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FLOOD EARLY WARNING SYSTEMS, MISCONCEPTION AND CHALLENGES - THE CASE OF COLOMBIA

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Abstract: In Colombia, highly populated urban centers are often located in extremely mountainous terrain. Overall, steep slopes and deep valleys is characteristic of the territory of the Andean mountain range. Furthermore, high climate variability associated with the intertropical zone causes extreme rainfall events throughout the year. In such environment, intense precipitations over steep terrain promptly saturates the watershed and causes overland runoff to rapidly concentrate in natural channels and rivers. The sudden rise of the waterline along the river way threatens vulnerable populations including risks to infrastructure and personal property. Preventive measures to such threat include the implementation of early warning systems in local communities in order to mitigate and limit damages. In order to implement such systems a correct and detailed understanding of the catchment is required including geomorphological parameters and historical rainfall data series of the area allowing one to correctly determine alert thresholds. This study reveals how standard protocols and methodologies for the implementation of channel flood routing early warning systems have shown limited success in Colombia, where limited and/or incomplete data series are available. In addition, common hydraulic modeling softwares are generally ill adapted to the characteristics of the terrain, and watershed response time requires real-time analysis and/or precipitation model prediction as well as up to date monitoring equipment. Difficulties in model calibration and alert threshold determination are also brought into question.

1 INTRODUCTION

Early warning systems (EWS) have been successfully implemented over the years as autonomous or semi-autonomous alert mechanisms meant to respond in a timely manner to various risks associated with flood events (Gestion del riesgo, 2017), thus mitigating the risk to human life and/or damage to personal or public property. Such system allows for the timely warning of any specific pre-established changes occurring over the watershed or channel way. A EWS is comprised of a number of elements. Firstly, a number of monitoring stations are generally set up to measure hydrometeorological variables such as precipitation intensity or channel waterline evolution. The whole system is integrated through a database archiving process with transmitter relays that communicate between the network. Finally, a base station is responsible for data processing, determining if a given alert threshold has been met, according to perceived risk. When deemed necessary, warning stations may generate a public alert or initiate evacuation protocols or trigger additional monitoring protocols (UMAC, 2011) as may be required. Figure 1, shows the general organization of such system with its different components.

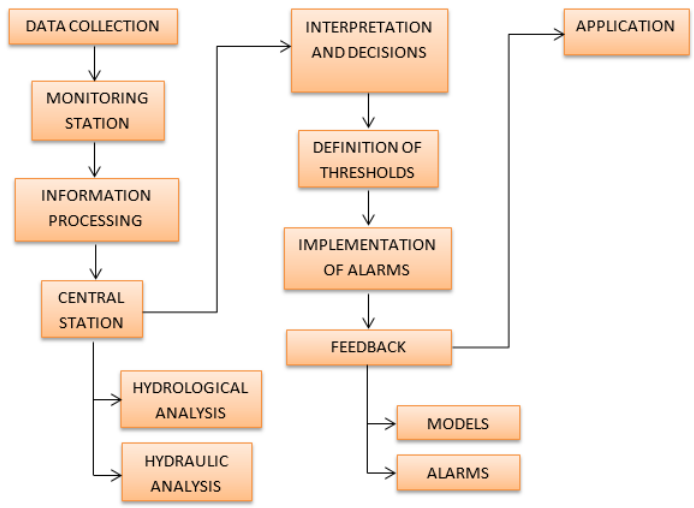


Figure 1. Components of a EWS, Rivera (2018)

Design and implementation of EWS usually require a detailed knowledge of the hydrological conditions of the watershed and the hydraulic properties of the main channel way. Also, a detailed understanding of the geophysical properties of the study area is required in order to allow one to correctly assess data and efficiently support the decision-making process of public authorities or decision makers (UNISDR, 2006).

In addition, monitoring stations are to be calibrated and maintained over time to correctly quantify the hydrometeorological conditions of the watershed. The EWS is often developed and improved over time as the network response is compared to flood events, striving to limit for example, false positives. Eventually appropriate alert thresholds are determined (Diakakis, 2012) considering a given set of risk criteria and thus determining a proportionate response plan considering previously identified vulnerabilities.

In the mountainous region of Colombia, the environment is affected by intense precipitation biannually, that is characteristic of the Inter Tropical Confluence Zone. Torrential precipitation events are typical for the region and combined with the general topography of the area leads to rapidly changing flow conditions with intense run off. This is characteristic for mountainous catchments (Mintegui et al., 2008) and often leads to flash flood events. In the Andes, rural urban centers have been situated along the floodplains. Often geographically isolated and dispersed, such small communities are based on a local agricultural economy. River ways are often the only means to access such communities. Little control is exerted over such areas and limited urban planning has been considered in the development of such settlements aggravating the situation further. Figure 2 shows a typically rural community of the Andeans mountains. On the other hand, major regional centers are also exposed to floods, as they are generally located along the main national river ways. The characteristics of such areas, including population density and exposed public amenities, often lead to greater vulnerabilities when extreme precipitation events occur.

Figure 2. Impoverished dwellings, Rio Blanco Caldas, F. Yara (2017)

On March 31st, 2017, a catastrophic flashflood impacted the small community of Mocoa without forewarning and 300 inhabitants perished and 2000 more were directly affected. Figure 3 illustrates the magnitude of the disaster in Mocoa.

Figure 3. Flashflood Mocoa (El Pais, 2017)

Following the event, the reliance on such local monitoring EWS in support of public safety have been brought into focus. Although various predictive or real time assessment technologies are available in the context of monitoring and alert networks systems, they remain costly and are hardly accessible for small communities. In such context, one understands the importance of correctly establishing emergency protocols and strategically implementing EWS, striving to protect local populations and property (Mendoza et al., 2015). This case study reviews the Colombian context in implementing EWS and highlights current challenges and limitations.

2 NATIONAL CONTEXT

2.1 Data availability and accuracy

In order to correctly implement an early warning monitoring system, valid historical data series that provide for statistically meaningful information is required. Few regions in Colombia are provided with sufficient historical data set for precipitation or river discharge for example to allow for data interpolation, even less so to correctly allow for model calibration. The ability to actually extrapolate from such hydrometeorological data is rarely considered meaningful as was found in various Andes regions (Carrera-Villacrés et al. 2016). Before being operational, a monitoring network and its associated alert systems must be calibrated and validated over a time period including all its components and subcomponents. When available, historical data is often difficult to acquire as field data and monitoring stations are often under the control of privately or semipublic entities or organizations that are not required by law nor are they mandated to disseminate such information.

In Colombia, most rainfall monitoring systems have, in the past, focused on measuring total rainfall over a time window in order to support local agricultural and crop management needs. Monitoring stations used in crop management often lack maintenance and calibration is rarely undertaken, as often limited financial resources are available. Weathering, equipment decay, recklessness, neglect, collapse of infrastructure, robbery, vandalism are common; affecting or altering the data acquisition process. Where in the past, recording errors and the absence of calibration had little or limited consequences; generally local communities would progressively adapt over time to new local environmental conditions or hydrometeorological changes; the lack of data or an erroneous data set, as part of an EWS may in effect have catastrophic consequences (Kundzewicz, 2013).

2.2 Management and Public Authorities

Where in the past, the responsibility for management and maintenance of monitoring networks fell upon local or regional authorities, the integration of alert systems or EWS is generally controlled at the national level. Often such centrally focused organizations are wanting in local knowledge or, lacking resources, are unable to cope with the operation, calibration and maintenance of specifics stations particularly in remote regions. Historically, in Colombia networks and data gathering systems have been neglected and/or purely and simply abandoned over time by local authorities. Furthermore, lack of communication, confusion, mismanagement and miscommunication have generated lost opportunities, have augmented overall implementation costs, and has subjected authorities to liabilities and caused overall delays (Rogers, 2011).

State of the art equipment, that allow for a rapid (often in real time) determination of rainfall intensity given local weather conditions exits (Arattano, 2008). For example, short wave radar technology would allow for a rapid meteorological prognostic and, when required allow for a quick response time at the local level. In Colombia, such systems are rarely found at the regional level and even less so implemented locally. When available, coverage does not extend over the whole area of the countryside which is often more vulnerable. No radar coverage is available in rural areas. In addition, sourcing of such technology is generally done overseas, through foreign agencies or international private interest, as the country is still lacking in the indigenous development of high technology systems. This situation further complicates the management and implementation processes of such technology and equipment.

2.3 Warning systems

Determining alert protocols with limited or inaccurate information remains challenging if not impossible. One has to recall that alarm threshold are meant as a risk mitigation tool for persons and property. Dissemination of alerts can be done through audible alarms such as sirens, local communication (phone, walkie-talkies, HAM shortwave radios) or even through social networks (SMS, phone messaging or texting apps) available locally in order to timely implement for example evacuation protocols. False positive or false negative are a reality. Public trust is rapidly affected by such events and mistrust affects the viability of the system in itself. Indeed confidence in the EWS is key, and one has to consider the social and cultural components of the affected local population. Often training exercises and education is required in order to ensure that indigenous or affected local populations respond correctly, efficiently and in due time to given alert and protocols.

In addition, monitoring stations have in some cases been installed without the required technical expertise or without considering global conditions of the watershed; have been wrongly situated; or have not been appropriately tuned or vetted lacking statistically meaningful historical data set.

Tragic events have occurred where alarms systems were not prompted, were initiated untimely or even have been delayed, being prompted after the tragedy occured.

2.4 Environmental Factors

Geographical information systems (GIS) are often used in the context of alert and warning systems, as they facilitate the geomorphological analysis of the area under concern (Li, 2011). Given the actual size of the watershed, data scaling determines the accuracy of the digital elevation model. Again, often limited topographical data is available in remote areas and map scale are often inadequate and GIS rending scarce. Public authorities have tended lately to supplement the lack of topographical data with aerial photos or through the use of locally purchased aerial drones. Considering the dense canopy that is encountered over the mountainous area of Colombia (Figure 4), such information is of limited help in determining local topography and in many cases is of limited value in even defining the size and the general layout of the catchment basin. Experience with LIDAR technology have proven to be of limited help in determining accurate topographical information in rural areas considering the dense canopy observed in the Andeans and is currently available for urban centers.

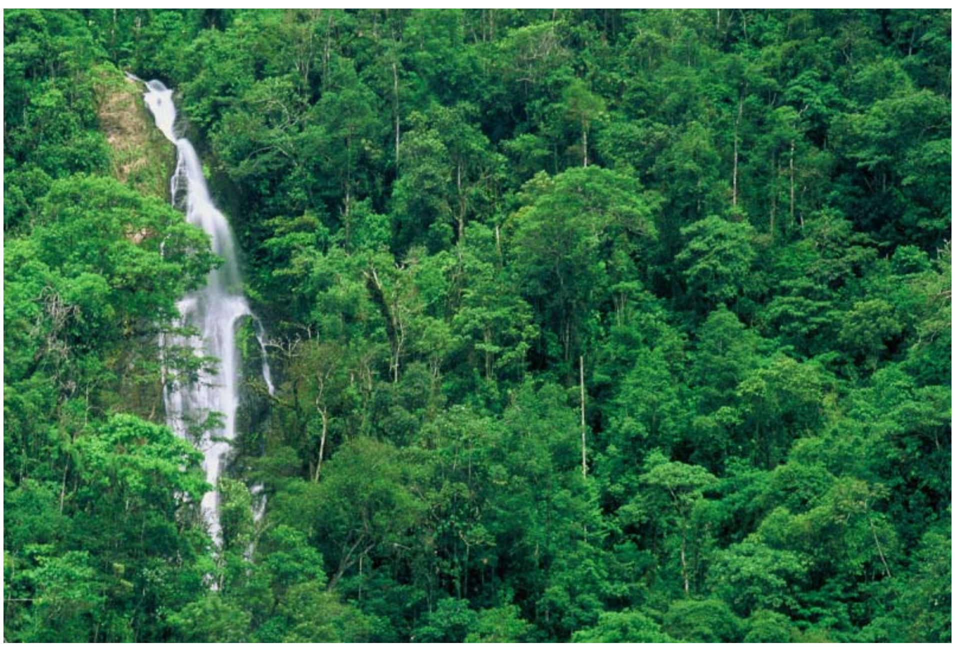


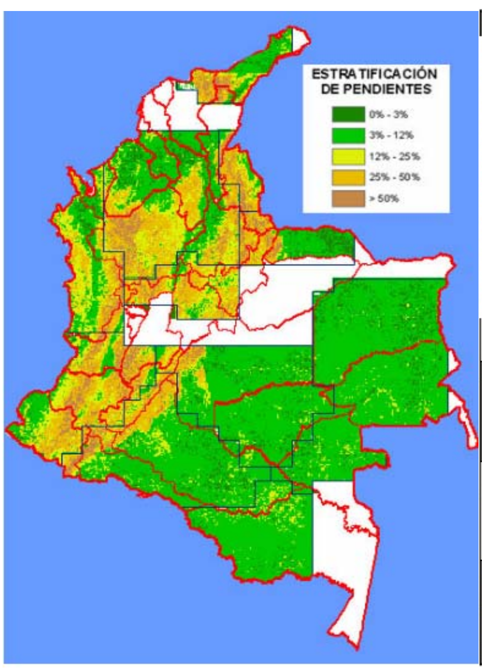
Figure 4. Typical canopy of the Andes mountain (Diego M. Garces, 2013)

Alteration of the watershed over time also present additional difficulties. Through urbanization and far-reaching agriculture, zoning and land use management is seldom enforced and soil geomorphology is heavily impacted (Slavoljub, 2011). For example, in a short period of time, significant erosion caused by intensive deforestation increases runoff and may alter flow patterns. In this case, one has to corroborate available topographical information with field data, while trying to establish a baseline study of the area. Such enterprise is not trivial in a developing country with limited technical resources.

2.5 Use of Numerical Modeling Tools

Accurate hydrological and river hydraulic modelling is of outmost importance in the assessment and implementation of flood EWS network, as one strives to correctly and accurately represent water flow processes occurring within the catchment to a sufficiently accurate degree to allow for such prediction tools to be useful. Lack of historical or field data has already been mentioned as a problem in itself, but this situation also limits the possibilities for a robust calibration process. In effect, an erroneous correlation of precipitation intensity vs channel stage could easily be detected and challenged, and in due course, variable correlation could be improved through model calibration. In the absence of accurate and sufficient field data relating observed events to predicted model response, model calibration is in the best case scenario made difficult, or more commonly, rendered impossible. Weather research and forecasting model (WRF) are available to model and predict macroscopic weather events but require downscaling in order to correctly predict or model local or regional events. Currently WRF models are being calibrated and validated but have not been implemented yet as forecasting tools. Research in this area is progressing.

Furthermore, determination of channel characteristics is essential in correctly modelling channel flow. Generally, the modelling of alluvial river flow can readily be undertaken considering spatial approximation of the discharge in 1 or 2 dimension, considering a river’s width, to depth, to length ratio, as well as mean uniform flow conditions. Open channel hydraulics in the Andes mountains is characteristically different. In Colombia, channel flow generally does not meet non uniform flow condition showing highly non hydrostatic pressure gradient with a significant vertical dimension component to the flow. The topography is notable for its steep gorges, deep valleys, sharp rises, sudden water falls, adverse slopes and sinuous flow patterns (Anderson et al. 2016). Figure 4a shows the elevation derivatives for Colombia. One can observe distinctively 25% to 50% or greater mean slope in the Andes mountain range. Whereas the watershed hydrograph response or concentration time following a given rainfall is ordinarily understood in terms of hours or even days in North America, that would allow for progressive approximation of the discharge over time. In the Andes, it is not uncommon for the catchment response time to be considered in terms of a few minutes or even to be “immediate”, requiring dynamic wave routing that may be more related to dam break theory that to the natural flow of a river flow. Figure 4b show the annual precipitation with 3000-5000mm not being uncommon for the mountain region. Accurately modelling such flow processes is not trivial.



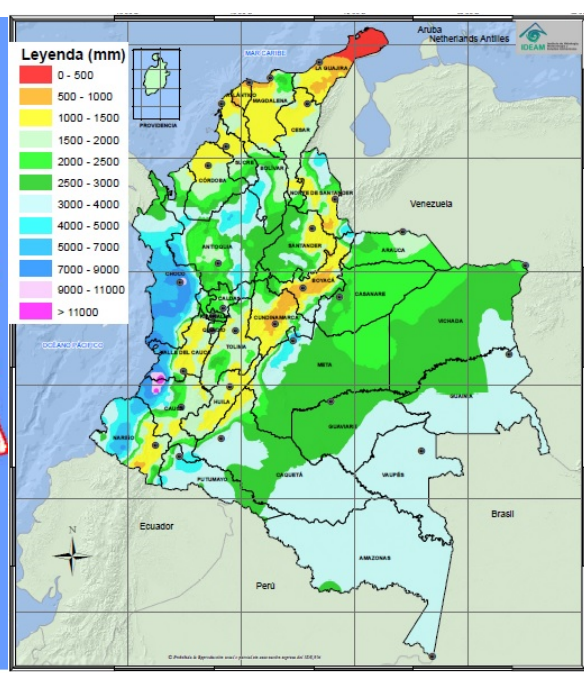


Figure 4a. Average Slope in Colombia (Biesimci, 2018) Figure 4b. Rainfall distribution over Colombia (IDEAM,2014)

2.5.1 Hydrological models

An accurate digital elevation model of the area is often required to allow one to determine the precipitation-runoff correlation of the catchment basin, hence determining its influence on channel flow stages over time.

Hydrological modelling strive to represent the interaction processes of the different components of the hydrological cycle, mass balancing the various intakes as suggested conceptually by equation 1 and presented as a flow diagram in Figure 5.

[1] $R = P - ET - I - Inf$

Where R represents direct runoff, P is associated with precipitation, ET is evapo-transpiration, I is interception and Inf infiltration.

Hydrological models may be lumped, semi distributed or distributed. The former being more common and generally easier to implement requiring less input variables than equivalent distributed models. On the other hand, lumped models require further simplifications and are hence limited in their ability to represent the hydrological balance.

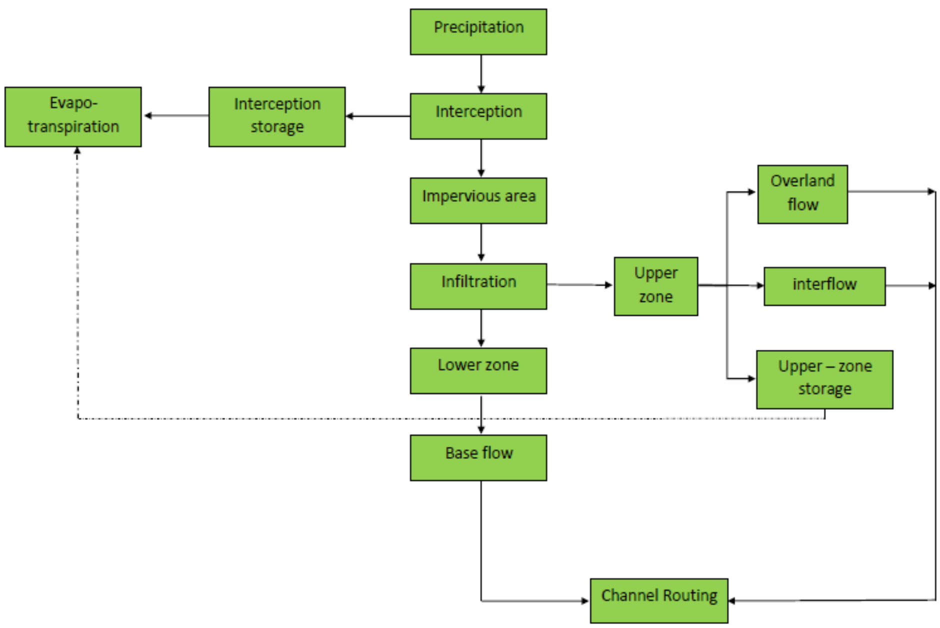


Figure 5. Flow diagram of a model for runoff estimating, Aguirre (2018)

Available integrated GIS models, such as infSWMM and PCSWMM, able to automatically delineate multiple watersheds of varying size.

As the Andean mountains present high climatic and terrain variability, e.j. slopes, soil and sub soil formations, canopy characteristics as well as intense torrential precipitation over the rainy season and periods of extensive dryness, distributed models are generally preferred to model such catchments although they may be more costly and computationally demanding requiring multivariable correlations (Modelos Hidrológicos, Cabrera). Inasmuch as one believes simplified models may be limited in their use as they tend to streamline the phenomena disproportionally, they are generally most often used in practice.

2.5.2 Open Channel Hydraulics models

As hydrological models establish average runoff over time, river hydraulics will determine flood routing characteristics of the event. Over the last 30 years, numerical models have evolved significantly and a broad range are nowadays available. Although more advanced hydraulic flow models like XPSWMM, Mike She, Mike 21, Deltares, HEC-Ras 2D and SWMM incorporate features such as unsteady conditions with a high resolution model of the terrain, readily available one-dimensional uniform or gradually varied flow models based on finite difference approximation and application of the energy equation are more common. Although such models may incorporate modelling of flow regime change and local effects induced by the presence of bridges, piers, jetties, culverts and causeways but are often limited in their use by not allowing for bed condition changes through erosion over time hence affecting changes in the waterline, and requiring the hydrostatic pressure conditions to be met (Cea and Bladé, 2007).

On the other hand, the 2D St-Venant equations may be implemented for shallow flow conditions considering hydrostatic pressure conditions and mild to moderate bed slope.

In all cases, modelling of channel flow processes based on the most common modelling techniques is ill adapted to the Andean mountains were model simplification does not allow one to correctly represent observed flow processes. Indeed, the channel geometry rarely meets the uniform flow conditions, the hydrostatic pressure condition or the one or two dimensional shallow flow requirement.

2.6 Calibration Processes

Flow model calibration requires sufficient data point to validate the channel stage to discharge relationship. In Colombia, few watersheds or channels are provided with gauging stations and when available, monitoring stations are usually restricted to the country's main waterways and navigable channels controlled at the national level. This situation inhibits systematic model calibration and often requires one to calibrate or validate model response based on the limited data that a field monitoring campaign may provide, the personal experience of investigators, or comparison of observed discharge of similar neighboring watersheds establishing correlations when available (Donnelly, 2016). Similarly, hydraulic calibration requires control stations and sufficient knowledge of flow parameters including sediment transport, roughness coefficient, and soil usage amongst other factors. Lacking any of the latter, one is left with field approximation and observation, identifying visually for example, the extent of the flood plain, through witness testimony (oral transmission, hearsay, tradition, local habits, local newspapers and historical photos).

3 CONCLUSION

In Colombia, recent catastrophic events have generated public scrutiny of meteorological monitoring networks and EWS, and a number of networks have been implemented recently at the local level with minimal previous experience in implementing such systems. Shortcomings in technical knowledge, personnel know-how and financial resources, as well as lack of field data and lack of accurate historical data that can be quantified systematically over time have limited the usefulness of such networks.

Hydrological modelling, to be accurate, requires a sufficient number of input variables. Where simplified models may be deemed adequate and less costly they are of limited use in modelling complex interception and run-off dynamics. Hydraulic channel modelling requires one to correctly assess model limitations as it relates to channel flow dynamics.

In such context model calibration and EWS validation and implementation remains an art more than a science at this stage. While recognizing that EWS can make a significant contribution in mitigating risk and improving emergency management processes, the reality is that in Colombia, implementation of such systems remains sketchy at best, often providing a false sense of security. Furthermore, the inability of systems to correctly predict or warn in due time of catastrophic event socially casts doubts on the whole process and on the efficiency and validity of such systems, especially in the case of indigenous populations in remote areas.

Overall, improvement and implementation of EWS in Colombia is hindered by the challenging physical characteristics of watersheds of mountainous regions: topography, concentration time and hydrometeorological conditions to name a few. Nonetheless, such challenges may also present an opportunity, requiring further investigation and improvement in such areas as extrapolation techniques, multiple correlation processes, prediction models, and data optimization. For the time being, the challenge is centered on improving information management including data availability and dissemination as well as extending the overall coverage of monitoring networks. The need for predictive models may very well be required in Colombia, forecasting or anticipating meteorological events before they even occur with real time assessment and analysis of data the implementation of such systems is to be explored further, for example validating downscaled WRF models at the regional level.

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