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Forensic Hydrology

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Abstract

This chapter is intended to call the attention towards a relatively new topic in engineering forensics: forensic analysis in hydrology. This type of analysis can be seen as a useful tool through which it is possible, in a fully objective way, to determine the real causes, natural or human induced that made a natural phenomenon a disaster. This branch of forensic analysis and particularly of engineering forensics can be applied directly to the case of floods and droughts but is not limited to those extremes phenomena. In particular, the application of these concepts to case of floods looks immediate, but other applications such as drought analysis can be addressed too. In the case of flooding events causing material damages and even loss of human lives, forensic analysis can provide results that help to clarify responsibilities but specially to prevent that future disasters happen again. This chapter will provide important information for the new forensic hydrologists, a discipline with great future, especially in the context of climate change, which will increase the magnitude, and frequency of extremes.

Keywords: flood, drought, methodological guide, forensic analysis, hydrology

1. Introduction

The term 'engineering' makes reference by definition, to the voice 'to produce'. Engineering can be considered as part of the technical sciences that put together the general and abstract scientific knowledge and the technology, being that as human activity, it is present in the design, construction and testing; maintenance, conservation and operation of structures, machinery (fixed and mobile), installations and systems [1].

Forensic activities are primarily oriented to the establishment of the origin and causes of a fact; that is precisely the reason why engineering should be involved in such activities, giving birth by this to what it is known as forensic engineering.

It is true that we are used to hear about the application of forensic science in crimes and felonies. In fact, even the dictionary definition for forensic science leads us to the application of scientific practices within a legal process. This can be translated into the participation of highly specialized professional or criminologists, who do research, seek and locate evidence—many times laboratory based—that can provide conclusive proofs about a fact that needs to be clarified. Sometimes, the evidence cannot be seen at first glance and a much deeper exam is needed in order to determine the true causes of an event. Even engineering or hydrology in particular have not been mentioned so far, a lot of the concepts described seem to fit very well in these disciplines. At the end, any forensic investigation has the objective of establishing how an undesired event happened and eventually, what to do in order to prevent that it happened again.

Forensic engineering has evolved to an interdisciplinary approach, considering another specialty such as anthropology, sociology and economy among others. It can be state that the general purpose of forensic engineering is to determine or clarify the causes of failure of certain system with the objective of improve the designs or assist in the operation procedures.

Common losses or failures that forensic engineers usually address include among others, damages to structures caused by natural phenomena such as thunderstorms, hurricanes, storm surge, saline intrusion, fires, etc. In fact, the need of research in this field is associated to a combination of climate conditions, topographic and physiographic conditions and resilience of the population: for example, coastal zones in poverty and a high potential of hurricanes incidence are highly susceptible to suffer. Nevertheless, some of these fields have rarely been addressed by forensic analysis, missing out on the advantages it could provide investigations on this topic.

All of these lead to derive from the environmental and earth sciences and forensics, the so-called forensic hydrology. Even though the term is often associated to the different quantitative components of the water cycle, forensic hydrology also includes topics as water pollution and contamination, floods, droughts, other water-related resources and water infrastructure operation among others. There will be occasions in which forensic hydrology would help to prevent or at least reduce severe damages and in some others, it would lead to better water management, improve its use and allocation.

The adjective forensic applied to geosciences appeared around 1980s [2], but few investigations have been developed since then. Derived from cases associated to pollution of water or soil, researchers started to talk about forensic geochemistry or forensic geology, as a synonym of the process to describe the use of specific techniques to find the sources of the pollution.

Some 20 years later, the growing concern on nature protection we could see the beginning of environment sciences forensics. On the other hand, the so-called engineering forensics, do research on materials, products, structures or components that fail or do not work in the way they were designed, generating or contributing to the collapse or failure of a civil work.

It is in the intersection of environment science forensic and engineering forensics where we can locate forensic hydrology with the main objective of determine the probable cause of an event or the human sources that contribute to increase damages or even human losses. This

type of analysis can be seen as a useful tool through which it is possible, in a full objective way, to determine the real causes, natural or human induced that made a natural phenomenon cause a disaster.

Forensic hydrology could be referred to the topics of water pollution, but also to floods, droughts or even water management, among others. In the case of floods, for example, forensic hydrology would help to identify responsibilities in a particular event and to plan for actions in order to prevent future damages. In the case of droughts, forensic hydrology allows to systematically address the effects caused by the phenomena, both immediate and in the mid-term, and also evaluate the measures that were taken in order to prevent future problems.

Precisely in the topic of extreme phenomena, forensic hydrology can be directly applied as we said to the case of flood or drought. In the case of flooding events causing material damages and even loss of human lives, forensic analysis can provide results that help to clarify responsibilities but specially to prevent that future disasters happen again. Even drought is a phenomenon much more complex to address, because its geographic scope is bigger and the impacts produced can extend a lot in time, forensic analysis can help to determine the main aspects and the locations that are more urgent to focus on.

Forensics hydrology procedures will give us the reconstruction of the event in order to determine what really happened, what factors contributed, what failed, who were the main actors that have something to blame about the damages, etc. In the case of floods, for example, forensic analysis should include principles for hydrometeorology, hydrology, hydraulics, social and political sciences, with the help of technology for modelling and simulating.

In this chapter, the topics of hydrological extremes, both floods and droughts are presented. In the first case, a methodological guide based on Ref. [3], is provided, while in the second a more general methodology is sketched. This investigation will provide important information for the new forensic hydrologists, a discipline with great future, especially in the context of climate change, which will increase the magnitude, and frequency of extremes.

2. Forensic analysis of floods

In the topic of extreme phenomena, forensic hydrology can be directly applied to the case of floods. Forensic analysis of floods consists on the application of a methodology immediately after the occurrence of the event. Its application will give us the reconstruction of the event in order to determine what really happened, what factors contributed, what failed, who were the main actors that have something to blame about the damages, etc. The analysis will then be directed towards performing an evaluation or study of the event after the points mentioned have become clear. The final objective of the analysis is to suggest what is needed to aid or improve the system and thereby prevent this type of disaster in the future, to whatever extent possible. Flood analyses need to integrate hydrometeorological, hydrological, hydraulic, social and political principles with the help of technological modelling and simulation tools. The likely causes of damages due to floods in a basin can thereby be determined and the key factors involved in causing the damage can be documented.

A methodological guide for flood forensics has been already developed by the authors of this chapter [3]. Particularly for the case of floods, the guide has been organized in five phases: (A) information gathering and integration, (B) hydrometeorological and hydrological analysis, (C) hydraulic analysis, (D) integrative analysis and (E) final diagnosis.

Each phase implies the development of several activities with the only objective of documenting and looking forward to clarify the actions that occurred. Some actions involve a detailed scientific analysis, while other needs the construction of a Geographical Information Systems (GISs) or even the implementation of a numeric simulation model. Some stages include field works in order to determine how the systems and action plans functioned and in what way the emergency was managed or even how the population lived the event.

Flood forensics looks for the integration of geographic, hydrologic, hydraulic, social, economic and political aspects in order to identify which of these factors intervened as main drivers to favour or diminish the impacts of the flood.

When commencing phase A, information gathering and integration, it has to recognize that this is not an easy step, since in many cases, information may not exist or if it does, it may be disperse and difficult to compile (**Table 1**).

Phase	Stage	Before	During	After
A. Information gathering and integration	1. Recopilation of geographic, hydrometeorological, hydrologic, hydraulic, socioeconomic and politic information			
	2. Status and quality of hydrometeorologic and hydrometric information			
	3. Geographical Information System			
	4. Geomorphological characterization of basins			

Table 1. Phase A of flood forensic analysis, based on Ref. [3].

The attention in this phase could be oriented towards the following:

- **Geographic:** Geographic and human aspects, theme maps, satellite imagery, aerial photographs, topographic surveys, photographic registers of the impacted zone of the streams and river, the basin and the urban environment.
- **Hydrometeorologic:** Records of daily basis climatologic stations, automatic stations and meteorological observatories. Such information will provide information of the rainfall event regarding its genesis, extension, magnitude, duration and intensity.
- **Hydraulic:** Records of flow gaging stations, physical conditions of hydraulic infrastructure as well as its design information; outflows from infrastructure and the official operation policy as well as the actual operation conditions during the flooding event. If it happens that the analyst can join the field inspections during the event, he can perhaps document or at least observe flood stages, depths, velocities and sediment transport rate in critical reaches.

- Socioeconomic and political: Information of interest in this regard includes action and development plans and programs, damages caused, emergency management, personal testimonies, historical records of past flooding events. Additional information may include data for soil use change in the basins, floodplain occupancy and poverty conditions of the population in high-risk areas. This can help in the verification of the preventive measures and the preparation actions that were taken in the zone of impact, the actions that have been implemented to improve the living conditions of the affected people and those actions oriented to the emergency management preparedness and the post-disaster reconstruction in order to avoid major damages. Personal testimonies become high value information because these are not usually included in technical reports. Interviews to direct affected people, observers and authorities can add significant value to the analysis.

With this information, a Geographical Information System (GIS) should be integrated. A base map can be used as basic platform for consultation and processing in the forensic analysis. One of the first processes would be the determination of the geomorphologic characteristics of the hydrologic system of the case study in the extents of the integral model. The use of this GIS results in advantages that are evident. If a GIS of the region exists at the moment of the flooding event, the possibility of uploading specific real time information would be of high value, transforming the GIS in a full dynamic tool. This can contribute in the execution of operative actions and in the strategic decision making facilitating the problems comprehension and eventual resolution.

Phase	Stage	Before	During	After
B. Hydrometeorological and hydrological analysis	1. Storm génesis			
	2. Spatio-temporal distributions			
	3. Time series analysis and statistical parameters estimation			
	4. Probabilistic frequency analysis			
	5. Precipitation in excess (event runoff) estimation			
	6. Establishment return period of the event (precipitation and discharge)			
	7. Modelling and simulation of the rainfall – runoff process			

Table 2. Phase B of flood forensic analysis, based on Ref. [3].

In this stage of phase A, an analysis regarding the quality of the information should be carried out. In the case of missing climatic data, for example, hydrometric information could be an alternative. It should be noted that the estimation of missing values or the use of transposition techniques from neighbour basins significantly affect the reliability of the analysis.

During phase B, hydrometeorological and hydrological analysis, the most critical steps of the methodology are addressed. The comprehension of these processes in the basin constitutes the base of the study, giving support to the full understanding of the event that generated the flooding (**Table 2**).

The comprehension of these hydrometeorological processes should include the analysis of the storms genesis. It is well known that a storm is the set of rains of well-defined characteristics that belong to a giving meteorological perturbation, but in this phase, the natural phenomena must be clearly identified and characterized in its relationship to the flood event. The fact that it was a single storm or a combination of events must be stated. The genesis of a storm that produces a flood event is a key to forensic flood analyses. Likewise, the temporal and spatial scales of the precipitations should be characterized, trying to represent their variability in the context of the basin or basins involved. For example, isohyet maps can be constructed in order to better visualize the distributions of the variables and be able to obtain information about the spatial evolution of the event. Graphs on the temporal evolution can also be obtained and further analyzed looking for tendencies, patterns of seasonal variations. The reconstruction of the rainfall field that occurred before and during the event is recommended. If the information is available, isohyet maps can be built with durations from 5 min (or even less) to up to 96 h, if this time window is relevant.

A basic but fundamental process is the determination of the descriptive statistical parameters of the event, since this could help to state in a few indicators, the whole set of observations of a single variable, making comparisons more precise and easier than those that can be done from graphs and plots. Monthly rainfall distributions as well as cumulative information of precipitation would help to identify seasonality and mass curves can give information on the temporal variation of the precipitation in the basin. All of this provides a background analysis and a reference framework.

In the hydrologic processes analysis, and due to the fact that the peak discharge and its corresponding hydrograph are associated to a lot of climatic and physiographic factors, their most reliable estimation is based on the probabilistic treatment of the information from historic observations, discharges or water depths. This process has been referred as flood frequency analysis. In addition, the probabilistic analysis of maximum data of precipitation makes possible the construction of intensity-duration return period curves, which characterize storms in the study region. These curves are also a valuable tool to study ungauged basins. Both for precipitation and discharge information, probability distribution functions must be analytically fitted to data. The distribution that fits the best is then selected. Later on, this can be used to evaluate the magnitude of events with different exceedance probabilities or return periods.

Determining the difference between total precipitation and the hydrologic abstractions, that is the effective (excess) precipitation (also called direct runoff), is a must in the analysis. In the case of gaged basins, a simultaneous registry of precipitation and runoff from a storm will be available, and therefore excess rainfall will be calculated based on direct flow determined from the flood hydrograph. Dividing the direct runoff volume by the basin area can do this. On the other hand, if these abstractions are not known, such as in ungauged basins, specific methods can be used, such as the curve number model developed by the Natural Resources Conserva-

tion Service [4]. The procedure to be applied in the forensic flood analysis is chosen according to the available information.

As part of the hydrologic process analysis within flood forensics, return periods of precipitation and discharge events should be stated. That is, to determine the time interval in which an event of a given magnitude can be equalled or exceeded on average and over time [5]. It is important to remember that given that the rainfall-runoff relationship is non-linear, the return periods for rainfall and flows need to be differentiated. The return period for a particular rainfall is not the same as the one for the runoff generated by the same rainfall. This is naturally complicated process involving key variables, namely the soil moisture content at the moment of the precipitation as well as changes in vegetation, land use and anthropogenic activities in the basin. Therefore, a rainfall with a 100-year return period does not necessary generate a flow having a 100-year return period. In a basin subject to increasing urbanization or deforestation, the same rainfall generates runoffs having increasingly longer return periods.

One key aspect of flood forensics is to determine the flow associated with the flood event in the list of assigned probabilities using a plotting position formula such as that by Weibull [5]. It should be considered that the record does not include the value of the event under study but rather only historical values, that is, only records up to the year prior to the flood event. If the magnitude of the flow lies within the magnitudes registered by the historical data, a return period for the event can easily be determined empirically directly from the sample. Nevertheless, if the flow is located outside the magnitudes found in the historical record then the return period T of the flood event can be calculated by fitting the sample to a PDF, considering that the fitting process does not include the value of the event in question. For this case, although the magnitude of the flow is larger than those in the historical record, a return period can be assigned to the flow through extrapolation. These two ways to assign T are intended to prevent that the length of the record or the magnitude of the event influence the value. The value of the flow associated to the flood event can be later incorporated into the historical records, which will result in a modification of the fitting of the records to the PDF as well as a change in the recurrence interval values through the plotting position. Thus, the assigned value of T will also change. The above is intended to highlight the fact that the assignment of the occurrence probability is evolutionary and not static.

Nevertheless, if hydrometric records are not available or are too limited to obtain a reliable interpretation or extrapolation, then rainfall-runoff relationships can be very useful because of their ability to infer flow information based on precipitation records.

For this, the application of models becomes very important since it turns the process more efficient and more reliable. Regardless of the model used to simulate the rainfall-runoff process, a calibration process must be included. The calibration makes possible to determine the value of the errors of the model when compare to a measurement or a reference pattern, all of this with sufficient precision and under specific conditions. It is crucial that these errors be sufficiently small and that they are determined with the highest precision possible. Regardless of the different rainfall-runoff models used, it is important to consider the limitations involved in applying each one to the zone, as well as the information restrictions that persists.

With this, a solid base for next phase, phase C. Hydraulic analysis is set. In phase C as in all the others, we look for the process to be efficient but always taking into consideration the limitations of the information and tools available. In this phase, the representation of the hydraulic behaviour of the systems should be obtained and studied; so, the conditions that intervened or favour the event. Simulation models of the river networks, floodplains, impacted urban zones; infrastructure operation and protection works efficiency should be addressed (Table 3).

Phase	Stage	Before	During	After
C. Hydraulic analysis	1. Simulation models of the river networks, floodplains, impacted urban zones			
	2. Infrastructure operation and protection works efficiency verification			

Table 3. Phase C of flood forensic analysis, based on Ref. [3].

It is precisely for the hydraulic modelling and simulation of the river network, floodplains and urban areas where the information gathered and integrated in GIS would be of great help.

For the analysis, information will be considered according to the scale needed. Initially, the geometry of the river, both longitudinally and cross-sections, and the hydrodynamic characteristics of the system have to be given. Among the physical characteristics of the river that are needed for the study are: soil type and vegetation in order to better estimate roughness coefficients (usually Manning's n), longitude, slope, elevations and depths, full cross sections and obstacles. Modelling and simulation can be reproduced both, the normal conditions and those present during the flooding event. The hydraulic modelling of a network of channels will provide enough information to determine the overall behaviour and that of the major event in the network. The information also enables determining the boundaries of floodplains during normal functioning and flood zones during major events. This information is important since once the floodplain is delimited and a determination is made as to whether human settlements are located there, a hydraulic analysis of the urban zone can be performed to establish the degree to which the dynamics of a city will be affected. To this end, the hydrodynamic functioning of streets can also be simulated.

Erosive processes and sedimentation cause damages, including the reduction in the productivity of the soil, loss and degradation of soil and sedimentation in reservoirs, drainage ditches and channels, as well as damages to hydraulic infrastructure. For the study case, the damages of most interest are those caused by scouring around infrastructure near or in the river, as well as changes to the flow capacity of the river due to sedimentation.

Changes in the hydraulic capacity of a river can be affected by the degree to which it and its respective floodplains are composed of unconsolidated sediments, which are quickly eroded by floods and high water levels. If the river transports fairly thick sediments during a flood, these will tend to be deposited along the bottom of the river and cause natural dykes to form.

This could raise the bottom of the river, thereby increasing water levels. When this occurs there is a very high risk of flooding. Natural and induced landslides are also cases that can increase the risk of flooding, in which the amount of sediments transported by the river increases, causing the hydraulic capacity to decrease or, in the worst of circumstances blocking the river.

Another factor is the development of tides, where the over height of the sea level can worsen flooding inland in areas relatively near the coast or cause coastal flooding. Coastal floods are primarily involved in obstructing natural runoff into the sea and blocking the flow of drainage systems, of course with their respective effects on the coastal area.

In general, to evaluate the hydraulic analysis of an urban zone, parameters such as water depth, velocity, permanence of flow and supply of solids should be taken into account.

Particularly in the revision of hydraulic works, as ending part of the hydraulic analysis, observation regarding the failure has to be carried out. In order to establish if the failure was caused by an event that surpassed the design conditions. Among others, the following has to be reviewed.

- Reservoir: The present condition according to the original design has to be verified, through the analysis of volumes routed and discharge of exceedances. From design criteria, a certain risk level is accepted. This is given by the design return period of the structure. This is the reference base.
- Pumping stations: The general objective of these structures is to drain waste water or storm water from facilities or even the streets. Their location and performance according to operation rules and characteristic curves should be revised.
- Channels and drains: The main focus will be in rivers that have been modified or rectified in order to improve the hydraulic system. A qualitative revision can be made prior to include them in the hydraulic model.
- Water supply systems: Their failure could also lead to public health problems, so their study is one of the key issues of flood forensics especially in urban settlements. Depending on the water source different flood problems arise, although the failure is often associated with the location of the infrastructure in floodplains and lower land.
- Drainage systems: The failure arises when the hydraulic capacity of the pipe system surpasses the design values, or because of the fact that sediments and garbage gets into the system obstructing the free flow. Although it is difficult to gather evidences on how the system was functioning just before the event, it is possible to infer the general performance of the network. Discharge measuring in the outlet of the basin and precipitation records may help in the evaluation. However, if no hydrometric information exists, techniques such as the synthetic unit hydrograph method can be used.

Up to this moment, flood forensics has been focused on the analysis of engineering processes, however, in to order to converge to strong and objective conclusions, factor beyond engineering have to be taken into account. Because of this, the next phase is dedicated to the integration of the analysis itself, with the socioeconomic and political part, being named as Phase D, integrative analysis, with its respective stages as can be seen in **Table 4**.

Phase	Stage	Before	During	After
D. Integrative analysis	1. Revision of action and development plans and programs			
	2. Analysis of the emergency management			
	3. Integration of hydrologic and hydraulic analysis with other			
	4. Generations of flooding maps and determination of impacts in human settlements.			

Table 4. Phase D of flood forensic analysis, based on Ref. [3].

This integrative analysis should consider the revision of action and development plans and programs in the region or zone where the flood took effect. The policies and strategies involved in these development plans should be reviewed for clarity and accuracy, and of course they should be evaluated as to whether they have been implemented or are in the process of being implemented. The follow-up of these actions should be reviewed since they are strategic visions for the future and the solutions they offer need to be maintained over time, making them crucial to the population, its safety and well-being. The designs of the plans need to be reviewed to verify that they are sustainable and contain improvements that will remain in the society after the plan has been completed. Thus, a development plan should be aimed at teaching the population to manage latent risks and not only be directed towards restoration actions. Even though this measure is secondary to the main action, it promotes self-sufficiency. Development plans should not neglect issues such as reforestation, protected zones that are directly related with levels of felling and deforestation in the disaster zone, as well as other changes in land use in supply basins which can be analyzed with historical vegetation and land use maps to see the evolution in the zone. Land planning should also be investigated to identify the location of high-risk lands sold at low values. The concentration of vulnerable human settlements should be determined as well as invasion into natural floodplains by urban settlements, commercial zones and other land uses. In particular, the legality of settlements in connection with the plan itself should be evaluated. It is also important to identify marginalization levels in high-risk settlements, as well as factors that influence the settlement of populations in these locations. Furthermore, the government's sensitivity to the risk situation should be identified, as well as any actions that it may have taken in this respect.

It will also significant the analysis of the emergency management itself, because it will consider actions taken prior to the event up to those implemented for the immediate attention of the population and infrastructure during the disaster. Actions in response to the population during an emergency could form the basis of all the procedures to be implemented in the event of an emergency, since everything that is done should be based on the protection and safety of the population and not only on economic losses. Since the actions taken are the result of planning and the projections generated by programs, adequate preparation should be ensured to reduce the impact during a disaster. A review of programs in the study zone should include their specific progress; efficiency and legitimate implementation, since the objectives proposed by each of the programs depend on their correct application. If programs are not executed as

planned, then the reason for this should be identified since it can become a determining factor in increasing the magnitude of a disaster.

In this phase, technical factors involved in the flood should be integrated with those of political, social and economic character. Main determining factors in the occurrence of the disaster should be identified. Also the factors that contributed or favoured the impacts of the disaster should be noted. This can be done through a hierarchic procedure in order to determine objectively the causes and effects of the flood event. It would be idyllic to think that all driving forces are taken into consideration; however, the analyst must integrate all elements that could have influence in the problem. If an adequate integration of each of the elements considered is reached, it would be possible to have a close picture of what really happened, minimizing uncertainty.

Finally, it is a good moment to generate the flooding maps and with these to determine related impacts. It should be remembered that flooding maps establish water depths in their relation with the topography for different discharges of interest. To generate flood maps with automated procedures, software that jointly performs hydrological and hydraulic modelling at the street level can be used. A semi-automated procedure can generate flood maps using separate hydrological and hydraulic modelling and perform external integration using GIS software. Flooding maps can be generated as follows. First, a Digital Elevation Model (DEM) is generated and a map of the basins obtained. The DEM is used again and with the detailed topography, the alignment of rivers and the characteristics of the banks and cross-sections are alternately obtained. The hydrological model is used to obtain flows, which serve as input for the hydraulic model. After performing the hydraulic simulation, flood levels are obtained from the cross sections. Finally, these levels are processed and the geographic and hydraulic information are combined to generate the flood maps.

After generating the theoretical flood maps based on the modelling, they can be compared to the actual flood area by analyzing the differences between them, attempting to locate zones that are more problematic and finding their associations with all the factors analyzed previously. The relationships between these factors and the flood zones can thereby be established. Theoretical flood maps delimit the risk zones in a general way and the map of the flood under study delimits the effects that have occurred. This enables objectively the determination of the main reasons why the event reached a particular magnitude.

After using the hydraulic modelling to determine the levels occurring in the urban zones, the percentage of damage can be identified according to type: direct (housing, educational buildings, health infrastructure, public facilities, etc.), indirect (supply of goods, interruption in services and communication systems, loss of work hours, among others) and intangible economic loss (those affected, the injured and loss of human life). The methodology used for this is divided into two steps—quantification of goods affected and the quantification of the costs of these effects.

With all of the above, phase E final diagnosis can be finally established. This corresponds to the culmination of the forensic analysis. The final objective is the identification of factors and giving relative weight to each one. This is done by establishing a contrast study with

historical events, the objective conclusion on the causes and effects, as well as the lessons learned and clearly the proposed actions (**Table 5**).

Phase	Stage	Before	During	After
E. Final diagnosis	1. Comparison with historical events			
	2. Objective conclusions on causes and effects			
	3. Lessons learned and proposed actions			

Table 5. Phase E of flood forensic analysis, based on Ref. [3].

Based on the history of flood events and the destruction caused in the study area, records from communications media and personal testimony from those affected, observers and authorities should be gathered into a document to perform a general analysis. Nevertheless, if complete analyses of previous events are available, those should undoubtedly be used. Thus, it will be possible to compare these events to the one that is currently occurring in order to identify recurring factors that influence floods in the study zone, with similar magnitudes or within a range of association. This will serve as a guide to discover whether the structural and non-structural actions have been adequately applied over the history of the study zone or if other actions not previously considered need to be taken.

An integrated analysis of technical factors (hydrometeorological, hydrological and hydraulic) along with the social and economic dimensions explained previously enables the production of an objective evaluation of the causes and effects. The result will provide documented evidence of how major was the event from the probabilistic point of view and to what degree other external factors contributed to magnifying the impact of the flood. It is important to note that a combination of all the factors may be the best explanation possible in most cases. In that case, a weighting of the causes is recommended, assuring of course that this is done based on objective findings from the analysis.

Undoubtedly, the best way to capitalize the findings and results of a forensic analysis of a flood event consists in the opportunity of learning and the potential development of actions oriented to reduce the impacts of future similar events. Among the lessons learned from this analysis, answers to several questions can be obtained. Questions such as: How extraordinary was the flooding causing event? What is the probability of exceedance (or return period) of precipitation or discharge? To what level, timely and effective warning about the magnitude of the event could have diminished damages? Were the major damages located in floodplains and high risk areas? What was the role of the hydraulic infrastructure? Was the infrastructure well operated? Did the operation of infrastructure help to control the event? The operation policy was the one pre-established or a change was made? The hydraulic design criterion of structures is the adequate? Plans for urban development were respected? Are these plans adapted for flood cases? If a risk atlas exists, is it necessary to make adaptations to it in order to consider flood risks? In what measure, lack of conservation of higher basins contributed to damages?

How adequate was the response to the emergency? Was the coordination among institutions favourable?

Duration for each phase and stage is given in **Table 6**.

Phase	Stage	Before	During	After			
				1 week	1 month	3–6 months	Up to 1 year
A. Information gathering and integration	A.1	X	X	X	X		
	A.2	X					
	A.3	X	X	X	X	X	X
	A.4	X					
B. Hydrometeorological and hydrological analysis	B.1			X			
	B.2	X			X		
	B.3	X					
	B.4	X			X		
	B.5				X		
	B.6				X		
	B.7	X			X		
C. Hydraulic analysis	C.1	X			X	X	
	C.2			X	X		
D. Integrative analysis	D.1	X					
	D.2			X			
	D.3					X	
	D.4					X	
E. Final diagnosis	E.1					X	
	E.2					X	
	E.3					X	X

Table 6. Suggested duration to complete stages and phases of a flood forensic analysis, based on Ref. [3].

Another product flood forensic analysis can provide is the proposal of actions, all oriented to reduce damages produce by future flood events. Clearly, general ideas always arise, but the courses of actions will depend on the particular case. Just to name a few of them, these can include:

- Hydrologic and hydrometeorologic monitoring networks strengthening
- Early warning system development (hydrologic)

- Review and adaptation of infrastructure operation policies
- Review of the hydraulic capacity of cross sections of the river in bridges and of other draining strictures
- Review of urban infrastructure vulnerability (water supply, sewage, treatment and etcetera)
- Determination of the vulnerability of irregular human settlements in face of floods
- Current status of natural streams and river in regard of obstructions and invasions
- Development of a Flood Risk Atlas
- Projects for works and actions for flood control
- Development of hydrologic criteria and its consideration in urban development plans
- Development of reforestation plans, soil control projects
- Incentives for the use of measures of rainfall control in the source (in site). Best management practices such as the ones considered as 'sustainable urban drainage systems'.
- Review of coordination plans among the different level of government.

3. Forensic analysis of droughts

Drought is a phenomenon that has always existed, even though mankind perceives it as atypical. This perception has caused that drought has not been studied as deep as it deserves. There are still few tools to address drought issues from the perspective of decision makers [6]. Because of this, forensic analysis of droughts can have a high relevance at the present and certainly it will be even more important in the future because of incremental climate variability and the eventual climate change.

Differences in hydrometeorological variables and socioeconomic factors as well as the stochastic nature of water demands in different regions around the world have become an obstacle to having a precise definition of drought [7]. For example, a definition of drought in terms of an insufficient humidity condition caused by a deficit in precipitation over certain period of time has been proposed [8].

Forensic analysis of droughts, because of the characteristics of the natural phenomena, will help to the establishment of the beginning and the end of a certain event. Effects derived from a drought are cumulative both in time and magnitude, making it a slow process that can extend for long periods even when the moisture condition is partially recovered by precipitation. This turns the phenomenon into a very complex one.

The general methodology presented here sets the basis to address the topic by looking the establishment of theoretical elements and applications that can help in the comprehension of the causes and impacts of droughts. Forensic analysis of droughts will provide a better

understanding of the phenomena on a solid base favouring the access to better information and products.

In order to carry out a forensic analysis of droughts, the following factors and variables must be at least considered:

- Geographical
 - General aspects
 - Edaphology
 - Land use and vegetative cover
- Climatic
 - Hydrometeorology
 - Historical climatology
- Hydrologic and water use
 - Flows and levels of surface and groundwater sources
 - Extraction zones subject to prohibition
 - Water availability
 - Water pressure degree
 - Water uses
 - Water demands
 - Water quality
 - Infrastructure for storage, recharge, conduction, treatment and distribution of drinking water, waste water, irrigation, etc.
- Socioeconomic and political
 - Population
 - Poverty and social backwardness
 - Economic and productive activities
 - Attention and mitigation plans and programs
 - Action and development plans and programs
- Historical events
 - Historical records regarding drought indicators
 - Documentation of historical droughts (categorized)
 - Paleoclimate studies if available

The general methodology recommends the fulfilment of the following processes and analysis:

- Integration of a Geographical Information System (GIS), by the use of commercial tools or freeware. An important step is the construction of the base map. Physiographic, geomorphologic and edaphologic characteristics have to be determined. Maps of vegetation and land use or economic activities will be of help. Information from agriculture, cattle rising, urban, etc., will contribute to the better understanding of the study area. All of these have to be integrated in the system for the study zone. The integration of the information allows the possibility to work with map algebra and other geo processes, making a lot easier any subsequent spatial analysis.
- Edaphology and vegetation analysis. With the help of the GIS, a detailed analysis on the edaphology of the study region and its vegetative covers should be carried out. Soil degradation and loss because of erosion are two important factors to consider. These topics, with special emphasis in edaphology, are not sufficiently addressed in drought studies.
- The forensic approach will seek to provide indicators of the internal biologic activity of the soil, among other processes associated to water storage and the resistance to deficits. As it is well known, vegetative cover favours water retention in the basin, reducing with it, the surface runoff. This helps to aquifer recharge and the better performance of the whole water system.
- Analysis of the status and quality of hydrometeorological records and climate in general. We seek to have flow records, surface water information and groundwater levels, rainfall, drought indices, operational policies, soil moisture and evapotranspiration. Observation, interpretation and analysis of sufficient data are of great importance for this type of studies. Basically, error or absence of a particular data may have effects on the estimates of probability of extreme events with high return periods. Before using a data set, its validity and accuracy should be verified. The accuracy is the correctness of the data, while validity refers to the applicability of the data for the purpose for which the values will be used [9]. The World Meteorological Organization recommends some techniques for data validation in its Document No. 168 [10]; for example, graphical representation of the rainfall or flow depends on the height of the water, in order to detect small bumps (or any episode of flooding) not accompanied by significant rainfall, and vice versa. The success of the analysis results and subsequent decision-making process depends on data quality.
- Spatial and temporal distributions: Once data have been validated, a geostatistical analysis can be performed. With this, spatial-temporal distributions can be constructed from recorded information. There are several methods to make this statistical spatial analysis, for example, inverse distance weighting, splines or even kriging [11]. Any of these techniques can be used, in order to determine the magnitude of the phenomena in space, which according to its causes, can be from local to regional. Of course, each method should consider its own restrictions. In the case of the time series analysis, it will allow characterizing the drought event in duration, both inter annual or seasonal. It should be noted that a drought variable should be able to quantify the drought for different time

scales for which a long time series is essential [7]. With this process, we look forward to establish the permanence, duration and frequency.

- **Drought indices determination:** Several indices of drought exist nowadays. These have been developed for a number of authors and most of them consider as the main or unique input variable the precipitation, either monthly or annually). From the Palmer Drought Severity Index (PDSI) developed by Palmer himself [12], up to the Standardized Precipitation Index (SPI) proposed by McKee [8] of wide use at the present, several indices could be used to characterize and evaluate severity and intensity of the drought event under study. An appropriate record should be considered both in type and length for each one of the cases. It is important to notice the restrictions and limitations of each index.
- **Climate indices determination:** It must be recognized that climate is related in some way to hydrometeorological variability. Climate indices allow the identification of climate variability at major scales. The most common indices in this regard can be averages and extremes, linear trends and standard deviations of long time series available. Other indices can be also studied, depending on the region, some of them can be of high importance, such as El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO) or even just the Sea Surface Temperature (SST). The history of these indices can provide information regarding the frequency of the event.
- **Probabilistic frequency analysis:** Flood frequency and precipitation frequency analysis as well as of other climatologic variables can be taken as a base. The basic premises of this kind of analysis must be taken into account: statistical independence, randomness of the process and equal distribution in time [13]. It is quite common that the records have gaps. Kalma and Franks [14] document that restrictions in the probabilistic method selection are among other: (i) characteristics of time and variability of the precipitations in arid and semiarid regions, (ii) external factors that influence decadal variability, such as ENSO and (iii) reduced availability and extension of information records. In Ref. [15], based on the work in Hosking and Wallis [16] a methodological guide for the regional frequency analysis based on L-moments has been established. This guide, when applied to droughts has given good results in the evaluation, estimation and mapping of the probability of drought occurrence in several pilot regions in Latin America. The procedure considers that several sites, within homogeneous regions, have a common frequency distribution, except for a specific scale factor, represented by the mean value of the variable under study. Since drought is a spatial condition, regional analysis is a better tool than conventional onsite analysis.
- **Establishment of the return period of precipitation deficit:** After the application of statistical, geostatistical and probabilistic methods, the next step is to determine the return period of the event under study. Return periods links the magnitude of the event to its frequency of occurrence. In such a way, this information can be compared with the system capacity. This allows to identify if the return period of the event is bigger than the one used to design all the works and establish the operation of the systems.

- **Water balance integration:** This balance allows to quantify diverse water cycle components by the establishment of relationships among hydrologic variables such as water offer and demand and by considering spatial and temporal distributions. This is used to calculate the so-called 'hydic pressure', as a result of the balance between offer and demand. This balance allows the quantitative evaluations of water resources and the modifications because of human activities, both past and present. A water balance can also be used to predict the impact derived from those modifications. Drought forensic analysis is used to identify the influence of those factors on the magnitude of the event and on its frequency, that is, its return period. Water balance is based on the mass conservation principle, sometimes called continuity equation, in which in a simple manner, the variation in volume, in each period, is given by the difference between inflows and outflows of the system. This can be stated as [17]:

$$P + Q_{S_i} + Q_{U_i} - E - Q_{S_o} - Q_{U_o} - \Delta S - v = 0$$

where

P is the precipitation in form of rain or snow (self-basin), Q_{S_i} and Q_{U_i} are the surface and groundwater inflows (both from within the basin or from outside), E is the evaporation from the water surface, Q_{S_o} and Q_{U_o} are the surface and groundwater outflows (both from within the basin or from outside), ΔS is the storage and v is the residual term in the difference.

The analysis can be more or less simplified depending on the available information and the different components in the study case: water bodies such as reservoirs, lakes, rivers, creeks, etc.; hydrologic characteristics (basins, sub-basins, etc.) and the period under analysis. Computation of the components should be independent as much as possible, avoiding the 'closure' of the balance with unknown components. Once the balance is finished, a series of different scenarios can be studied.

- **Hydraulic analysis of actual Infrastructure in terms of resilience:** More than just an audit, infrastructure must be revised in order to find the capacity that the region had to adapt infrastructure management and resist alterations without disturbing its functionality in a significant way. Infrastructure requires adaptation in accordance to needs of the region in order to satisfy demands. Because of this, responsible institutions or organizations must have a strategic vision plans, more preventive than reactive and corrective. In the ideal case, systems should have been designed adequately and in comply with standards and norms. Infrastructure should have been operated according to the policies established.
- **Population and productive activities status and growth:** Emphasis in this point is on classifying the study zone in terms of the main activities so the effects and impacts of drought in them can be clearly determined. By considering the differences for example between agricultural and urban sector, a more precise analysis can be performed. For all sectors considered, according to the productive activity, the social and poverty indices

should be taking into account. With these and the action and development plans and programs, the identification of the level of services and social exclusion can be clearly identified. All of these should be considered in relation to the infrastructure growth and development. It is clear for example that when large reservoirs exist, the impacts of short duration droughts can be hardly perceived.

- Action and development plans: This is a socially sensible topic. So, as in the flood forensic analysis the designs of the plans need to be reviewed to verify that they are sustainable and contain improvements that will remain in the society after the plan has been completed. Plans and programs should prioritize preventive actions in order to have integral solutions both scientific and technologic. This revision is important from two points of view: prevention and mitigation. In each plan or program, one should identify the different entities from government and civil associations involved in drought management and clarify the processes on how the drought event was handled: surveillance, warning systems, impact evaluation, emergency response, risk management, recovery and logistics.
- As in the case of floods, there will be factors, that even though they are not critical, could have favoured the severity of the impacts, as changes in land use in supply basins, soil degradation, deforestation, extensive agriculture, etc., considered all within the environmental degradation topic. For example, with the use of GIS historical vegetation and land use maps can be analyzed to see the evolution in the zone.
- Integration of damages and help provided: The effects of droughts are gradual and with great extension both in space and time (they remain for prolonged periods). These effects are not so noted as the ones associated with flood events, since the latter are observed almost immediately. That is why specialists refer to those kinds of damages with the adjective direct. Even though, impact of droughts can be even huge since social aspects are included beside the economic ones. These are type of impacts are called indirect and they are much more complicated to evaluate. Damages caused by droughts will be present in agriculture, as a reduction in production; urban zones can be affected in their economy or a reduction in production; also, in urban zones some it can be some other economic effects not only in the poorest sectors, but also in other segments. In extreme conditions and special conditions even deaths can occur. In this regard, reports from the civil protections agencies or disaster prevention centres should be considered. These reports will integrate damage evaluation and costs involved but not necessarily will report the supports and help received, so there is an extra task for the integration of such information which has to be oriented to governmental and non-governmental organizations.
- Comparison with historical events: Existing information regarding the impact of historical droughts should be gathered and integrated. Review of past news in informal sources will be of value because it will show how the information flowed, how the event was lived, damages perceived, problems with water supply systems, fires, etc. Reports from governmental and academic organizations as well as official declaratives of drought. Reports on the actions that were taken, programs executed and economic help are of high value. The magnitude and frequency of the event under analysis when compared to the

help and support granted would serve as a base to determine if the application of those resources was efficient. The construction of performance indicators would be appreciated for future analysis and future use of the damages—support—effects relationship. For example, Jiménez [18] shows methodological guides for the construction of indicators, defining them as a tool that offers quantitative information with respect to achievements of results in the delivery of products or services generated by the institution, covering both quantitative and qualitative aspects. Also, historical water demand data and its relationship to drought declaratives need to be analyzed. In the forensic analysis, even paleoclimatology studies can be considered, such as tree ring studies that can offer information of long past events.

- Integration of analysis and objective establishments of causes: In this phase, the integration must classify each variable and factor analyzes, giving them the adequate weight. Based on all analysis performed, an integral model with matrix array for the evaluation of categories, variables and factors in a weighted form can be implemented. The results of the model may show two groups, historical trend if it exists, and the causes directly associated to the event under study. Once the causes that favoured or increased the impacts of the phenomena have been determined, the making of a simplified tree diagram can be built. This tree will show the main causes, asking and answering in a very concise and objective manner the why's and what's. This will converge to the main cause of the disaster and to the actions that should be taken immediately. Also it will establish the strategies to be followed in order to reduce the impacts of this phenomenon in the region under study.
- Integral actions: The final report should include (a) prioritized causes, (b) lessons learned, (c) actions and recommendations for the immediate time and short and medium terms, (d) critical elements for prevention and preparation in case of droughts and (e) fundamental cultural elements to be implemented so the lessons would become effectively lessons learned in the emergency management. Inclusive vision should be taken as seriously as possible. More than a policy that must be adopted, it will be an action that should be implemented. No stakeholder or decision maker should be excluded. Just remember that drought is a phenomenon that is not scale selective, nor sectorial. It affects big spaces and affects the least resilient systems. Integrative actions favoured by drought forensic analysis should include the institutional, methodological, public and operational parts, so they allow success in the face of a new event. Inclusive vision considers, for example, investments in monitoring and early warning systems, implementation of prevention and mitigation programs, legal framework strengthening, institutional coordination, capacity building, communication and of course research. It is well known that something that can be measured, can be improved, so evaluation and action updating as well as adaptive capacity towards resilience represent step to success. Those are the type of things drought forensic analysis is seeking.

4. Final conclusion

Forensic analysis in hydrology can provide the necessary and sufficient information for the authorities and decision makers to establish programs of attention and control of these phenomena in the future elements. Though this to some extent has been given, it is desirable that the process rests on objective technical reports based.

It seems obvious to say that the issues in which forensic hydrology can be applied are numerous and varied. Cases of floods and droughts are perhaps the most evident, especially urban pressure that every day affects the ability of natural streams that drain a basin or a cultivated area.

As a result of all this, forensic hydrologists, a specialty with a great future, can apply a large number of technical tools in order to make detailed studies on the precise causes of a disaster. From our ability to select, the best forensic techniques depend largely harm reduction or the safety of our sources of supply.

The results of forensic analysis in hydrology effectively contribute in the search for better alternative solutions to recurring problems in all our countries.

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