Dynamics of Hydro-Meteorological and Environmental Hazards

A W Jayawardena

1. Introduction

Disasters can be broadly classified as natural or human induced. The former type is difficult if not impossible to prevent whereas the latter type is preventable. In terms of the cost and damage induced by various types of natural disasters, "water-related disasters" by far exceed those by any other type. In this context, water-related disasters include all types of floods, land and mud slides, storm surges, tsunami, tidal waves, debris flow, avalanches, droughts, and all types of cyclones. In addition to such geophysical disasters, water-related biological disasters such as epidemics and endemics also take a significant toll in terms of human lives. Human induced disasters include various types of pollution, accidents, and wildfires, among others. In the modern world, pollution of the water environment is a major environmental disaster in many regions, with some places reaching irreversible conditions. The objective of this article is to highlight the causes and mechanisms of such disasters and explore how they can be modelled to predict their outcomes. A better understanding of the initiation and fate of any disaster is important for taking preventive and mitigative actions.

Except for tsunami and tidal waves, all hydro-meteorological disasters are caused by rain or snowfall. Drought, which is lack of sufficient rainfall, can lead to shortage of water that can lead to a disaster if it continues for long periods of time. Under such conditions, the quality of water gets deteriorated resulting in the growth of undesirable microorganisms that can cause water-borne diseases. In uncontrollable situations such conditions may lead to epidemics. Thus rainfall, or the lack of it, can be considered as the triggering cause of almost all water-related disasters.

The preferred approach of attempting to describe and understand the mechanics of such disasters is to use the basic laws of physics to quantify the problem mathematically and to solve the resulting governing equations numerically. However, such an approach cannot be easily implemented without making many assumptions and simplifications at the problem formulation stage as well as at the numerical solution stage. In this article some alternative approaches for particular cases are described.

2. Hydro-Meteorology

2.1. Lapse rate and atmospheric stability

Lapse rate refers to the temperature gradient with respect to altitude. There are 3 types of lapse rates in meteorology and their relative magnitudes determine atmospheric stability. The dry adiabatic lapse rate has an approximate value of 9.8°C/km. The environmental (ambient) lapse rate can take a wide range of values. When the moist unsaturated air rises it will at some altitude reach saturation resulting condensation adding the latent heat of condensation to the thermodynamic process thereby decreasing the lapse rate to a value of approximately 6°C/km. The lowered lapse rate is referred to as the saturated or moist lapse rate.

Instability of the atmosphere can occur if the air is warmer, or, if the air contains more water vapour than dry air. The former condition is maintained when the environmental lapse rate exceeds the dry adiabatic lapse rate. It is also possible for vertical lifting to take place in a stable environment when the surface temperature is very high, e.g. over forest fires, chimneys, explosions, etc.

2.2. Water vapour in the atmosphere

The amount of water vapour contained in the atmosphere is a function of several factors such as the availability of a source of moisture, place, temperature, elevation, etc. A water vapour particle undergoes various phases and physical changes before precipitation takes place. The water vapour must first be carried to upper levels where expansion and cooling take place. When the temperature has reached the dew point, condensation will take place releasing the latent heat to an otherwise adiabatic process. Cloud formation will take place with nucleation around impurities in the water vapour. Droplets coalesce with other droplets forming raindrops which are large enough to cause precipitation. Condensation nuclei range in size from a radius of 10^{-3} μm to 10 μm. The average raindrop size is in the range 500–4000 μm. Large drops are formed by condensation of water droplets on ice crystals or by the collision of droplets with ice crystals. This means that the rain producing clouds must extend to the region where ice crystals are formed (about 5 km). Falling crystals continue to grow both through condensation and the capture of liquid droplets. They change into rain after entering air in which the temperature is above freezing. It is also possible that rain drops may be formed at temperatures above freezing, by the mixing of warm and cold droplets. The warm droplets evaporate and condense on cold droplets. Showers produced by this method are usually light.

2.3. Energy in the atmosphere

Energy in the atmosphere is composed of solar energy, terrestrial energy and tidal energy. The latter two types are small compared to solar energy. Solar energy comes from the sun mostly in the form of short wave radiation. The solar radiation which is received at the surface of the earth is partly reflected back into the outer space as long wave radiation. Of the 1380 W/m^2 (solar constant) of energy received at the top of the atmosphere, only about 350 W/m^2 is received on average at the earth's surface. The energy absorbed by the earth's surface is used to heat the unsaturated air in contact by conduction which then gets lifted by convection, orographic or frontal mechanisms.

Energy utilised in the atmosphere comes from two sources — the heat content of rising air and the heat released by water vapour when condensing to form clouds. The first source is indirectly from solar radiation. Energy in the atmosphere is dissipated mainly as kinetic energy in various wind systems but lightning also discharges some amount of energy.

2.4. Forces in the atmosphere

The forces in the atmosphere include gravitational, pressure gradient, frictional, and Coriolis. The vertical pressure gradient near the ground is about 100 mb/km whereas the horizontal pressure gradient is about 1 mb/100 km at ground level. The horizontal pressure gradient is important in producing wind. The frictional force is significant only near the ground (up to about 1 km). Coriolis force is a fictitious force (or acceleration) introduced into the Newtonian equation of motion to make it valid for a rotating frame of reference since atmospheric motions are measured from a frame of reference on earth which is rotating and therefore is accelerating.

2.5. Governing equations

The governing equations for atmospheric circulation are based on the laws of conservation of mass, momentum and the first law of thermodynamics. They can respectively be written as

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) + \frac{\partial}{\partial z}(\rho w) = 0, \tag{1}$$

$$\frac{Du}{Dt} = 2v\Omega \mathrm{Sin}\,\varphi - 2w\Omega \mathrm{Cos}\,\varphi - \frac{1}{\rho}\frac{\partial p}{\partial x} + F_x, \tag{2a}$$

$$\frac{Dv}{Dt} = -2u\Omega \mathrm{Sin}\,\varphi - \frac{1}{\rho}\frac{\partial p}{\partial y} + F_y, \tag{2b}$$

$$\frac{Dw}{Dt} = 2u\Omega \mathrm{Cos}\,\varphi - \frac{1}{\rho}\frac{\partial p}{\partial z} + F_z - g, \tag{2c}$$

$$dQ = c_v dT + p dV, \tag{3}$$

where u, v and w respectively are the velocity components in the x- (east), y- (north) and the z- (local vertical) directions; ρ is the density of air; p is the pressure; Ω is the angular velocity of rotation of earth; F_x, F_y and F_z are the frictional forces per unit mass; φ is the latitude; g is the acceleration due to gravity; Q is the heat source/sink per unit mass; c_v is the specific heat of air at constant volume; T is the absolute temperature; and V is the volume.

By an order of magnitude analysis the general equations of motion (Eq. (2)) can be simplified to represent different scales of motion. For example, for the synoptic scale of motion ignoring friction terms and acceleration terms, Eq. (2) simplify to the "geostropic equations" (x- and y-directions) and the "hydrostatic equation" (z-direction). For small scale motion, the x and y components of Eq. (2) simplify to (neglecting higher order terms) to the equation for a forced vortex when transformed into polar coordinates. Tornados and waterspouts are described by this equation. In a small scale phenomenon such as a tornado, the velocities are of the order of 50 m/s within a radius of about 100 m. The resulting pressure gradient therefore is of the order of 25 mb/100 m which is very powerful and destructive.

2.6. Atmospheric General Circulation Models (AGCM's)

Early general circulation models of the atmosphere were developed to solve the governing equations at 5° × 5° latitude-longitude grid (≅ 550 km × 550 km). Present day AGCM's have a much higher resolution. For example, the Japan Meteorological Agency Global Spectral Model (JMA-GSM) uses 1920 (longitude) ×

960 (latitude) grid cells corresponding to a size of approximately 20 km × 20 km with 60 vertical layers extending up to a pressure level of 0.1 h Pa (Mizuta *et al.*, 2006). This corresponds to 1,843, 200 nodal points on the surface of the earth with several degrees of freedom at each nodal point. Such computations can only be carried out with supercomputers such as the "Earth Simulator" which is a parallel vector supercomputer system developed by the Japan Aerospace Exploration Agency (JAXA), Japan Atomic Energy Research Institute and the Japan Marine Science Technology Centre, which at one time was the fastest computer in the world.

The governing equations (sometimes called the "primitive equations"), or their simplified forms, together with the boundary and initial conditions constitute the basis for AGCM's. For a solution to be obtained the frictional force term F and the heat source/sink term Q must be expressed as functions of the unknown variables u, v, w, p, ρ and T. Any two of the three thermodynamic variables p, ρ and T would describe the system completely.

3. Hydrology

The two principal processes in the hydrological cycle are precipitation and evaporation. Runoff is the outcome of precipitation that can be thought of as an integrator of all catchment processes which in excessive quantities leads to flooding. Mitigation of flood damages has now become an essential step towards economic development. Issuing early warning is one of the main non-structural measures favoured and adopted nowadays.

The basic input information that goes into an early warning system for flood damage mitigation is rainfall. Runoff, or river flow, can also be used as basic input information, but it is more difficult and costly to measure. Therefore runoff is predicted using mathematical models that transform the input rainfall to a corresponding output runoff or stage. River discharge (or "stage") prediction becomes an important component of any early flood warning system.

The unit hydrograph approach, which relates rainfall excess to direct runoff is perhaps the earliest rainfall-runoff model. Due to its simplicity and linearity assumption, it has stood the test of time. Other types of rainfall-runoff models can be broadly classified into two categories: Data-driven and distributed. Data-driven types include regression methods, stochastic methods, artificial neural networks, genetic algorithms, and phase-space reconstruction methods, among others. Distributed types are generally physics-based, but some semi-distributed models are conceptual in formulation. Regression models, which are purely statistical in character, aim to find a relationship between the rainfall data and the corresponding runoff data. Stochastic models decompose the time series of rainfall data and/or runoff into constituent components such as trends, periodic parts, dependent stochastic parts, and random residual part. Once the structure of the time series is determined, more samples that will have the same statistical structure could be generated for different random samples of the residual component. Such methods can be used for synthetic data generation as well as for forecasting purposes.

Emerging data driven methods of rainfall-runoff modelling include the application of artificial neural networks (ANN), genetic algorithms (GA), genetic programming (GP), support vector machines (SVM's) and phase space re-construction methods. A typical multi-layer perceptron (MLP) type artificial neural network has a layer of input nodes, one or more layers of hidden nodes and a layer of output nodes and is said to possess universal approximation capability. In addition to MLP's, there are several other types of ANN's such as radial basis function networks (RBF's), recurrent neural networks (RNN's), wavelet neural networks (WNN's) and product unit neural networks (PUNN's) with each type having its own pros and cons. Theoretical details of ANN's can be found in several textbooks while applications in hydrology can be found in several research papers. References to these and others can be found at the end of Chapter 8 of "Environmental Hazards".

Distributed models may be of the conceptual type, such as for example, the Xinanjiang model and the Variable Infiltration Capacity (VIC) model, or physics-based type such as for example the MIKE-SHE model. The approach to the development of a physics-based model involves the description of the problem, simplification of the problem, definition of a set of governing equations, choice of a set of boundary and initial conditions, identification of the solution domain in space and time, solution of the simplified governing equations subject to the given boundary and initial conditions within the domain of interest using a numerical scheme, calibration, verification and application. Distributed models are more resource intensive and need a great deal more input information than data driven models. Although, potentially, such models are capable of accommodating spatially varying inputs, outputs and parameter values, their calibration becomes quite difficult. Because of the interactions among different parameters, very often it is not possible to obtain a unique set of parameter values. A practice that is often adopted is to ignore spatial variation of physical and hydraulic parameters and obtain their spatially uniform values by optimisation techniques, thereby diluting the meaning of distributed models. Practical applications of such models in a truly distributed manner are still some way ahead.

4. Water-Related Environmental Hazards

Unlike hydro-meteorological hazards which cannot be prevented, environmental hazards in general are preventable. Water-related environmental disasters may be caused by pollution in rivers, streams, lakes, reservoirs, coastal bays, groundwater, inland seas and the open oceans. They may also be caused by the lack of water causing diseases and loss of food production leading to famine. Pollution of waterbodies may take place slowly over a long period of time or by accidents in a short time. To mitigate the consequences of such pollution the first step would be to have a better understanding of the dynamics of the fate and transport of pollutants in waterbodies. Due to the complex nature of the mixing, decay and transport characteristics of different pollutants under different hydraulic conditions, certain assumptions and simplifications are necessary.

4.1. Well-mixed waterbodies

The well-mixed assumption implies that there are no concentration gradients spatially. This is an idealised assumption. Concentration is assumed to vary only in the time domain. Nevertheless, the assumption enables an understanding of the gross effects of how a pollutant attains steady-state conditions from an initial state. In addition to the well-mixed assumption, several other assumptions are also necessary to obtain solutions to the governing equations. For example, the input waste load, corresponding outputs, hydraulic parameters of the waterbody as well as the reaction rates may be considered as time-invariant or time-varying. Finally, the system can be assumed to be either linear or non-linear. Under a linear assumption, the parameters and inputs may also be considered as time-invariant or time-varying. Different combinations of these assumptions and their variations can lead to a large number of possible modelling options.

4.2. Dissolved oxygen systems

The health of a waterbody can be measured by the amount of dissolved oxygen (DO) which depends upon its temperature, elevation and salt content. Under pristine conditions, the concentration of dissolved oxygen would be at saturation level, which at 0°C is about 14.6 mg/l, at 30°C about 7.56 mg/l, and at 40°C about 6.41 mg/l. The dissolved oxygen concentration decreases with decreasing pressure and increasing salt content. For fish to survive in a waterbody, the dissolved oxygen concentration must be at least 4–6 mg/l.

The fluctuation of DO in a waterbody takes place as a result of oxygenation and de-oxygenation. Oxygenation takes place via re-aeration, which is the process of oxygen transfer from the atmosphere to the water body, from tributaries carrying water with higher DO concentration, and by photosynthesis. De-oxygenation takes place via the oxidation of Carbonaceous Biochemical Oxygen Demand (CBOD), Nitrogenous Biochemical Oxygen Demand (NBOD), Sediment Oxygen Demand (SOD), and, algal respiration. CBOD refers to the reduction of organic carbon to CO_2 in the presence of micro-organisms such as bacteria, NBOD refers to the biological oxidation of ammonia (NH_3) to nitrates (NO_3^-), and SOD refers to aerobic decay of organic benthic material, which is negligible in flowing water. Assuming that there are no external inflows and outflows contributing to the oxygen mass balance, the rate of change of concentration c, can be written as

$$\frac{dc}{dt} = \left(\frac{dc}{dt}\right)_{\text{decay}} + \left(\frac{dc}{dt}\right)_{\text{re-aeration}} = -k_d L + k_r(c_s - c), \quad (4)$$

where k_d and k_r are the de-oxygenation and re-oxygenation coefficients L, the BOD remaining in the water at time t, and c_s, the saturation value of dissolved oxygen concentration. In many situations, it is convenient to convert this equation to represent the oxygen deficit D which is defined as $D = c_s - c$. The solution to Eq. (4), assuming first order decay for the BOD, is of the form

$$D = \frac{k_d L_0}{k_r - k_d}(e^{-k_d t} - e^{-k_r t}) + D_0 e^{-k_r t}, \quad (5)$$

where L_0 is the ultimate BOD remaining in the water at time t and D_0 is the initial oxygen deficit. Replacing the time variable by a distance variable, Eq. (5) can be re-formulated as

$$c = c_s - \frac{k_d L_0}{k_r - k_d}\left(e^{-k_d \frac{x}{u}} - e^{-k_r \frac{x}{u}}\right) - D_0 e^{-k_r \frac{x}{u}}, \quad (6)$$

where x is the distance from the outfall, u is the average velocity in the river, and $t = x/u$. Equation (5) (or Eq. (6)) is referred to as the Streeter–Phelps equation, or the Oxygen Sag Curve. Implicit in this equation are the assumptions that the flow in the river is non-dispersive, steady state flow BOD and DO reaction conditions, and the only reactions are de-oxygenation by decay and re-oxygenation by aeration. It should also be noted that the equation is not valid when $k_r = k_d$. The critical (minimum) oxygen deficit can be estimated by setting $(dD/dt) = 0$.

4.3. Water quality in rivers and streams

Water quality variation in a river system depends upon many factors such as the hydraulic parameters, presence of tributaries and abstraction points, outfalls of waste material at fixed discharge points, non-point sources of pollution, and whether the system is considered as at steady state or unsteady state. Different conditions lead to different formulations and solutions. The system should therefore be considered under specific assumptions and specific waste input conditions. The simplest is when there is a point source of waste loading in a river which is assumed to be a one-dimensional waterbody. The formulation in this case is carried out under the idealised assumptions that there is no concentration gradient across the width and depth of the river, that there is no dispersion in the longitudinal direction, and that steady state conditions prevail. Although analytical solutions under specific assumptions and specific time dependent input waste loads can be found, the general water quality problem is solved using numerical methods. A number of commercial software packages for this purpose are currently available.

5. Concluding Remarks

In this article, an attempt has been made to highlight the dynamics of the processes that lead to hydro-meteorological and environmental hazards and some of the approaches that are available for predicting their consequences. It is an abridged version of Chapter 8 in the book entitled *Environmental Hazards* published by World Scientific. All the references relevant to this article are cited and listed in the unabridged version.

References

[1] R. Mizuta, K. Oouchi, H. Yoshimura, A. Noda, K. Katayama, S. Yukimoto, M. Hosaka, S. Kusunoki, H. Kawai and M. Nakagawa, 20-km-mesh global climate simulation using JMA-GSM model – Mean climate states, *J. Meteorological Society Japan* **84**(1) (2006) 165–185.

[2] A. W. Jayawardena, Dynamics of hydro-meteorological and environmental hazards, *Environmental Hazards: The Fluid Dynamics and Geophysics of Extreme Events*, Lecture notes series, Institute for Mathematical Sciences, National University of Singapore, Vol. 21, eds. H. K. Moffatt and E. Shuckburgh (World Scientific, Singapore, 2011), pp. 229–267.

A W Jayawardena

International Centre for Water Hazard and Risk Management (ICHARM) under the auspices of UNESCO, Public Works Research Institute, Tsukuba, Japan

A W Jayawardena is currently the Research and Training Advisor to the International Centre for Water Hazard and Risk Management (ICHARM), a UNESCO centre hosted by the Public Works Research Institute of Japan, and a Professor at the National Graduate Institute for Policy Studies (GRIPS) in Tokyo, Japan. Before joining ICHARM, he was attached to the Department of Civil Engineering, and has also been an Honorary Professor in the Department of Statistics and Actuarial Sciences, both of the University of Hong Kong. His research interests include, hydrology, environmental systems, data driven techniques in hydrological modelling, among others. He has been a specialist consultant to UNESCO and several consulting engineering companies dealing with water related projects.