 m	0.286	0.457	0.272	0.6	0.6
Regular Mesh, 10 m	0.286	0.625	0.261	1.2	0.4
Adaptive Mesh, 20 m	0.286	0.439	0.272	0.5	0.6

Finally, in order to investigate roughness data impact on flood maps, 3 different land covers were assigned to the 2-D model. Obtained results showed that flood extent as well as water depths resulting from 2-D simulations are not deeply impacted by roughness data.

5.1 Hazard Maps

Maximum flood depth maps obtained from the 2-D model was used to produce hazard maps: flood hazard levels were evaluated by crossing information related to return periods (T) and maximum flood depths spatial distribution (MFD) resulting from 2-D models (Fig. 9).

Local authorities tend to perceive hazard maps in an exact and deterministic way: probability is equal to 1 for flooded area and is equal to 0 for non-flooded areas. Nevertheless, hazard maps are deeply affected by uncertainties. Flood hazard maps should include all possible event scenarios, their associated probabilities, and corresponding return periods, as well as the associated uncertainties and potential damage resulting from them. To this aim, flood probability maps [29] [30] (**Errore. L'origine riferimento non è stata trovata.**) were derived, associating to each cell of the 2-D domain the probability of being flooded, with reference to investigated parameters. for fixed return periods (T=50,100,300 years): probability values were divided into 5 ranges: 0-0.2 (very low probability), 0.2-0.4 (low probability), 0.4-0.6 (medium probability), 0.6-0.8 (high probability), 0.8-1.0 (high probability).

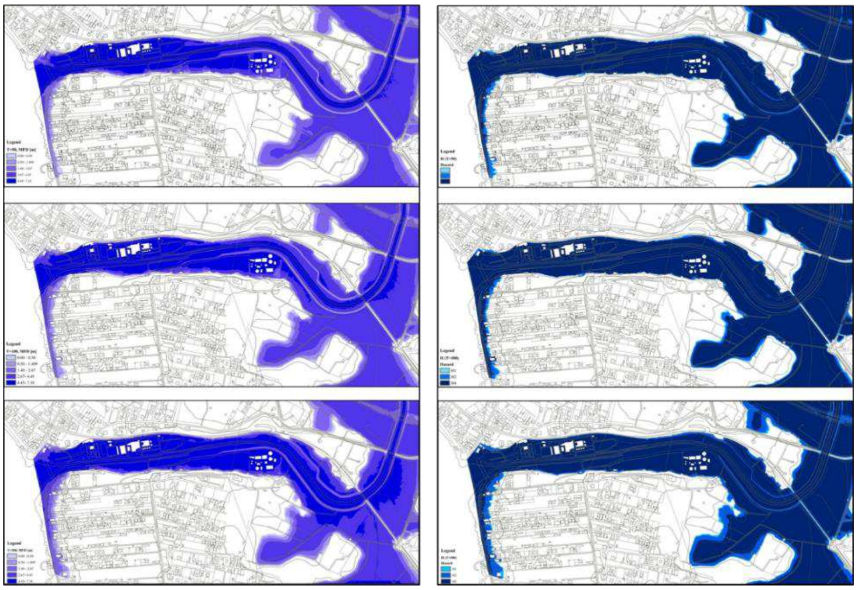

Fig. 9 Maximum Flood Depth Maps (left) and Hazard Maps (right) from 2-D Study

Even for 50 years return period rainfall event, some buildings located on Arena river right side (direction according to water flux), and located inside camping, present high probability to be flooded, while other buildings probability to be flooded is very low. Instead, with reference to 300 years return period events, all the buildings in camping have probability to be flooded (medium to very high), while buildings located in waste-water plant (Arena river’s right side) have low to medium probability to be flooded.

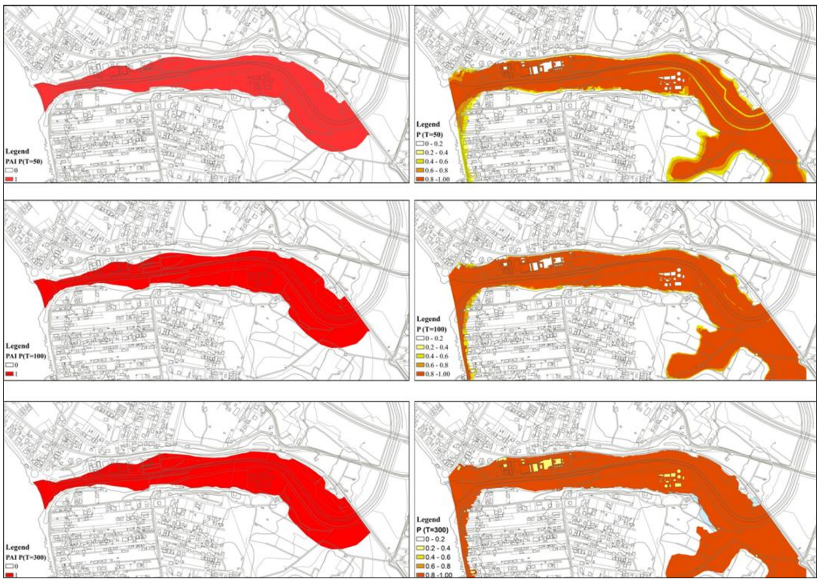

Fig. 10 Deterministic Flood Maps (Left Side) vs Probability Flood Maps (Right Side) for Return Period T=50,100 and 300 years

5.2 Assessment Of Morphological Channel Dynamics

A 2m resolution DEM was used for Arena river watershed and hydrographic network delineation [28], while land use data in the study-area were obtained from regional land use maps downloaded from the Region's website [29].

Arena river was divided into segments, which therefore represent the unit of application of *MDI* and CDE indexes. Calculation of indices, based on the evaluation of a series of indicators, took place partly in GIS environment and partly through data collection during site-surveys.

Indicator M1 was determined during river segmentation phase and is based on riverbed status recognition achieved through in situ surveys. For the calculation of indicator M2, available orthophotos over the last 15 years were analyzed [32], while judgment regarding bank nature was achieved through observation during situ surveys. Indicator M3 required in situ observations aimed at identifying factors that can determine resistance against river erosion, such as presence of artificial bottom coatings (e.g. thresholds), bed protections with rocks or armored bottom. Indicator M4 were chosen by comparing bank positions on aerial pictures dated 2000 with respect to bank position on the same pictures dated 2020. River average width (M5) was estimated on aerial pictures of different years 2000/2021. Site surveys in terms of sedimentary evidence, and of the height difference between the top of the riverbed bars and the top of the gravels outcropping in the floodplain were used for M6 indicator. A1 and A2 indicators are responsible for giving an estimate of river segment's artificiality.

The judgments assigned to indicators (**Errore. L'origine riferimento non è stata trovata.**) for each segment (S_1-S_7) are reported in **Errore. L'origine riferimento non è stata trovata.**, together with the value of *MDI* obtained for each segment. *MDI* values for all segments, as a result of the low-energy morphology, presence of bank protections, extent of artificial elements preventing vertical and lateral channel mobility, are very low, confirming that all segments are stable and/or characterized by strong planimetric and altimetric artificial control.

Table 5 Arena River Morphological Dynamics Index

		Arena river reach	**S_1**	**S_2**	**S_3**	**S_4**	**S_5**	**S_6**	**S_7**
Morphology and processes	M1	Channel typology	3	0	3	0	3	0	0
	M2	Bank Erodibility	8	0	0	8	8	0	0
	M3	Bed Erodibility	6	2	2	2	2	2	2
	M4	Bank erosion processes	2	0	2	0÷2	2	0	0
	M5	Channel Width Trend	0	0	0	0	0	0	0
	M6	Bed level trend	4	0÷4	4	4	4	0÷4	0÷4
	M5e	Channel Width Trend	0	0	0	0	0	0	0
	M6e	Bed level trend-induced	3	0÷3	3	0	3	0÷3	0÷3
Artificiality	A1	Bank Protection	0	8	12	0	0	8	8
	A2	Bed protection	15	8	0	0	15	8	8
Channel Adjustments	V1	Adjustment in channel	0	0÷3	0	0	0	0÷3	0÷3
	V2	Adjustment in channel	3	0	3	3	3	0	0
	V3	Bed Level Adjustment	3	0÷3	3	3	3	0÷3	0÷3
Morphological Dynamics Index (MDI)			0.44	0.22	0.2	0.2	0.25	0.22	0.17

Event Dynamics Classification Index (*EDC*) for each segment (S_1- S_7) is reported in **Errore. L'origine riferimento non è stata trovata.**. The *EDC* for segment S_1 results in class “high”, deriving from the combination of low expected morphological changes, due to the presence of crossing infrastructures within the segment and a “high” clogging probability.

In fact, within Arena River, among shrubs of Tamerici and different plants, Eucalyptus trees, even large, have been found, in some cases located inside river channel. Eucalyptus trees size in almost all river segments, some of them exceeding 20-25 m in height, pose serious problems linked to occlusion risks at bridge openings, especially during flood events when all the debris is conveyed into the water and drags trees.

The *EDC* for river segments S_3, S_5 and S_7 results in class “medium”, since even if low morphological changes are expected, the presence of big trees makes clogging probability high.

The *EDC* for river segments S_4 and S_6 results in class “low”, deriving from the combination of low expected morphological changes, and “low” clogging probability, due to absence of crossing infrastructures or absence of big trees.

Obtained results indicate that S_1 is the most critical segment for Arena river, while in other segments, even if not properly critical, interventions should be designed in order to increase flood safety.

Table 6 Arena river Event Dynamics Classification Index (*EDC*)

Arena river reach	**S_1**	**S_2**	**S_3**	**S_4**	**S_5**	**S_6**	**S_7**
Channel Dynamics	Medium	Medium	Low	Low	Low	Low	Low
Clogging probability	High	Low	High	Low	High	Low	High
Event Dynamics	High	Medium	Medium	Low	Medium	Low	Medium

5.3 River arrangement design

Once the problems and critical segments have been identified by using the set of assessment IDRAIM tools, a series of possible intervention scenarios was formulated.

Arena river segments’ morphological conditions are in general discrete, while hydraulic risk occur for almost all the segments, especially for segment S_1.

As resulting from 2-D flood models, for segment S_1 flooding probability is very high (**Errore. L'origine riferimento non è stata trovata.**), in addition IDRAIM tools suggest that the segment is a critical one due to high clogging probability.

Despite refurbishment interventions during the latest years, Arena river's terminal stretch demonstrated to be hydraulically insufficient to contain flows: the primary goal in this segment could not be improving the quality, even if attempt was made, but mitigate flood risk.

Arena river's insufficiency causes flood inundation and consequent hydraulic risk, especially for the waste-water plant, located on right over bank, and the numerous buildings located close to right banks.

In order to reduce flooding risk for this segment, it was considered appropriate to suggest the following interventions:

- cleaning and restoration of the hydraulic efficiency of all the gullies and gullies present in the lateral inlets abundantly covered with earthy materials and plant essences weeds such as brambles and intense reeds.
- deteriorated defense structures re-make or protection with gabions and cliffs,

intended as reshaping and arrangement of relocated lithoid material to protect against erosions banks,

- re-profiling and slopes re-efficiency,
- reed beds and bushes removal,
- individual trees cut-off.

These interventions are expected to increase segment S_1 flood safety while inevitable consequences on hydro-morphological quality do not compromise river status: this goal was achieved evaluating effects of suggested interventions through IDRAIM tools.

For the other segments, the following interventions were suggested:

- Cutting, removal and cleaning of the banks and active beds from the presence of bushes vegetation.
- Removal of bulky solid waste and tree trunks from river crossings
- Improvement and regularization of embankments and floodplains, with removal of material improperly deposited along river-bed.
- Deteriorated defense structures re-make or protection with gabions and cliffs, intended as reshaping and arrangement of relocated lithoid material to protect against erosions banks;

- Cleaning and restoration of the hydraulic efficiency of all the gullies and gullies present in the lateral inlets, abundantly covered with earthy materials and plant essences weeds such as brambles and intense reeds.
- High trees cut, organized so that to cause minor possible disturbance to the body water.

These interventions are expected to increase all segments' flood safety and disturbance to the body water will be reduced as much as possible.

6 Fluvial dynamics evaluation for a non-controlled river: Tempio river case Study

The procedure developed for Arena river fluvial dynamics evaluation, was adopted to a less controlled river located in Sicily, Tempio river (**Errore. L'origine riferimento non è stata trovata.**): this river falls inside Simeto Watershed and originates from Elsa stream and Margi stream confluence.

For river evolutionary trend identification, historical data (maps, pictures) of the area were consulted, in-situ surveys were conducted and riverbed sediment were collected and analyzed. Furthermore, movable bottom hydraulic modeling was performed, that allowed identification of river segments subject to deposition/erosion.

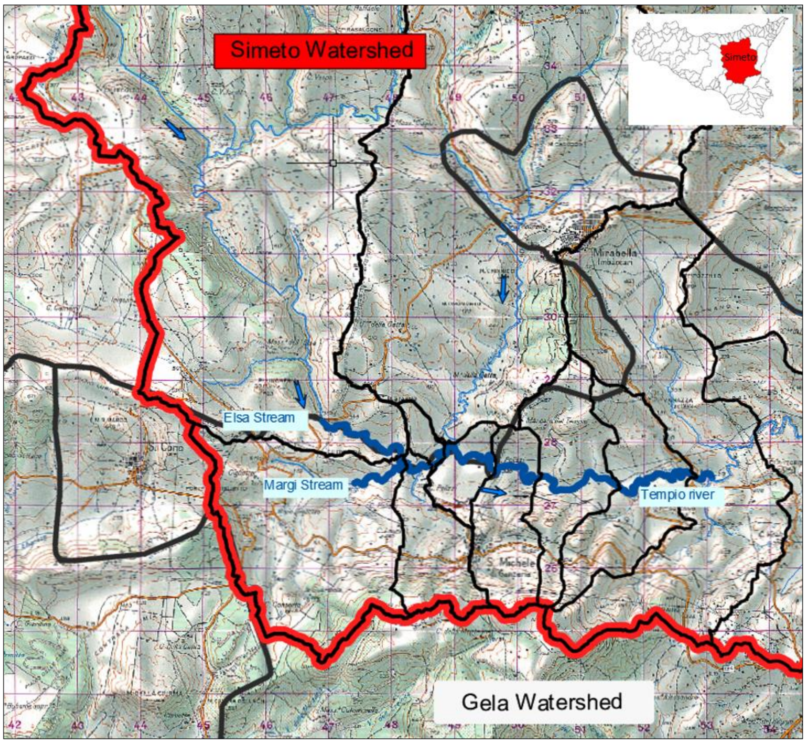

Fig. 11 Tempio river in Simeto Watershed

6.1 Assessment of morphological channel dynamics

A 2 m resolution DEM [28] was used in hill-shade display (simulation of solar radiation on a corrugated surface), which allowed a quick and intuitive identification of flat surfaces within the valleys and the limits of slopes and cones and on the CTRs, whose altitude data made it possible to detect differences in height that cannot be determined with the DEM but are still essential for the correct tracing of the limit of the plain.

For Tempio river subdivision phase, the following data were processed in GIS environment:

- Axis (or center line) of the riverbed: determined based on cartographic data.
- Altimetric profiles: obtained from a 2 m DEM (the only one available in this

processing phase

- Riverbed margins: obtained by digitization on orthophotos.
- Margins of the plain: the plain represents the surface made up of alluvial sediments that can potentially be affected, albeit occasionally, by one or both of the main types of geo-morphological processes that determine lateral continuity (erosion, flooding) [10].

As can be appreciated in Fig. 12, Margi stream (referred to as segment Ia) presents a sinuous course: since no sudden changes in slope or significant confluences were observed in this stream, no further subdivision was made.

For Elsa stream, whose name changes into Tempio river after Margi stream confluence, an initial subdivision into two segments was made based on morphological classification (a meandering segment (II) and a sinuous segment (III)). Due to the change in flow condition caused by Margi stream lateral inflow, meandering segment II was further divided into two parts: segment I before confluence and segment II from the confluence to the beginning of segment III (Fig. 12).

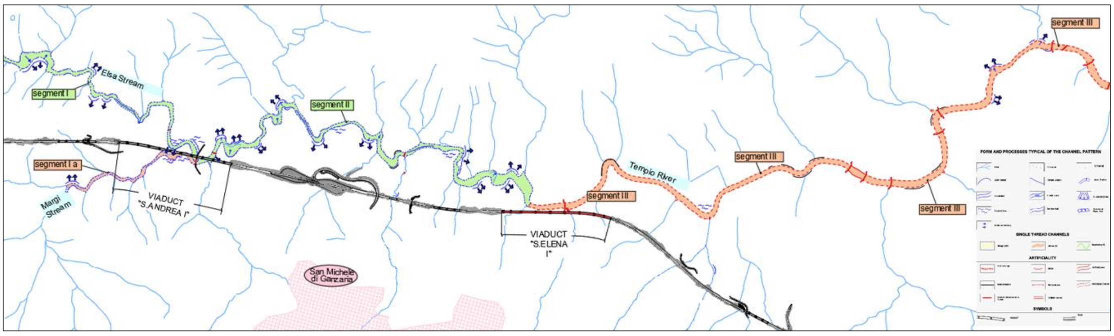

Fig. 12 Tempio river subdivision into segments.

Once watercourse subdivision into segments was completed (Fig. 12), the indicators for the calculation of the River Dynamics Index (*MDI*) were applied.

Particular attention was paid to the analysis of river segments interfering, or going parallel to roadways and/or railways.

Viaduct S. Andrea I's piles P.2, P.3, P.4, P.5, P.6 are located nearby Margi and Elsa river confluence (refer to View 1 in Fig.13), being the confluence identified as flooded area, while other Viaduct piles P.7, P.8, P.9 and P.10 are located outside flooded area.

Foe Viaduct S. Elena I (refer to View 2 in Fig. 13), that goes parallel to segment III, all Viaduct piles are close with respect to river segment, but the area was not recognized ad flooded area

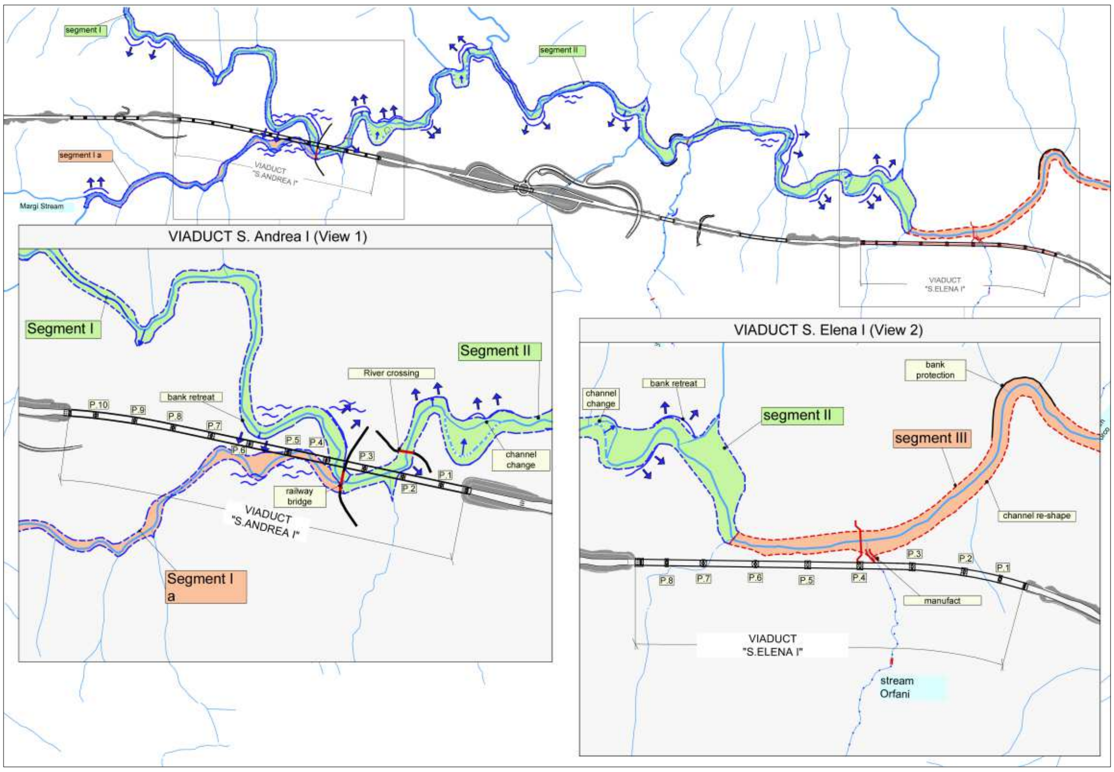

Fig. 13 River crossings: Viaduct S. Andrea (view 1) and Viaduct S. Elena (view 2).

Along segment I, banks retreat occurred in many points; consultation of photos of latest 50 years confirm segment I trend to migrate mainly towards the south. Close to confluence between Elsa river and with Margi stream, there is a floodable area.

Indicators developed through digital processing are M1, M4, M5 with regards to morphology and processes, V1, V2 for morphological variations. Indicator M1 (river bed type) was determined during river segmentation phase and is based on riverbed status recognition achieved through in situ surveys.

M2 indicator, related to river banks erodibility, was estimated through available orthophotos over the last 15 years; judgment regarding bank nature (non-cohesive or composite banks, consisting mainly of gravel and sands or cohesive banks, entirely constituted from silt / clay) was achieved through observation during situ surveys.

Indicator M3, related to river bottom erodibility, required in situ observations aimed at identifying factors that can determine resistance against river erosion, such as presence of artificial bottom coatings (e.g. thresholds), bed protections with rocks or armored bottom.

Furthermore, for river bottom erodibility evaluation, a movable-bottom hydraulic model was used and judgment regarding bottom erodibility was given based on results of solid transportation analysis.

Indicator M4 (banks withdrawal processes), was evaòuated by comparing bank positions on aerial pictures dated 2000 with respect to bank position on the same pictures dated 2020.

For indicator M5 (width trends), river average width was estimated through measurements on aerial pictures of different years 2000/2021 (Fig. 14).

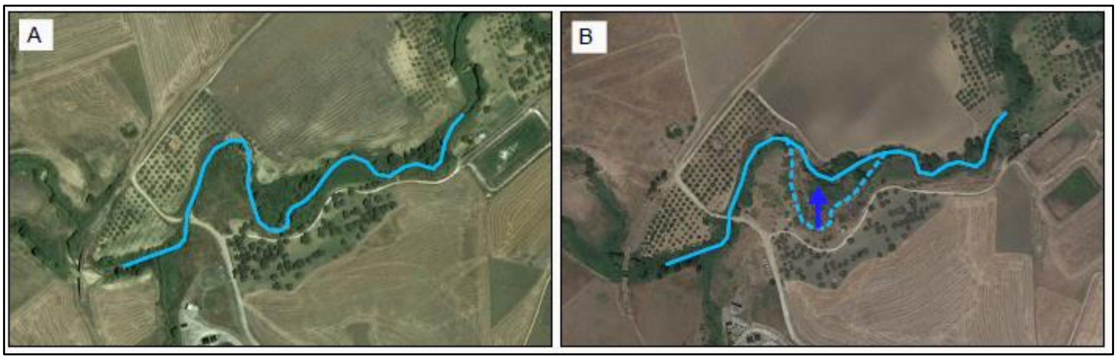

Fig. 14 Changes in channel pattern (A-Year 2005; B-Actual)

Answers to be assigned to artificiality indicators (A1, A2) were chosen during in situ surveys, considering all those structures that perform a certain function of protection to river banks and bottom.

For indicator related to river bottom erodibility, in situ observations can help in identifying factors that can determine resistance against river erosion, such as presence of artificial bottom coatings (e.g. thresholds), bed protections with rocks or armored bottom.

For river bottom erodibility evaluation at each segment, a movable-bottom hydraulic model was used and judgment regarding bottom erodibility was given based on results of solid transportation analysis. For the purpose of interpreting the average riverbed variations obtained through numerical simulations, the classification shown in Table 7 was adopted, which represents the cases of incision, stability and elevation.

Table 7 Channel Invert Change Classification

from [m]	to [m]	Channel Invert Change
0.50	1.50	Moderate deposition
-0.50	0.50	Stability
-0.50	-1.50	Moderate erosion
-1.50	-2.50	High Erosion
-2.50	-3.50	Very High Erosion

For Segment I, the morphological dynamics class resulting from the application of the IDRAIM methodology is average (*MDI* = 0.59). Proceeding from upstream to downstream, segment I present equilibrium conditions (variations in bottom elevations in the range -0.3 m +0.2 m) for about 800 m, and toggles moderate sedimentation and incision (bottom erosion in the range 0.3 - 0.7 m) in the central part of the segment. In the final segment portion, equilibrium conditions are recorded for approximately 150 m, with variations in the bed elevation less than 0.01 m (Fig. 15).

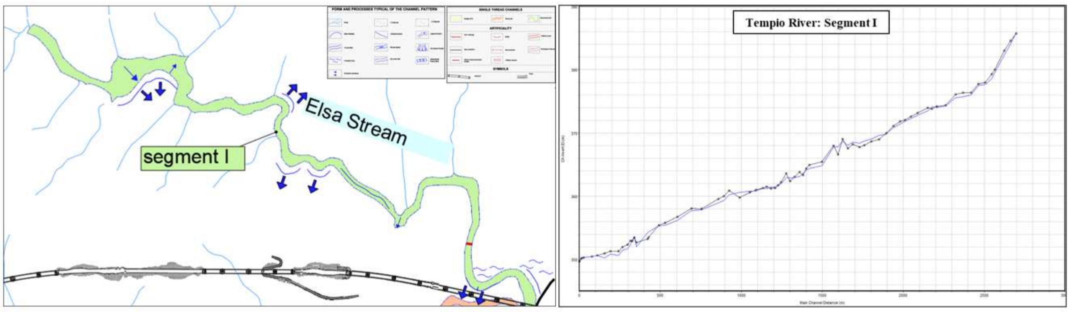

Fig. 15 River Segment I dynamics evaluation

Segment II, shows a meandering trend, with strong lateral erosion at curves, as well as meander jumps of both natural and artificial type and river migration both on north and south direction over the years. During site-surveys, it was found that many bank protection interventions have been realized along the segment, in order to contain river migration. Proceeding from upstream to downstream, segment II trend is incision (bottom erosion in the range 0.2-0.7m), and toggles moderate sedimentation (Fig. 16). For Segment II, the morphological dynamics class resulting from the application of the IDRAIM methodology is average (*IDM* = 0.54): this is confirmed by available orthophotos of different years (Fig. 17), showing segment II fluvial dynamics.

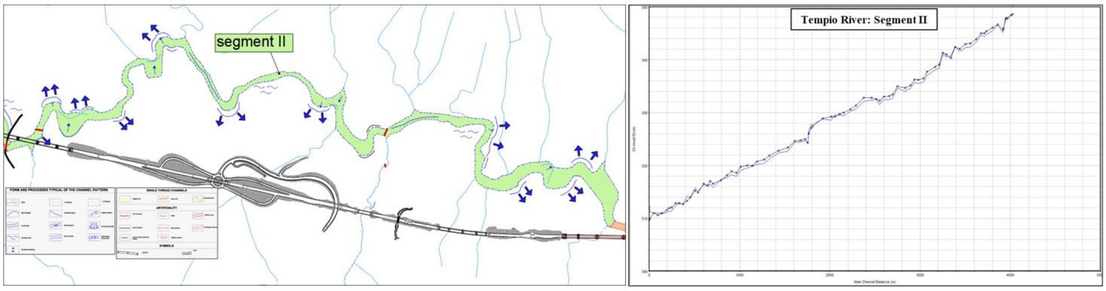

Fig. 16 River Segment II dynamics evaluation

Fig. 17 Segment II: river bed in its natural conformation on year 2000 (a), 2005 (b), 2011 (c), 2021 (d).

Unlike the two previously described segments, segment III presents a sinuous course. During site-surveys, it was found that along the segment, important human interventions were realized, such as banks and riverbed re-profiling, construction of defense structures and bridles, coatings at river bottom and banks

Proceeding from upstream to downstream, segment III present equilibrium conditions (variations in bottom elevations in the range -0.5 m:+0.5 m), with the exception of isolated sections subject to riverbed incision (bottom erosion in the range 0.6-0.8m). Results of sediment transport simulation confirm segment III low river dynamics: this is confirmed by morphological analysis.

For Segment III, the morphological dynamics class resulting from the application of the IDRAIM methodology is average (*IDM* = 0.37).

6.2 River arrangement design

For each segment, one identified erosion/deposition trend or riverbed stability conditions, the relationship between fluvial dynamics and existing structures was analyzed. Results from both hydraulic and geo-morphological watercourse characterization provided information regarding structures level of safety related to fluvial dynamics. Furthermore, by comparing results related to the Morphological Dynamics Index (*MDI*) with estimation of evolutionary trend resulting from hydraulic modeling, it was possible to define structures Level of Attention suggested for maintenance (*AM*) (Table 8).

For each *AM*, a "suggested frequency" for maintenance inspections was identified, aimed at:

- periodical verification on the minimum free board over structures
- periodical sediment balance examination

The suggested frequency for maintenance inspections is based on the seasonality of the simulated flow rates.

Table 8 Recommended frequency of maintenance inspections based on *MDI* for all Segments

	MDI	Evolutionary Trend	EDC	AM
segment I/Ia	Medium	Stability	Low	every 2-3 years
segment II	Medium	Moderate Stability /Erosion	Medium	every 1.5-2 years
segment III	Low	Stability	Low	every 2-3 years

Based on results obtained from the geomorphological analysis, conducted using the IDRAIM methodology, all segments present medium morphological dynamics, a part from segment III, since evolutionary dynamics was prevented by many human interventions.

Based on results obtained from sediment transportation analysis, for all segments river bottom is mainly stable conditions, a part from segment II, where moderate incision occur.

7 Conclusions

Integrated approaches for river management are increasingly required by public agencies as they are challenged to support the achievement of many demanding policy objectives (ecological quality, flood risk management, renewable energy production, agricultural etc.).

In the present study, an integrated flood risk management procedure was applied that incorporates safety and quality issues. Flood hazard mapping was identified with the spatial analysis of the probability and magnitude (i.e., depth, velocity) of inundation, while hazards related to channel dynamics were evaluated through IDRAIM tools (*MDI, EDC*).

Flood hazard mapping was performed going further common deterministic approach that uses single simulation results in order to produce flood maps, without considering uncertainties deriving from all the variables involved in flood modelling process.

This work intended to contribute further in the knowledge of how uncertainty affects the flood inundation maps: both 1 - D and 2-D models were developed for Arena River in Western Sicily and effects of topographic data, roughness data, as well as mesh size and shape for 2-D Models, were evaluated.

Results clearly demonstrate the impact of uncertainties in flood maps. However, the intend of this work was not nullify the current state of process in creating flood hazard map, but rather to emphasize the need to properly take into account these uncertainties while developing flood maps.

A transition should be initiated towards flood probability maps that also take into account the uncertainty of hydraulic modeling: hydraulic hazard study should provide a result associated with a confidence interval, that takes into account the assumptions made during hydraulic modeling.

It is desirable to move from hydraulic hazard and risk deterministic assessments to "ensemble" assessments that take into account the different causes of uncertainty.

By considering the uncertainty variables in flood hydraulic modelling, more information may provide and could be used to guide mitigation toward to higher risk area instead of all exposed area.

A part from uncertainties, the present work goes further the standard approach that does not consider hazards related to channel dynamics in flood mapping: at this aim, IDRAIM tools [10] are useful for river dynamics definition, together with movable bottom hydraulic models.

As demonstrated for Arena river, for which a static channel geometry scenario was adopted due to river high control level and presence of artificiality, standard approach could have been potentially sufficient. Nevertheless, integrated approach used in this work was crucial for a comprehensive evaluation of measures required for flood mitigation purposes: once areas at risk of flood were identified through flood models and critical river segments have been identified through IDRAIM tools, different possible intervention scenarios were formulated and tested.

The prioritization of measures and the choice of the most possible options were crucial and a comprehensive evaluation of the different scenarios was required in order to properly fulfill synergistically both quality and safety issues.

The integrated methodology, a part from Arena river, was tested also on another river located in Sicily, Tempio river.

For this river, that is a low energy river, far less subject to artificiality with respect to the previous one, and affected by erosion phenomena during latest years, a static channel geometry scenario was not sufficient.

After Tempio river subdivision into segments, and morphological quality evaluation, that turned out all river segments being in quite good status, river dynamics evaluation at each segment was investigated through movable-bottom hydraulic models: river segment erosion/deposition trend or stability conditions were achieved through average riverbed variations resulting from numerical models.

Flood maps produced for Tempio river showed that the river is safe with respect to flood phenomena, being safety free-boards guaranteed on all river crossings.

Geo-morphological analysis for Tempio river, instead, enabled identification of problematic river segments in which moderate incision occurs and in some cases threaten structures safety located inside river channel or in its proximity. Tempio river is therefore an example of good morphological quality combined with medium channel dynamics and associated hazards.

In this latest case, hazard associated to river dynamics should not be neglected while designing interventions and scenarios that result in a reduction of channel dynamics, reducing as much as possible adverse effects in terms of morphological quality should be searched for.

Driven by aforementioned considerations, for both cases, interventions that provide the most favorable impact in the long term both in terms of risk mitigation and morphological quality were designed.

In the first case, Arena river, designed interventions probably have some effects in terms of morphological quality but their realization allows flooding conditions substantial improvement and drastical hydraulic risk reduction.

In the second case, Tempio river, even if morphological quality is good and flooding conditions not at risk, investigation of river dynamics pointed out some situations that should be particularly sought-after, such as bridge piles in the proximity of eroded segments or even worse, subject to local scour.

In this latest case, interventions that could alter river morphological quality were avoided, but frequent site inspections should be assured in order to prevent hydraulic risk induced by structures failure.

Declarations

Availability of data and materials

All data generated or analyzed during this study are available upon request to the authors

Competing interests

The authors declare they have no competing interests.

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Authors' contributions

MC and SDF equally contributed to the work. All authors read and approved the final manuscript.

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