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Review Article

Irrigation and Drainage Systems in Flood-prone Areas: The Role of Mathematical Models

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Abstract

In the agricultural sector, the prospects of increasing the gross cultivated area are limited by the dwindling number of economically attractive sites for large-scale irrigation and drainage projects. In this context, most of the world's irrigated land and rainfed land with drainage facilities are located in flood-prone areas.

Floods are among the most damaging of natural hazards, and are likely to become more frequent, more relevant and more damaging in the future due to the increase in population, urbanization, land subsidence and, to a certain extent, the impact of climate change .One-third of the annual natural disasters and economic losses and more than half of the respective victims are flood related.

Knowledge and advanced scientific tools play a role of paramount importance in the strain of coping with flooding problems. In this context, flood modelling represents the basis for effective flood management mitigation and control.

The modelling approach aims to provide the best means for assessing and, subsequently, reducing the vulnerability of rural and urban prone areas.

Within this context the following paper provides a review and a general description of the main features and characteristics of the mathematical models currently used in flood management, mitigation and control, along with quantity and quality of experimental and field data to be used both as input and for model calibration.

Mathematical models are the best tools, nowadays available, for the design of efficient flood protection strategies and excellent supporters of decision-works.

Introduction

In the agricultural sector, the prospects of increasing the gross cultivated area are limited by the dwindling number of economically attractive sites for large-scale irrigation and drainage projects. In this context, most of the world's irrigated land and rainfed land with drainage facilities are located in flood-prone areas.

Floods are among the most damaging of natural hazards, and are likely to become more frequent, more relevant and more damaging in the future due to the increase in population, urbanization, land subsidence and, to a certain extent, the impact of climate change [1,2].

The term "flood" and "flooding" are often used in different ways. According to Munich-Re [3] flood is "a temporary condition of surface water (rivers, lakes, sea) in which the water level and/or discharge exceed a certain value, thereby escaping their normal confines". Flooding is defined "as the overflowing or failing of the normal confines of a river, stream, lake, canal, sea or accumulation of water as a result of heavy precipitation where drains are lacking or their discharge capacity is exceeded" [4].

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Knowledge and advanced scientific tools play a role of paramount importance in the strain of coping with flooding problems. In this context, flood modelling represents the basis for effective flood mitigation and control.

The modelling approach aims to provide the best means for assessing and, subsequently, reducing the vulnerability of rural and urban prone areas.

By using a model an attempt is made to replace trial and error based strategies, as practiced in the past, with more physically based measures of flood management and control. Mathematical models are the best tools, nowadays available, for the design of efficient flood protection strategies and excellent supporters of decision-works.

Within this context, mathematical models are used, mainly, for the following purposes [5]:

- Simulation of flood waves in rivers and in their floodplains;
- Assessment of flood protection measures;
- Evaluation of flood damages;
- Design of flood risk maps;

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- Flood forecasting and warning;
- Increase communication and public awareness.

Mathematical Models

Research work on flood dynamics has traditionally specialised in different mathematical models. They can roughly be categorized into stochastic and deterministic models.

Stochastic models are based on flood frequency analysis, defined as the means by which flood discharge magnitude is related to the probability of its being equaled or exceeded in any year or to its frequency of recurrence or return period.

Deterministic models are, generally, based on physical properties of elements that feature or influence the phenomenon under investigation, such as the catchment characteristics, the channel geometry, the rainfall-runoff process.

Stochastic models

Estimation of floods corresponding to specified return periods is essential for the design of flood protection measures, assessment of regions at risk of flooding, and the pertinent management of flooded areas.

Due to climatic variability, which drives flood events, stochastic modelling has become widely applied to estimate the magnitude of flood corresponding to a specified risk [6,7].

In particular, flood frequency analysis was developed, in the first instance, in response to the need for information for the safe and economical design of engineering structures, either for the conveyance of flood flows (bridges, culverts, diversion channels, reservoirs, spillways) or for the protection or mitigation from flooding of land and property (embankments and walls). Moreover, this procedure is currently used for planning purposes and the design of land-use categories based on flood zoning with respect to vulnerability.

Frequency analysis is most commonly applied to peak discharges, instantaneous or averaged over a specified duration. Analysis is carried out on an observed historic record of river flow with the aim of assessing future probabilities of exceedance. It is also usually assumed that there will be not temporal change in the underlying statistics due to climate variability or to land use changes.

A large number of probability distributions and methods of application have been used for interpolation or extrapolation.

The two main approaches to select the flood series for fitting a stochastic model to the observed floods are based on the series for maxima annual flows (MAF) or partial duration series of floods (PDF). The MAF series selects the maximum flood event for each year, while the PDF series consists of all flood peaks above a specified magnitude.

The MAF approach ignores the fact that the highest flows in some years can be lower than flood events in other years, and hence it excludes significant high flood events in the parameter estimation process. The PDF procedure, on the other hand, considers all significant flood events in its parameter estimation process and its size can extend far beyond the available years of recorded flows.

Recently, a new relation between the return period of the PDF and the MAF series was proposed , based on the assumption that flood events are independent [8]. The General Extreme Value (GEV) distributions, in addition to the Generalized Pareto (GP) distribution have been fitted and applied to analyse flood events.

Deterministic models

Deterministic modelling (flood routing) can be defined as a mathematical procedure for predicting the changing magnitude, speed and shape of a flow wave as a function of time (i.e. the flow hydrograph) at one or more points along a watercourse. The watercourse may be a river, stream, reservoir, estuary, canal, discharge ditch, or storm sewer. The flow hydrograph can result from precipitation runoff, reservoir releases, landslides into reservoirs, or tides. Flood routing may be classified as hydrologic (lumped), or hydraulic (distributed), or hybrid.

Hydrologic models

Hydrologic modelling involves the balancing of inflow, outflow and volume of storage through the use of continuity equation. A second relationship, the storage-discharge relation, is also required between outflows rate and storage in the system. This implies that water surface is level through the watercourse, usually a reservoir or lake. More complex relationships are to be sought for long and narrow reservoirs or open channels where storage is a function of both inflow and outflow. Both graphical and mathematical techniques for solving the continuity equation have been proposed.

The attractiveness of hydrologic modelling consists in its relative simplicity compared with hydraulic models. However, these procedures neglect backwater effects and are not accurate for rapidly rising hydrographs routed through mild to flat sloping rivers. They are also inaccurate for rapidly rising hydrographs in long reservoirs.

Hydrologic models can be categorized as [9]:

- Level-pool types, used for reservoirs;
- Storage types, used for rivers;
- Linear systems types, which assume that the routing channel is composed of linear reservoirs connected by linear channels.

Hydraulic models

A good understanding of a complex flooding event can only be achieved by means of hydraulic models, because the flow rate, velocity, and depth vary in space along the watercourse and across a floodplain and/or a flood prone area. Estimation of these properties can be obtained by using the complete differential equations of 1D or 2D unsteady flow, known as the De Saint Venant (SV) or Shallow Water (SW) equations. Those equations allow the flow rate and water level to be computed as functions of space and time rather than time alone, as in the lumped flow routing methods. Distributed flow routing based on the complete SV or SW equations is known as hydrodynamic routing.

In some cases, the governing equations can be simplified to a 1D continuity equations and a uniform flow relationship, referred to as kinematic wave routing, which implies that the discharge can be computed as a simple function of depth alone. Uniform flow implies a balance between gravitational and frictional forces in the channel. This assumption can rarely be justified, especially on very flat slopes where effects of water surface cannot be ignored.

Selection of a flow routing model for a particular application is influenced by the relative importance placed on the following factors:

- The model's suitability to answer the user's questions;
- The model's accuracy;
- The type and availability of required data;
- The complexity of the mathematical formulation.

Distributed flow routing models are useful tools for determining floodplain depths, required heights of structures (bridges or levees), inundation maps for dam-break contingency planning, transient waves created in reservoirs by gate or turbine changes, landslide-produced waves in reservoirs and unsteady flow in storm sewer systems. The real flow process in each of these applications varies in all three space dimensions. However, normally the spatial variation of the flow characteristics can be approximated as varying in only one space dimension – the direction along the flow channel. Thus the 1D equations of unsteady flow are widely used.

Hybrid models

Until recently, hydraulic models were not reckoned a practical alternative for flood routing because they were considered not economically viable to obtain cross section data over the reaches involved in flood routing.

Recent investigations have revealed that hydraulic routing can be successfully used to determine discharge hydrographs in reaches where little channel geometry data are available, by approximating the model reach by a rectangular channel [10].

It was found that this "limited geometry" modelling approach – based on 1D SV equations – could accurately determine discharge hydrographs, making it an effective and suitable alternative to hydrologic flood routing. It was also found that this hybrid model offers the advantage of operationally combining the flood routing and the determination of flood levels [11]. In addition, the use of a hydraulic model opens up the potential for modelling more dynamic flood events such as ice jam release surges, which cannot be handled by traditional hydrological modelling approaches.

In practical applications, flood forecasting involves two steps.

First, a flood routing model (usually hydrologic) is used to obtain the flood peak by routing flood events between stream flow gauging stations. This flood wave must then be put into a hydraulic model based on detailed channel geometry in order to forecast flood events at key-sites.

A new deterministic approach uses unsteady flow hydraulic modelling for both flood routing and flood level determination. This hybrid model offers the advantage of operationally combining the flood routing and the determination of the flood level. Moreover, this procedure opens up the potential for modelling more dynamic flood events such as ice jam release surges, which cannot be handled by traditional hydrologic or hydraulic modelling approaches.

Challenges and Developments

Hydrological models play a role of paramount importance in the monitoring, forecasting and early warning process of flood events. To this end, it is a demanding task to precisely define the input data needed for flood modelling. Within this context, the most important question to be addressed when defining the quantity and quality of data to be used as input of a model is the purpose pursued. Modelling a flooding event in a specific area, caused by the failure of a dam, or by heavy rain, concern different data and ask for different approaches. In the event of dam failure, precise information on topography and soil characteristics are much more necessary than data on earlier flooding, while in flood forecasting over a broad area, data of historic flooding are essential [7, 8].

The exceptional conditions in which such extreme events occur do not generally permit a sufficient number of observations, for the same type of territory reality to work out the particular behavioral laws for that area. So references to different territorial situations for the same hazard typology are needed.

The ideal sequence that should be pursued in response to the challenge presented by the management and mitigation of floods by using hydrological models can be outlined as follows [12]:

- Systematic collection of field data should be made to provide a large reliable database;
- Effective mathematical models should be constantly developed, updated, tested and applied;
- Hydrological and geological mapping techniques and identification of possible scenarios should be then set up;
- The best mitigation solutions should be designed and implemented on the basis of the knowledge gained in the planning phase;
- a program of systematic observations at the sites where risk has been mitigated should then be planned and carried out to detect any shortcomings and test the efficiency of the investigations and the models used.

Each of the above phases needs improvements and depends, on achieving them, on improvements in the other fields.

As an example, the application of existing models based on data collected in the field and the developments of the new ones would allow, on one hand, to better focus what to observe in the field and, on the other, improve mitigation methodologies and the models' reliability. In this way a sustainable development can be achieved.

Concluding Remarks

In the agricultural sector, the prospects of increasing the gross cultivated area are limited by the dwindling number of economically attractive sites for large-scale irrigation and drainage projects. In this context, most of the world's irrigated land and rainfed land with drainage facilities are located in flood-prone areas.

One-third of the annual natural disasters and economic losses and more than half of the respective victims are flood related. These hazards are likely to become more frequent and more relevant in the future, due to the effects of increase in population, urbanization, land subsidence and the impact of climate change.

A flood is a natural event of great complexity. The hydrological parameters of a flood (magnitude, frequency, celerity, volume, duration) reflect the stochastic behavior of precipitation, interception, infiltration, evapotranspiration, soil moisture, overland and ground flows and river and channel hydraulics. Models not only help in understanding these phenomena, but are also essential for flood risk assessment of the current situation and for the assessment of the expected changes.

By using a model an attempt is made to replace trial and error-based measures. The modelling tool aims to provide the best approach to assess and reduce the vulnerability of rural and high-value urban flood-prone areas as well as industrial zones.

Mathematical models, combined with other measures aiming at solving water management problems, allow good opportunities to develop a set of measures suitable to reduce flood damages to an acceptable level. To this end, the model approach represents the best tool feasible to compare the effectiveness of the options against all the possible flood events, and to choose the best alternative. In this way a harmonious coexistence with floods can be achieved.

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