TRANSPORT PROCESSES IN RIVER SYSTEMS

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Contents

Summary

A short overview of some problems related to the transport processes in river systems is presented. At first the basic elements of river hydrology like the catchment and all the components of the mass balance equation are described. The catchment receives water from precipitation and loses some water in the process of evapotranspiration and the river outflow. These three components of the mass balance equation are described. The methods of measurement and estimation of these components are also presented. The main river with all its tributaries forms the river network. This network is fed by rainfall and snowmelt in the form of surface overflow and subsurface ground water inflow. The whole process of creation of a river network is very complicated and its form depends on many hydrological and geographical factors.

Rivers flowing through the catchment transport water, sediment and other chemical substances and biological species. River sediment is mainly formed in the catchment as the result of surface erosion. The sediment can be transported as bed load or suspended load. Bed-load and suspended load sediment are defined and exemplary data for total sediment transport by rivers are cited. Rivers transport many chemical substances and biological species because of domestic, municipal and industrial wastewaters. Usually,

the wastes are collected in sewerage systems and after their treatment are discharged into rivers. In case of electrical power plants the hot water is only cooled and discharged into rivers. There are many different kinds of pollutants in river water and some of them are depicted. Also, a general criterion for assessment of river quality on sewage disposal is described.

1. Introduction

The purpose of this chapter is to give a brief overview of some problems, which are discussed in depth in the following five sections:

1. River Flow
2. Thermodynamics of Rivers
3. Constituent Transport
4. Transport of Sediments
5. Dissolved Substances

Let us start from some basic definitions. First of all the river systems and transport processes are defined precisely. To define a river system we begin with the description of a catchment, a river itself and a river network. These three objects are related to each other. A river begins in the high region of the catchment where snowmelt and rainfall wash over creating small streams. As the streams descend, they join with others and create rivers. In the lower parts of catchment, rivers slow down and start to meander, seeking the path of the least resistance. In case of a big river flowing into a sea, in area where its catchment is flat and strength of flow is too low to carry sediment; the sediments settle down forming a delta. The main river with its tributaries, and the tributaries with their tributaries, and so on create the river network. This network is fed by rainfall and snowmelt in the form of surface overflow and subsurface groundwater inflow. The whole process of creating a river network is very complicated and its form depends on many factors like topography of the region, climate, kind of earth surface, types of soil, and others.

The catchment receives the water from precipitation and loses some water in the process of evapotranspiration, i.e. evaporation from open water, vegetation and land surface. All processes, which take place in the catchment, are introduced and some relationships between them are discussed. These relations are derived from the fundamental law of physics, the mass conservation law. The main hydrological process in the catchment is the river outflow (discharge). The stream flow hydrograph shows the time variation of discharge for a given cross section and a period of time. The hydrograph is a very important tool for analysis of different properties of catchments. Also, the large river systems of the world are presented together with their main characteristics.

The primary role of rivers is the transport of water, sediment and other chemical substances and biological species. Rivers and their rich variety of plants that they sustain provide our society with water for drinking, washing and agriculture. While rivers provide life, they also bring a risk of catastrophic floods. To avoid this, big dams are constructed to create large reservoirs. Dams are used to control river discharge and to regulate its seasonal pattern of floods and low flows. Also, dams trap sediments and

nutrients, alter the natural river circulation, and disturb the geological processes of erosion and deposition. River sediment is mainly formed in the catchment as the result of surface rainfall erosion. The sediment can be transported as bed load or suspended load depending on the strength of river flow. There is in no sharp distinction between these two forms. Bed-load and suspended load sediment are defined and some data on the total sediment transport by rivers are cited.
Towns and cities use rivers to carry away their domestic sewage. Also municipal and industrial wastewaters are discharged into rivers. Usually, the wastes are collected in sewerage systems and after treatment are discharged into rivers. In case of electrical power plants the water is only cooled and discharged into rivers. There are many different kinds of pollutants in river water and some of them are depicted. Also, the general criterion for assessment of river quality in sewage disposal is described.

2. Catchments

Rivers flowing to the seas or to lakes are fed by tributaries and also by small gullies through which water trickles from rain, snow, and ice or from subsurface sources. The area of land draining into a river is called catchment. Most commonly, the catchment is defined as the area that topographically appears to contribute all the water that passes through a given cross section. The location of the river cross section that defines the watershed (boundary between catchment areas) is determined by hydrologists. Hydrologists are usually interested in delineating watersheds above river cross sections where the river discharge is measured in order to determine the region (catchment) contributing to stream flow. Since there are many measuring cross sections along a river, many watersheds can be drawn for each cross section of the river. Figure 1 shows the catchment of the Vistula River.

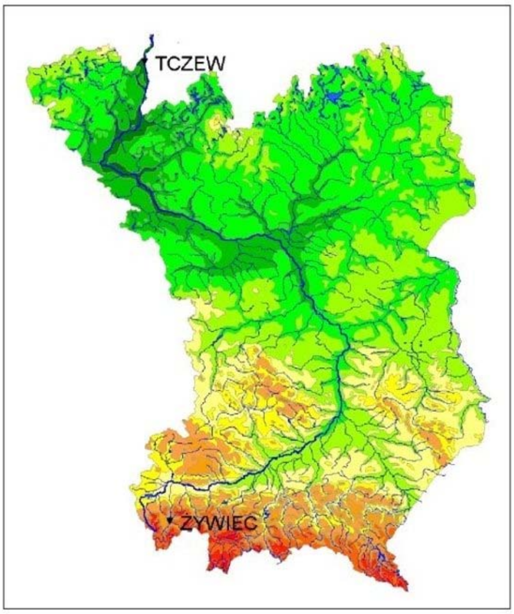

Figure 1: Catchment of the whole Vistula River. The gauging cross sections at Tczew (Vistula River) and Zywiec (Sola River, tributary to Vistula) are depicted. (Source: IMGW Warsaw, Poland)

A catchment can be described in terms of size, topography, geology, vegetation cover and surface draining pattern. The main geometrical characteristics of a catchment are its area A, the mainstream length L, the largest width B and shape coefficients: A/B, A/L and B/L. Hydrologists suggest a relation between the catchment area and the mainstream length in the form: $L \sim A^{0.5}$ (L is proportional to square root of the area) and the shape similarity of catchments especially within the same catchment, i.e. sub-catchments and the main catchment often have similar characteristics. The catchment descriptions in other terms can be found in specific scientific literature or textbooks listed in Bibliography at the end of this chapter. The river and its tributaries have also been investigated with respect to the stream network of which they form a part. The smallest streams are defined as being of order one. When two streams of order one meet, a stream of order two is formed, and so on. The number of streams of order one, two, etc. (N_1, N_2, N_3,..) provide an insight into the degree of branching or bifurcation by the ratios N_1/N_2, N_2/N_3, N_3/N_4, etc. When the bifurcation ratio is large, the catchment has many small streams and relatively few big ones. Many rivers have approximately constant bifurcation ratios. The variation of this ratio between different river catchments ranges from 2 to 5.

3. Conservation Laws

The basic relations of river catchment are derived from fundamental laws of classical physics like the conservation of mass, momentum and energy. These fundamental laws can be stated as follows:

> The amount of a conservation quantity entering a catchment volume during a defined time period, minus the amount of the quantity of leaving the volume in this period, equals the change in the amount of the quantity stored in the catchment volume during the time period.

This statement can be rewritten in the form:

Amount in – Amount out = Change in storage (1)

Applying the mass conservation law to the catchment, it can be stated that the water falling on the catchment area partly evaporates, partly infiltrates while the remaining part leaves (flows through the adequate cross section) the catchment. Consider the process over a reasonably long time period, the mass balance for the catchment volume can be written as (details are displayed in Figure 2.):

$$P + G_{\text{in}} - (Q + G_{\text{out}}) - E_{\text{T}} = \Delta S \qquad (2)$$

where:

P = precipitation
G_{in} = ground water inflow
Q = river outflow through the considered cross section
E_{T} = total evaporation or evapotranspiration, i.e. the total mass of water that leaves the catchment via direct evaporation from surface-water bodies, snow, and ice,

plus that which is called is evaporated after passing through the vascular system of plants, what transpiration

G_{out} = ground water outflow

ΔS = net changes in storage

The expression in parenthesis in Eq. (2) is called the runoff. It represents the total amount of water leaving the catchment in the period of time under consideration.

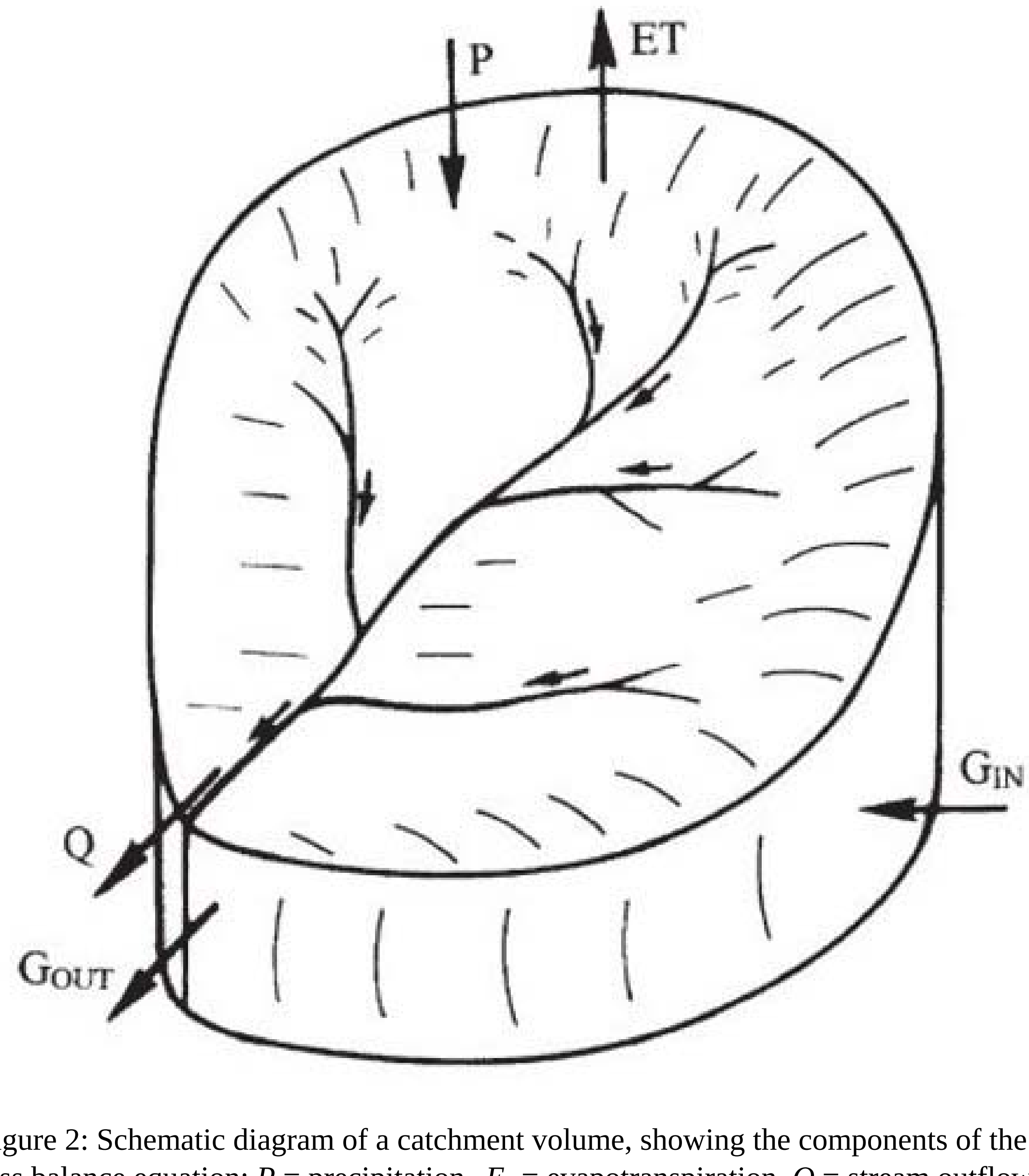

Figure 2: Schematic diagram of a catchment volume, showing the components of the mass balance equation: P = precipitation, E_T = evapotranspiration, Q = stream outflow, G_{in} = ground water inflow, G_{out} = ground water outflow.

All the quantities appearing in the above equation are subjects of measurement, evaluation or calculation in hydrology. Usually, a constant density of water is assumed and all these quantities are expressed in volumes (sometimes as the ratio of the volume and catchment area) of water by the duration of measurement period. Some details about quantities that appeared in the mass balance equation are described below.

- The evaporation is one of the crucial catchment processes. It occurs from three main situations: from open water bodies, like lakes, reservoirs and large rivers; from water droplets stored in the upper soil; from leaves of plants or generally from vegetation-covered surfaces (this process is called transpiration). The process of evaporation occurs because molecules of a liquid attain sufficient kinetic energy to overcome the surface tension of the main body and escape. The process requires a vapor pressure deficit in the air adjacent to the evaporating surface. Evaporation is determined largely (but not solely) by meteorological variables like solar radiation, temperature, humidity and wind speed. There is a variety of evaporation pans (small tanks) to measure direct evaporation form the water surface. However, these small tanks of water are only scale models of the lakes and they do not give a reasonable estimation of the real evaporation. To measure the transpiration from soil or vegetation lysimeters are used. The lysimeters are enclosed areas (columns, tanks, or plots) of soil and vegetation, open to the sky from which infiltrated moisture can be collected and moisture storage measured. There are different types of lysimeter. The largest ones enclose hundred square meters. The process of transpiration is too complicated for direct measurements. The lysimeters like the evaporation tanks do not give reasonable values for the transpiration from the catchment area. Therefore the evaporation is estimated from the water-balance equation after neglecting some terms in it. This approach is applicable because there are techniques to determine the precipitation over the catchment area and the stream flow from the area, and because it is impossible to measure evaporation directly from the catchment area.
- The precipitation is only one income term (G_{in} is negligibly small) in Eq. (2). Thus, in order to assess, predict, and forecast any quantities in the balance equation, we need to estimate the amount, rate and duration of precipitation as well as distribution over the catchment. The precipitation in Eq. (2) shows the total mass (volume) of water entering the catchment in the considered period of time. The precipitations are measured by the precipitation gauges (gages) at some observation points and estimated over the whole catchment. The precipitation gage (rain gage) is a simple vessel open to the air located at the point of observation. It collects the rainwater and the volume of the water is periodically measured or continuously recorded. However, there are many reasons for concern about the accuracy related to the precipitation measurement at a point and transformation of it over the catchment area. The quantity of water that enters the gage depends on the size of orifice gage, its orientation and location. Hydrologists agree that to get more true precipitation, the orifice diameter should not be so small, the gage orifice should be leveled (sometimes parallel to the ground surface) and the gage should be located within an open space where the wind effects are reduced. Unfortunately there is not any standard for rain gage sizes, its installation and observation. Each country has its own standard, for example, the orifice diameter ranges from 127 mm (MK2, UK) to 225 mm (SPIEA, France), and the orifice position above ground ranges from 300 mm (UK) to 1000 mm (France). The average precipitation over a region can be calculated from point measurements by special methods. Some

methods give only the spatially averaged precipitation, whereas others provide additionally spatial distribution of precipitation in a given catchment. The choice of method depends on the objectives of computations, existing precipitation-gage network and the nature of the region. Of course, each method produces errors and the final average precipitation is only an estimation of real value.

The measurement of snow in precipitation gages is full of difficulties and therefore is a subject to several sources of errors which are very difficult to remove. For these reasons, it is preferable to measure the water content of snow by other than standard precipitation gages.

Usually, the depth of snowfall or snow cover is measured and its water equivalent. The depth is measured by a simple ruler and the water equivalent is expressed as the depth of water that would result from the complete melting of the snow. Having these parameters the water content in snow cover of the whole catchment can be estimated.

- The net change in storage over a period of time is the difference between the amount of water in storage in the catchment at the end of the period and the amount of water in storage in the catchment at the beginning of this period. Writing the mass conservation equation over a reasonably long time period in which there are no significant climate changes and no anthropogenic inputs, outputs, or storage modification, we can assume that net change in storage is zero.
- Ground-water inflow G_{in} represents the ground-water inflow from neighboring catchments. It occurs when the boundaries of the subsurface drainage system do not coincide with the boundaries of the surface drainage system (watershed). The ground-water inflow is so small compared to other terms in the mass balance equation that is not worth considering. However, such simplifications can be obtained by analysis of particular geological situation.
- Ground-water outflow G_{out} is usually considered negligible in the mass balance equation. However, it is strongly dependent on particular geological situation as well as the topography of the catchment. For example, the higher the elevation of catchment area and the larger hydraulic conductivity of catchment geological composition, the more likely it is to lose water by subsurface flow.

Taking into account what was said about all terms, the mass balance equation for a given catchment and reasonable long period of time, e.g. one year, can be written in simpler form:

$$P - Q = E_{\mathrm{T}} \qquad (3)$$

Knowing the precipitation and evapotranspiration for a given catchment, one can estimate the amount of water which can be used for human water supply. Usually the Eq. (3) is used to estimate the evapotranspiration, which is very difficult and expensive for direct measurement.

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Biographical Sketch

W. Czernuszenko, Professor, Institute of Geophysics, Polish Academy of Sciences, Warsaw, Poland.He has graduated from the Faculty of Civil Engineering of the Warsaw University of Technology (M.Sc. Degree) as well as from the Faculty of Applied Mathematics of the Warsaw University, also with M.Sc. degree in Mathematics. He received his Ph D degree from the Warsaw University of Technology upon presentation of the doctorate thesis "Mass transfer in the open channel flow " and his Dr. Hab. Degree based on his monograph "Dispersion of Pollutants in Rivers and Channels. During 1991 – 1994, he occupied the position of visiting professor at Mechanical Department of the University of Mississippi and he worked for National Center for Computational Hydroscience and Engineering at the same University.

As a researcher he is interested in application of fluid mechanics to environmental problems related to mass and heat transfer in open channel flows and particularly to modeling of pollution transport and sediments in rivers. He has been doing experimental works in fields and water laboratories related to turbulence in rivers and open channels, mixing processes in flowing surface waters and fluvial hydraulics. Also, he has been doing some theoretical works on mathematical modeling of free surface flows, modeling of turbulence and transport of mass in turbulent flows.

The results of his works have been published in many scientific international journals and presented at some international conferences.