DYNAMICS AND CYCLING OF MATERIALS IN RIVER SYSTEMS

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Contents

Summary

Materials enter the hydrological cycle primarily by erosion from rocks and soils and, to a different extent, by dissolution during that process. Land use is a major factor which, superimposed upon geology, determines the nature and quantity of materials transported. Their nature in flowing waters depends upon their elemental and molecular properties. Once in river systems, the processing of materials has been described by a number of concepts which incorporate hydrological processes with in-river ecological processes—the River Continuum Concept, the Spiralling Concept and the Floodpulse Concept are the most important. Nowadays they are collectively referred to as ecohydrological concepts. Apart from water, undoubtedly the two most important materials in river systems are the nutrients nitrogen and phosphorus which, although not considered 'major' elements in terms of quantitative composition, are 'major' in terms of the control they exert on biological systems. In most natural circumstances phosphorus is considered to be the limiting factor for photosynthesis, hence also autotrophic growth and ecosystem productivity.

1. Introduction

Living organisms require around 40 of the elements that naturally occur in the Earth's crust and atmosphere to sustain growth and reproduction. The most important, carbon, is usually considered separately from the others, because it is the energy locked into chemical bonds between carbon atoms and those with oxygen and hydrogen atoms which is the basis of the photosynthetic conversion of solar energy into living tissue. Oxygen and hydrogen are freely available in water under most circumstances. Other essential elements are usually considered in two groups: the macronutrients or major elements, required in large quantities, and the micronutrients or trace elements, required in small quantities. Calcium, magnesium, potassium, nitrogen, phosphorus, sulphur and iron are the most important of the macronutrients, together with silicon (used in cell frustules by diatoms and a few other algal species), whilst copper, cobalt, molybdenum, manganese, zinc, boron, vanadium, chlorine and vitamin complexes are the most important of the micronutrients. Phosphorus and selenium are the elements derived from the Earth's crust (lithosphere) essential to life, whose proportional abundance is lower in the lithosphere than in plant tissue. Phosphorus is thus often the limiting macronutrient for life. Selenium, followed by zinc, molybdenum and manganese are potentially limiting micronutrients.

In a natural, undisturbed aquatic environment, the nutrient supply is derived from the drainage of the catchment together with direct rainfall and any internal recycling which may occur from the sediments. Studies that have been made of such catchments (and in the northern hemisphere the more natural catchments are generally forested) have shown that nutrient runoff is very low because cycling within the vegetation of the terrestrial ecosystem is very tight. The same is true of tropical forests and savannahs. In the temperate zones, runoff from natural or secondary grassland is higher in nutrients than runoff from forested land, and runoff from arable land is higher still. Urban areas and effluents produce a range of high-nutrient effluents.

The initial natural source of most material is weathering of rocks. Using phosphorus as an example, igneous rocks contain apatite—complexes of phosphate with calcium—the weathering and subsequent marine sedimentation of which have led through geological history to phosphates being widely distributed in sedimentary rocks. The common weathering processes of such rocks lead to clays in which the phosphate is moved from apatite into the clay complex. It is both tightly bound into the clay lattice in place of hydroxyl ions and more reversibly bound by electrostatic attraction to aluminium or iron ions. The atmosphere naturally contains few minerals of importance to aquatic systems other than those derived from nitrogen gas. The main source of nitrogen for all biological activity on this planet is the atmospheric reservoir of gaseous nitrogen, which is made available to organisms by fixation into a variety of oxides or reduction to ammonium. These events occur as a result of electrical or photochemical processes in the atmosphere but the major pathway is fixation by microorganisms in the soil, which is about seven times greater than nitrogen from all atmospheric processes brought to Earth by rainfall.

2. Primary sources of materials

Soil erosion processes, including material eroded from the riverbank, from riparian areas, from agricultural soils and from deforested mountain slopes, provide the bulk of the suspended materials which accumulate in river systems. Of secondary importance are contributions provided by wash-off from urbanized areas, direct effluents produced by human activities other than farming (industrial, mining, transport) and autochthonous material formed within water bodies (i.e. calcium carbonate precipitation, particulate organic matter formation). Anthropogenic particle sources which do not relate to agricultural practices, provide the primary origin for most trace metals and Persistent Organic Pollutants (POPs).

Under natural, undisturbed, conditions, erosion processes would be concentrated in upland, higher gradient, areas. In addition to natural erosion forces associated with rivers and glacier movements, infrequent catastrophic events such as floods, avalanches and landslides cause the bulk of soil erosion. Much of this material becomes trapped in the higher parts of floodplains from where it is slowly mobilized by further infrequent high floods.

The largest portion of the particulate load, under the current conditions of anthropogenically-accelerated erosion, comes from deforested and inappropriately-farmed slopes and cultivated floodplain soils. The flushing of the soil surface acts selectively and removes a disproportionate amount of fine fractions, rich in nutrients and organic matter. The enrichment ratio between the sediment eroded and the original soil is usually of the order of 1.2 to 2 times but may be as high as 12 times in fertile tropical soils.

The major contributions of material in early storm runoff are provided by rapid hydraulic transport pathways, known as macropores—tiny (mm), vertical, preferential flow channels, through which surface soil solutions migrate rapidly, avoiding contact with the soil profile. Earthworms are primary natural causes of macropores, but many agricultural fields are often nowadays tile-drained, a practice that favours water percolation through soils leading to macropore development. Extensions of the hydrologic network through surface drains, pathways and cattle tracks throughout the catchment, constitute additional sources. Thus, subsurface flow often transports significant fluxes. Unequivocal evidence for top-soil migration through macropores has been demonstrated by means of 137 Cs measurements. Top-soil nutrients become lost and cause eutrophication as subsurface flows join with groundwater. Soil type seems to be a determinant factor in this process which still needs to be better understood. On the other hand overland flow becomes relevant later, following soil saturation which tends to be delayed, especially in sandy soils.

3. Materials and the hydrological cycle

All materials enter water as it runs off or through rocks, vegetation and soils, either as soluble compounds (ions) or particulate material (usually eroded soil or rock particles). The contrast between the P and N cycles (above) illustrate these differences well. The quantity of materials depends upon the magnitude of water discharge, which changes through a year with changing seasons. In the temperate zones these are winter (colder and wetter) or summer (warmer and dryer); in the tropical zones where there may be little year-round temperature change, they are rainy and dry seasons. Annual river discharge measured at any site thus shows certain regularities, depending upon the latitude, altitude and position in the river catchment. This is a more-or-less predictable pattern but with several unpredictable (storm or drought) events. Thus, superimposed on the annual sinusoid discharge curve are peaks from storm run-off or troughs from extreme dry periods. In smaller streams, these effects can be so great that the annual discharge curve is barely recognizable. Figure 1 shows the annual discharge in three decades of a small Dutch stream of 25 km and an effective basin of 50 km^2.

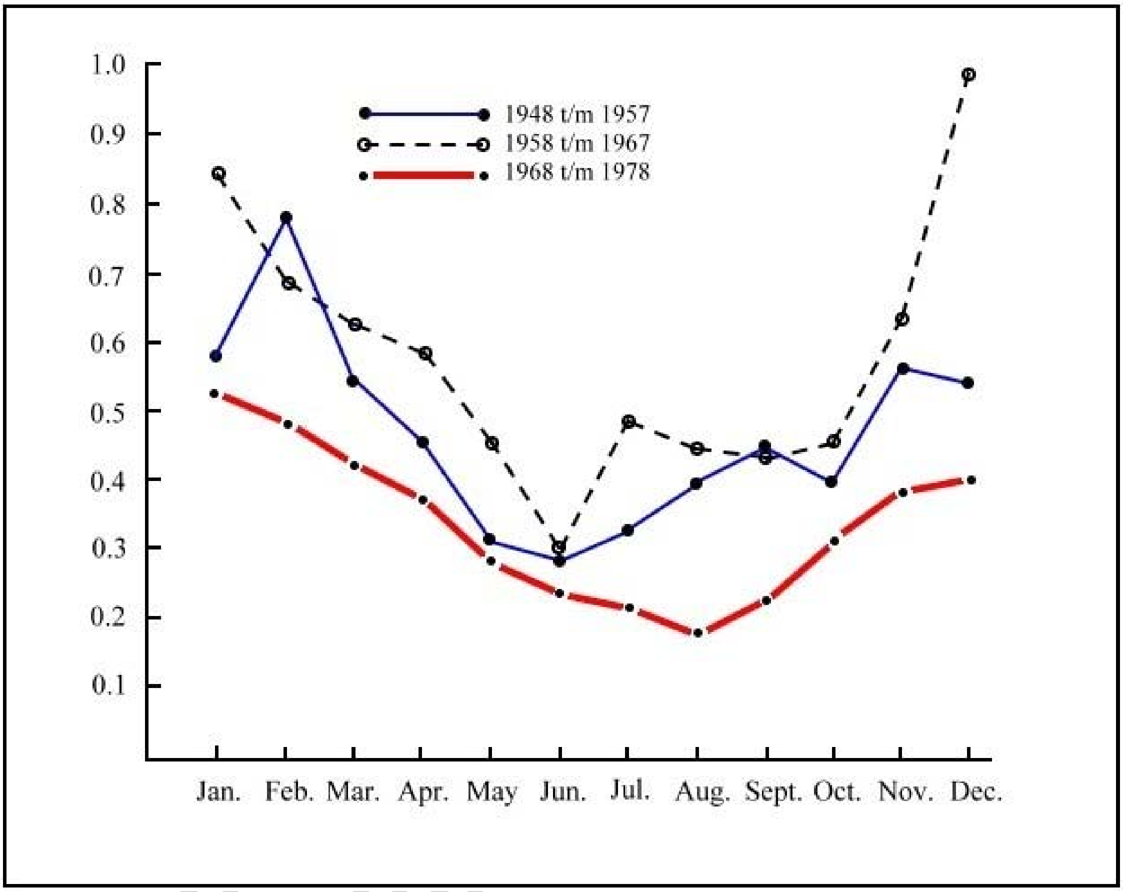

Figure. 1. Discharge in the Hierden stream, Netherlands, over three decades

Figure. 2 shows the discharge in two extreme years, 1966 and 1970. It is obvious that the total discharge in both is different (an average 0.92 $m^3\ sec^{-1}$ in 1966 and 0.49 $m^3\ sec^{-1}$ in 1970).

Particles are transported by running waters in two modes—by rolling/sliding along the streambed and suspended in the flow. Little is known about the former—the bedload—contribution to particle transport.

In general quantitative bedload estimates are believed to be between 10 and 20% of the total annual particle load carried by streams. Particles moving along the streambed consist mainly of coarse sands and gravels.

Their relative importance in the dynamics of element transport in streams is minor, due to the refractory nature of the elements transported and their slight impact on biogeochemical cycles. From a geomorphological point of view, however, bedload contributions are very important in contributing to the structuring of floodplain soils and estuaries. Suspended particles are chemically and biologically more important.

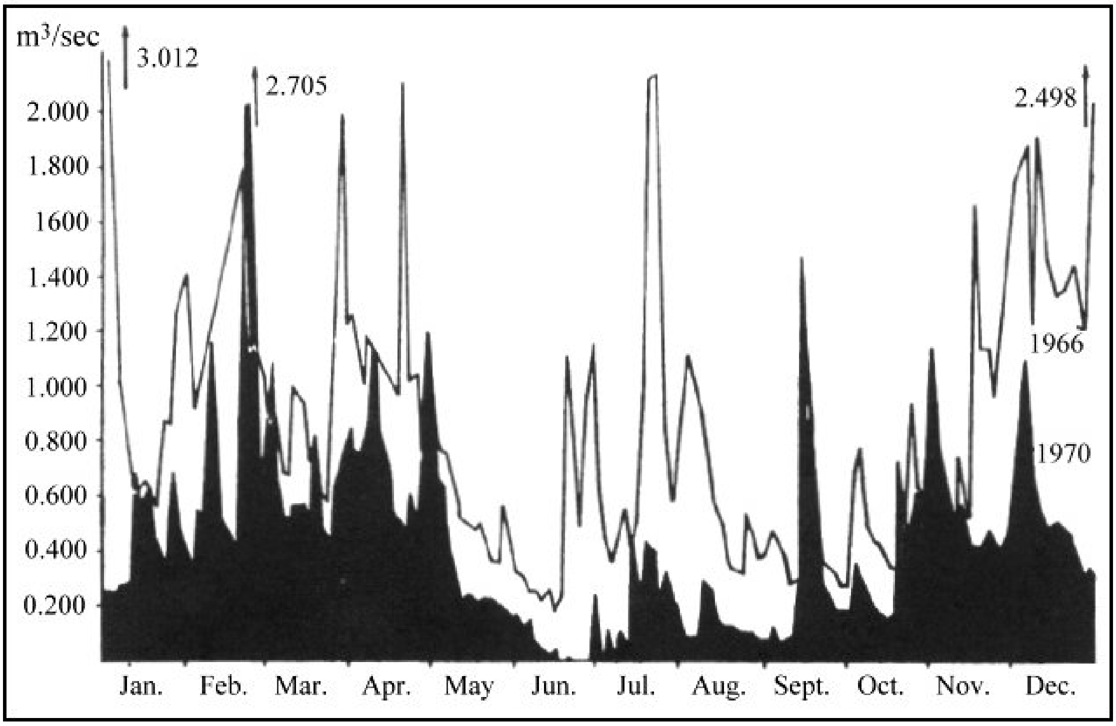

Figure. 2. Discharge in the Hierden stream during two extreme years

In reality, suspended particle transport is discontinuous, as virtually no single particle moves directly from the headwaters to the mouth, but rather intermittently, or by saltation, by passing through a series of temporary deposition zones within the hydrologic network.

The average sediment yield of river basins is highly variable between seasons and between different years and is the reflection of a number of erosion controls which are specific to climate, basin slope, vegetation and degree of anthropogenic impact.

On the global scale, absolute annual yields vary between 2 t km^{-2} and over 10,000 t km^{-2}. The following table shows estimates of material carried by some major world rivers.

River basin	**Sediment load 10^6 t a^{-1}**	**Sediment concentration mg l^{-1}**
Ganges/Brahmaputra	1,670	1,700
Amazon	1,100 - 1,300	200
Yellow River (Huang He)	1,080	23,000
Mississippi	210	360

Table 1. Sediment concentrations and loads in some of the world’s major rivers

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Biographical Sketches

Nic Pacini graduated in Organism and Population Biology (Ecology) at the University of Lyon (France) and then received an M.Sc. and a Ph.D. (1994) from the University of Leicester (UK) for his researches carried out in Kenya, attached to Nairobi University. After a one-year appointment at the University of Leicester (UK) and two post-doctoral years at the Biogeochemistry Department of the Swiss Institute for Science and Technology, he joined the Italian Ministry of Environment as a member of the Technical and Scientific Commission. Currently he is a private consultant under contract by the Italian Environment Agency, where his main task is to act as national focal point for designing guidelines on environmental risk assessment.

Stemming from a hydrobiological and limnological background, his research converged towards the analysis of nutrient and sediment transport in rivers and reservoirs under different climatic and geographical conditions. In particular, observations of the biogeochemical pathways involved in phosphorus transport and fate (cycling up through biotic processes) led him to develop an interest in the control of modified and eutrophic waterbodies, watershed management policies and watershed based ecological risk assessment.

His research activities included the study of the ecology of rivers, reservoirs, lakes and coastal waters in France and Kenya as well as in the Czech Republic and in the UK. As advisory expert for national and European water management policy he contributed significantly to the implementation process of the EU Water Directive 2000/60 both in Rome and in Brussels.

David Harper took a first class honours degree in Zoology from Oxford University and then a PhD from the University of Dundee, in limnology. Following his doctorate he was employed in the UK water industry for 4 years, initially as the Divisional Biologist in the Anglian Water Authority, responsible for the monitoring of streams and rivers and the quality of the new storage reservoir, Rutland Water. He then moved to the University of Leicester, first in the Department of Adult Education, then the Department of Zoology (promoted to Senior Lecturer) and currently the Department of Biology.

He has carried out research on river restoration and eutrophication problems in the UK and has been a member of the UNESCO Steering Group for Ecohydrology under the IHP V programme. For over 20 years he has worked on conservation and management issues of Rift Valley lakes in Kenya, mainly funded by the Earthwatch Institute. He was voted the Institute’s Principal Investigator of the Year in 2001, ‘in recognition of outstanding work combining original scientific inquiry, training of future local leaders, and applied conservation and policy’.

Bert Higler investigated macroinvertebrate associations in relation to vegetation structure in standing waters and in relation to hydraulics in running waters. His primary research took place in The Netherlands, where the results are being used by water managers.

His international activities comprise research and education, both in developed and in developing countries. The latter has resulted in a manual on water quality monitoring for use in developing countries.

He retired as head of the department of Aquatic Ecology of the Institute for Forestry and Nature Research (now ALTERRA, Research Institute for the Green World), which comprised freshwater and marine research. His present activities as a senior scientist include work for the European Water Framework Directive, nature restoration projects and biodiversity research on macroinvertebrates and fish.