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Hydro-meteorological disasters: Causes, effects and mitigation measures with special reference to early warning with data driven approaches of forecasting

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Abstract

In this paper, an attempt is made to highlight the causes, effects and mitigation measures of hydro-meteorological disasters with special reference to data driven approaches of forecasting. Recognizing the fact that the frequency of occurrence of water related disasters as well as the consequent damages including human casualties are on the increase in recent years, mitigation measures have become a high priority issue in all vulnerable countries. Structural measures taken by developed countries cannot be applied to developing countries because of the high capital investment. Non- structural measures such as early warning systems are more appealing to developing countries. One of the most important components of an early warning system is a mathematical model that links the input variables to the corresponding output variable. Several approaches of model formulation are discussed and some examples of the more recent fuzzy logic approach to flood forecasting is presented.

Key words: Hydro-meteorological disasters, physics-based models, conceptual models, data driven models, artificial neural networks, fuzzy logic approach

1. INTRODUCTION

Of the 3 main types of natural disasters in the world, geological, hydro-meteorological, and biological, hydro-meteorological disasters account for over 75% in terms of the damages including casualties, economic losses, infrastructure damage and disruption to normal life. They include floods, droughts, cyclones of all types, landslides, avalanches, heat waves, cold waves, and debris flow. Of the hydro-meteorological disasters, floods account for the majority of disasters followed by wind storms. Regionally, Asia suffers the most compared to other continents.

In recent years, flood disasters resulting from extreme rainfall have been on the increase in many regions of the world. In developed countries, the usual practice of mitigating flood disasters is by structural means which are unaffordable in most developing countries. The alternative then is to look for non-structural means that involve, among other things, early warning systems. They are cost effective and in some situations the only option.

The primary causes of all hydro-meteorological disasters are water and wind (風水). Precipitation, in many different forms at the upstream end leads to flooding when it is too high and droughts when it is too low. Wind systems caused by differential heating between the equator and the poles assisted by the Coriolis force lead to different forms of cyclones which have uncontrollable destructive power. Landslides and debris flow are triggered by rainfall whereas avalanches are triggered by excessive snowfall which is another form of precipitation. Heat waves are caused by stationary high pressure regions in the atmosphere which remain aloft for up to several weeks thereby trapping the heat instead of allowing it to lift. Cold waves occur when unusually cold and dense air near the surface in the high latitudes moves into the mid and lower latitudes. In addition to these primary causes, abnormal weather and climate patterns also cause natural disasters which many attribute to ‘climate change’.

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The effects of all these disasters can be in many different forms. For example, frequent floods bring untold miseries, loss of lives, economic damages etc. in many parts of the world. Droughts on the other hand lead to crop failures, famines and diseases which may last for extended periods. Windstorms in the form of cyclones do not last for more than a few days but their consequences can be very destructive. The South-east Asian Region and some parts of USA are particularly vulnerable to windstorm disasters. Slides occur in mountainous areas due to slope failures caused by the weakening of soil cohesion when rainwater infiltrates into the sub-soil. Debris flows occur when movable solid particles in hilly areas are carried downslope by overland flow. In this paper the description is confined to flood disasters.

An early warning system is a set of procedures designed to protect human lives and minimize damages to be expected from a disaster which exceeds a certain critical level. It consists of a number of related and connected parts: forecasting, transformation of the forecast into a warning, transmission of the warning to local decision makers, conversion of the warning into remedial action. Forecasting of an impending event needs an understanding of the causes and effects in quantitative terms and formulation of a mathematical model that links the cause and the effect. The focus of this paper is how this can be achieved.

The basic technical components of an early warning system involves a measurable input data set that trigger a disaster, a measurable output data set that quantify the extent of the disaster and an appropriate mathematical model that transforms the input data set into a corresponding output data set. In the context of floods, the input that triggers a natural flood is the rainfall and the output is the runoff or discharge at a downstream point. There are many types of mathematical models that can be used to transform the input data into corresponding output data. They can be broadly classified into physics based, conceptual and data driven. In this paper, the emphasis is to highlight some of the recent developments in the latter type. In particular, the application of fuzzy logic systems to predict daily discharges in two rivers in two countries including the reliability and robustness of the approach are demonstrated.

2. PHYSICS-BASED APPROACH

In this approach, the starting point is the basic laws of physics: conservation of mass, momentum and energy. They can be described either by following a fixed mass of matter (water in this case) as it moves from a given point in space to another point leading to the Lagrangian approach, or by considering a control volume which would have inputs, outputs and changes in storages leading to the Eulerian approach. The latter is preferred as it leads to differential equations which will have only a single independent variable, or partial differential equations, which may have two or more independent variables. In the case of surface water flow, the governing equations are the St. Venant's equations, or the shallow water equations, which for a one-dimensional physical domain take the following form:

$$\frac{\partial q}{\partial x} + \frac{\partial h}{\partial t} = (i - f) = Q \qquad \text{Continuity Equation} \qquad (1)$$

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} + g\frac{\partial h}{\partial x} + \frac{Qv}{h} = g(S_0 - S_f) \qquad \text{Momentum Equation} \qquad (2)$$

where q is the discharge per unit width; h is the depth of flow; Q is the lateral inflow per unit length per unit width; v is the velocity of flow; S_0 is the bed slope of the flow plane; S_f is the friction slope of the flow plane; i is the rainfall rate; f is the infiltration rate, and x, t are the distance along the flow plane, and time. These two equations in general have no exact mathematical solution. They are normally simplified by making certain assumptions. Two such simplifications lead to the diffusion wave equations and the kinematic wave equations which still have no analytical solutions.

Numerical solutions to Eq. 1 and 2, or their approximations can be obtained by using the finite difference method, the finite element method, or their combinations. Several examples of such numerical solutions of the shallow water equations for a one dimensional flow plane are available in the literature[1,2,3,4]. In order to seek numerical solutions to these or other partial differential equations, it is necessary to define a spatial domain which should be discretized.