Co-funded by the European Union

Basics in Water Quality

HYDROEUROPE

Erasmus+ Programme Cooperation Partnerships
2022-1-FR01-KA220-HED-000089658
HydroEurope

WP4: Accidental Water Pollution

Basic principles of water quality and modelling

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Version 1 - 25 October 2024

1. Introduction

This teaching material is part of the teaching unit dealing with "Accidental Water Pollution". This document deals with the principles and basic knowledge of water quality, pollution and modelling. It describes the main characteristics related to water pollution in water bodies and the processes that lead to this condition. At the same time, it describes water quality modelling and how this kind of tools can be used to assess impacts and define strategies for warning systems.

2. Beginning of water issues

One of the main issues concerning water bodies is the one related to his quality. This means that engineering seeks to determine the state of it aiming to control its quality under certain environmental conditions. The problem arises usually because water bodies (oceans, seas, lakes, rivers, etc.) tend to be contaminated by the discharges of human residues and natural activities. The use of water and its desirable condition constitute a matter of discussion, confronting the socio-political views and the economic constraints that each place presents. Different levels of water quality can be present depending on its use and the state of development of the area. According to Thomann & Mueller (1987) the main uses of the water are:

- Water supply (municipal and industry)
- Recreational (swimming, boating and aesthetics)
- Fisheries (commercial and sports)
- Ecological balance

2.1 Main pollution problems

Water quality can be analysed considering the interferences with the various uses of it. The table 1 shows the water uses and the interferences that conditions it.

This can be understood considering for example, the quantity of dissolved oxygen in a stream. In that case, it is known that this condition interferes with aquatic life (survival of fishes). In the same sense, water engineering seeks to diagnose the problems presented in the table, making judgements and proposing solutions and control measurements to improve the water quality of a specific area.

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Table 1. Principal pollution problems, affected uses and associated water quality variables (taken from Thomann & Mueller, 1987).

Manifestation of problem	Water use interference	Water quality problem	Water quality variables
Fish kills. Odours, H_2S, organisms Radical change in ecosystem	Fishery Recreation Ecological health	Low DO (dissolved oxygen)	BOD NH_3 org. N Organic solids Phytoplankton DO
Disease transmission Gastrointestinal Disturbance, eye irritation	Water supply recreation	High bacterial levels	Total coliform bacteria Fecal coliform bacteria Fecal streptococci Viruses
Taste and colour – blue green algae Aesthetic beach nuisances' algal mats "Pea soup" Unbalanced ecosystem	Water supply Recreation Ecological health	Excessive plant growth (Eutrophication)	Nitrogen Phosphorus Phytoplankton
Carcinogens in water supply Fishery closed – unsafe toxic levels Ecosystem upset: mortality, reproductive impairment	Water supply Fishery Ecological health	Right toxic chemical levels	Metals Radioactive substances Pesticides Herbicides Toxic product chemicals

2.2 General view

Engineers and scientists seek to analyse water quality problems considering the following components:

- **Inputs**: the discharge of residue into the environment from man's and nature's activities
- **Reaction and physical transport**: the chemical and biological transportation and water movement that result in different levels of water quality at different locations in time in the aquatic ecosystem
- **Output**: the resulting concentration of a substance, such as dissolved oxygen or nutrients, at a particular location in the water body, during a particular time od the year or day

The inputs can be discharged, for example, into a river, a lake, estuary o ocean. These inputs represent concentration of substances (chemical, biological, etc.) into the water body. Policies and legislation define water quality for particular places and uses, defining standards that are related with the concentration of substances present in the water body. These proposed standards imply the use of engineering for the environmental control of this substances making the resource available for the different used classified.

3. Waste load allocation principles (WLA)

The central problem of water quality management is the assignment of allowable discharges to a water body so the following water use and quality standard is met using basic principle of cost-benefit analysis.

3.1 Steps in the WLA process

- A designation of a desirable water use or uses (recreation, water supply, agriculture, etc.)
- An evaluation of water quality criteria that will permit such uses
- The synthesis of the desirable water use and water quality criteria to a water quality standard promulgated by a local or regional agency.
- An analysis of the cause – effect relationship between present and projected water load inputs and water quality response through the use of:
    - Site – specific field data or data from related areas and a calibrated and validated mathematical model
    - A simplified modelling analysis based on the literature, other studies and engineering judgment
- A sensitivity analysis and a projection analysis for achieving water quality standards under various levels of waste load input
- Determination of the “factor of safety” to be employed through, for example, a set-aside of reserve waste load capacity
- For the residual load and evaluation of:
    - The individual cost to the discharges
    - The regional cost to achieve the load and the concomitant benefits of the improved water quality
- Given all of the above, a complete view of feasibility of the designated water use and water quality standard
- If both satisfactory, a promulgation of a waste local allocated to each discharger

From a water quality point of view, the basic relationships between waste load input and the resulting response is given by a mathematical model of the water system. The development and applications of such a water quality models in the specific context of a WLA involves a variety of consideration including the specifications of parameters and model conditions.

4. Nature of the inputs

The inputs can be divided in 2 main categories:

- **Point sources**: inputs with a well-defined point of discharge which is in most of the cases, continuous (e.g. Pipes). The 2-principal point source grouping are:
    - **Municipal**, which result in discharges of treated and partially treated sewage (with associated bacteria and organic matter, biochemical oxygen demand - BOD, nutrients and toxic substances)
    - **Industrial**, which also result in discharges of nutrient, BOD and hazardous substances.
- **Non-point sources**: inputs with an origin of discharge that can be diffusive. The most common are:
    - **Agricultural**
    - **Silviculture**
    - **Atmospheric**
    - **Urban and suburban runoff**
    - **Groundwater**

In these cases, is not easy to relate the discharge to a specific well-defined location. Furthermore, the source may enter the water body (river or lake) via overland runoff as in the case of agriculture or through the surface of the land and water as an atmospheric input. The urban and suburban runoff may enter the water body through a large number of smaller drainage pipes not specifically designed for the carriage of wastes but for the carriage of storm runoff.

Other non-point sources include pollution due to groundwater infiltration, drainage from abandoned mines and construction activities and leaching from land disposal of solid waste.

An important point to consider is the determination or measurement of the load of the input, which is the total mass of a material discharged per unit time into a specific body of water. It is also important to mention the mass input depend on both the input flow and the input concentration. The figure 1 shows the variability of flow and concentration for point and non-point sources.

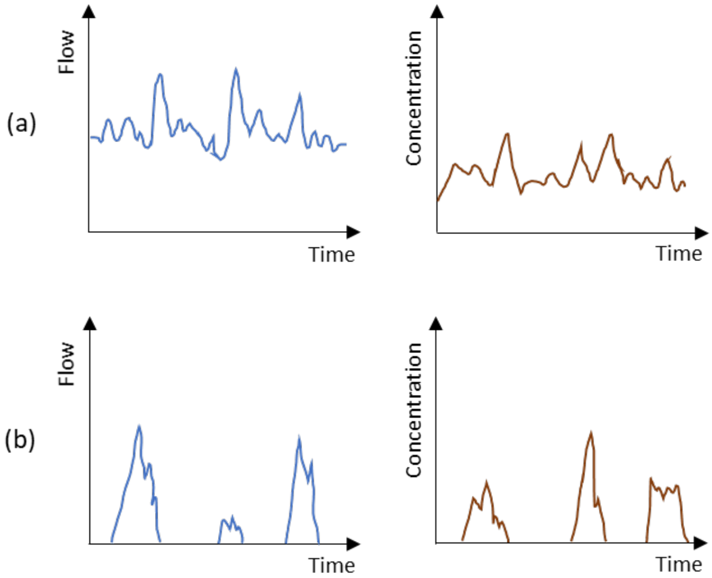

Figure 1. (a) Flow and concentration for continuous point source discharges. (b) Flow and concentration for noncontinuous, usually non-point sources (taken from Thomann and Mueller, 1987).

5. Discharge of residual material into rivers

There are some specific methodologies to describe the discharge of residual substances into rivers and streams. These residuals may include discharges from waste treatment plants, from combined sewer outflows or from agricultural and urban runoff.

5.1 Main assumptions

The main idea in describing the discharge of material into river is to write a mass balance equation for various reaches of a river. The figure 2 shows some assumptions for the release of a pollution load into a river.

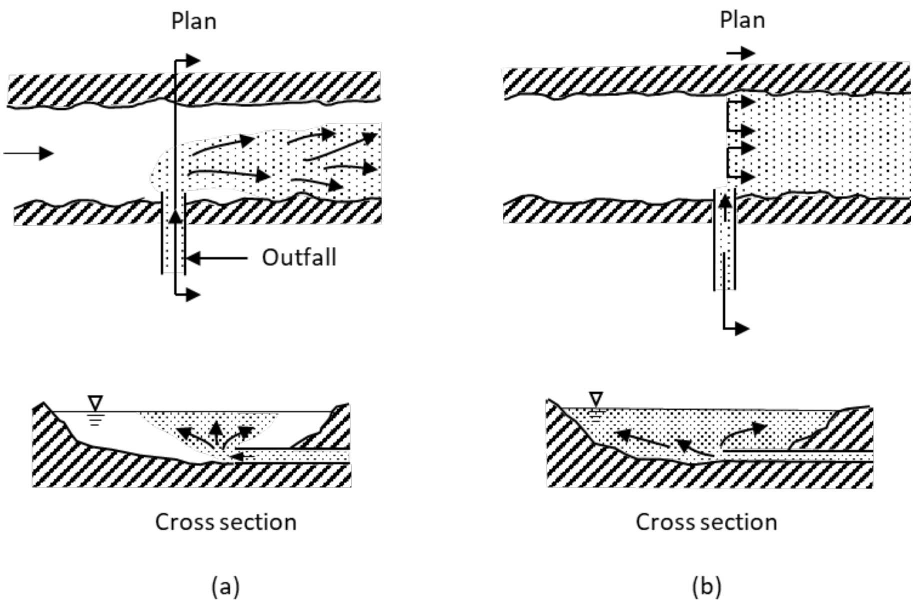

Figure 2. (a) Typical situation from an onshore discharge. (b) Well mixed lateral and vertical assumption (taken from Thomann and Mueller, 1987.

The figure presents the assumption (a) that the river is homogenous with respect to water quality variable along the river, vertically (depth) and laterally. In that case the plume, normally develops and it gradually extend over the entire depth.

If the assumption (b) is presented and the discharge is from ports along the length of the pipe and across the river, then the discharge will tend to be more uniform in the cross section.

To calculate the order of magnitude of the distance from a single point source to the zone of complete mixing is obtained from:

$$L_m = 2.6U_H^{B^2} \quad (1)$$

For a side midstream discharge (Yotsukura, 1968):

$$L_m = 1.3U_H^{B^2} \quad (2)$$

Where:

L_m= distance from the source to the zone where the discharge has been well mixed laterally (ft)

U= average stream velocity (fps)

B= average stream width (ft)

H= average stream depth (ft)

It important to mention that under this assumption for water quality, there is no mixing of water in the longitudinal downstream direction (advective system). This scheme is mostly suitable to steady state flows. In actual stream and rivers, lateral and vertical velocity gradients, “dead” zones in the river (coves, deep holes, backwater regions), produce some mixing and retardation of the material in the stream.

5.2 Mass balance at discharge point

The mass balance at the outfall can be declared as:

Mass rate of substance upstream + mass rate added by outfall = mass rate of substance immediately downstream from outfall

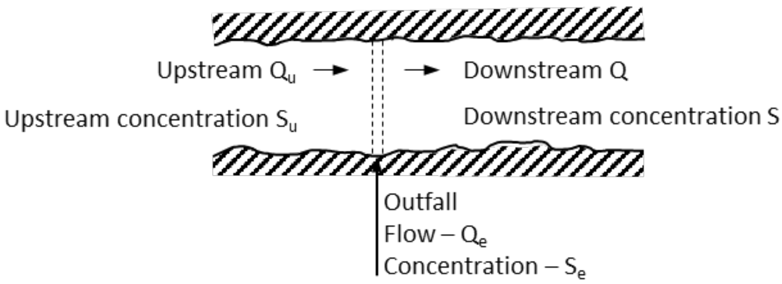

Figure 3. Notation for mass balance at outfall (take from Thomann and Mueller, 1987)l.

Considering that the mass rate is the product of flow and concentration, the mass balance is therefore given by:

$$Q_u s_u + Q_e s_e = Qs \qquad (3)$$

or,

$$Q_u s_u + W = Qs$$
$$[L^3/T][M/L^3] = [L^3/T][M/L^3]$$
$$[M/T] = [M/T]$$

Where:

$W = Q_e s_e$

Similar statement can be also made for the balance of the flows, what is called, flow continuity:

$$Q_u + Q_e = Q \qquad (4)$$

In this sense, the upstream conditions of flow and concentration (***Q_u*** and ***s_u***) are often known or can be measured, and typically some information is available on the effluent condition (***Q_e*** and ***s_e***).

For estimating the concentration of the substance in the river at the outfall after mixing of the effluent with the upstream concentration, equation 3 is solved for downstream concentration s as follow:

$$s = \frac{Q_u s_u + Q_e s_e}{Q} = \frac{Q_u s_u + W}{Q}$$
$$[M/L^3] = \frac{[L^3/T][M/L^3]}{[L^3/M]} = \frac{[M/T]}{[L^3/T]} \qquad (5)$$

In this equation ***Q*** is obtained through equation 4. Thus, the downstream concentration is dependent on the upstream and downstream flows and the concentration of the upstream and effluent inputs. If the upstream concentration of the substance, ***s_u*** is zero, then s is calculated as:

$$s = \left(\frac{Q_e}{Q}\right) s_e = \frac{W}{Q} \qquad (6)$$

The equation shows that the downstream concentration is the effluent concentration reduced by the ratio of influent flow to total river flow. This is a dilution effect. If the river flow is increased, a given mass discharge ***W*** will result in a decreased concentration in the river due to the diluting effect of the increased river flow.

When analysing the water quality downstream the source point, the concentration can be considered as a **conservative** substance or **non-conservative**. When conservative, there is no losses due to chemical reactions o biochemical degradations. Thus, there is no change in the concentration between tributaries or waste inputs.

On the other hand, non-conservative substances assume that it decays with time due to chemical reactions, bacterial degradations, radioactive decay or perhaps settling of particulates out of the water column.

A more complete description of the methodologies and equations involved in the process described before, can be found in Thomann & Mueller (1987), Lung (2001) and (1994).

5.3 Time variable analysis

The description of the variable time can be also important to be included when analysing the behaviour of the water quality in a river downstream of an outfall or tributary input. These actions may include the study of the

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downstream transport of a peak in a waste water discharge load, an accidental spill of a chemical or the day to day variation in water quality due to day to day changes in waste load inputs.

When analysing the movement of a substance under **non-dispersive** streams conditions, it expected that the mass of load (slice) moves along the stream not changing its concentration. That means that the discharge would work as a transport of the concentration once this is spilled in the stream. If the decay were to occur in the slide of river water, then the concentration in the slide would be reduced proportional to the travel time.

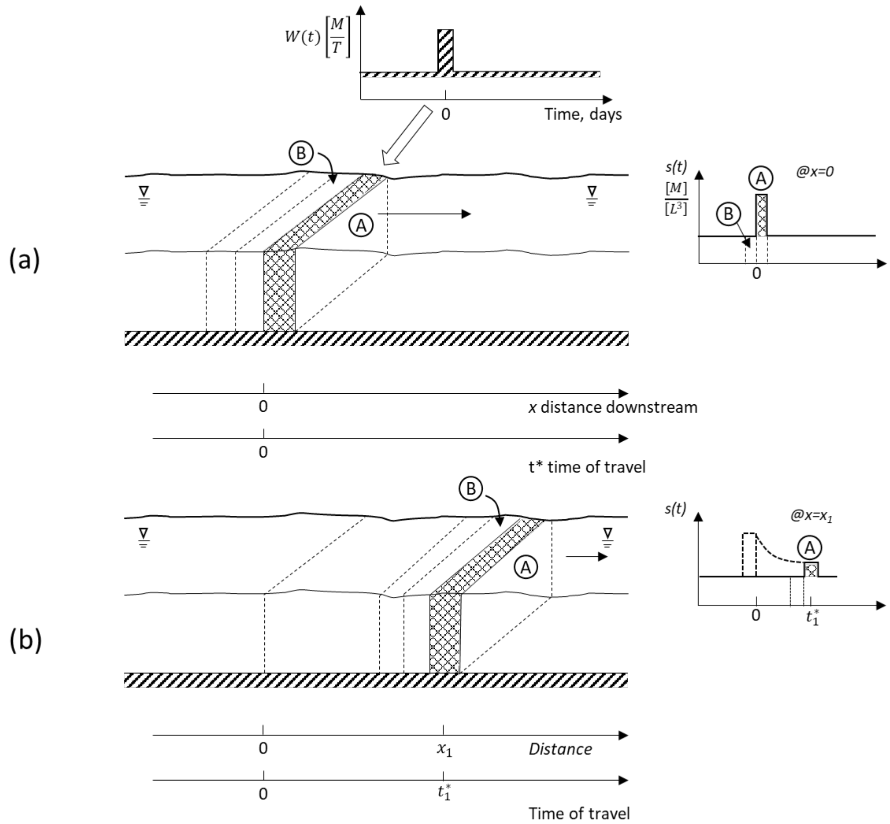

Figure 4. Schematic of water quality response in a nondispersive, advective stream due to a "pulse" input. (a) At time t = 0. (b) At time t = t_1 (taken from Thomann and Mueller, 1987).

The differential equation with constant coefficient in time and space that describes the concentration ***s(x, t)*** in an advective nondispersive stream is the following:

$$\frac{\partial s}{\partial t} = -U\frac{\partial s}{\partial x} - Ks \quad (7)$$

For boundary condition $s = s_0(t)$ at $x = 0$

where:

$$s_0(t) = \frac{W(t)}{Q} \quad (8)$$

For upstream conditions equal to zero

In this simplified situation, only the waste load is considered to be varying in time. The solution for this equation is the following:

$$s(x,t) = \frac{W(t-t^*)}{Q}\exp\left(\frac{-Kx}{U}\right) \quad (9)$$

where:

t^* = time of travel to location x

The last equation corresponds to the expression for the translation of any variation in ***W(t)*** in the downstream direction at a velocity ***U***. Therefore, ***W(t – t*)*** means that the time varying input at the outfall is translated downstream a distance equal to ***U · t****. The concentration is then given by the dilution due to the flow and the loss of mass due to decay.

As it is expected the situation is a bit different than the one described before. In rivers, grades of mixtures happens most of the time along the length of the stream due mainly to the horizontal and vertical gradients of velocity. This phenomena es called longitudinal dispersion.

When the analysis is conducted along the stream (long distance) and during a short time interval of discharge (e.g. spill of a substance), then the longitudinal dispersion must be considered. The mass balance equation for constant cross-sectional area, river flow and dispersion with no other input of ***s,*** except at the outfall is as follow:

$$\frac{\partial s}{\partial t} = -U\frac{\partial s}{\partial x} + E_x\frac{\partial_s^2}{\partial x^2} - Ks \qquad (10)$$

where:

E_x = longitudinal dispersion coefficient $[L^2/T]$.

The spills occurring in a stream can behave differently and, in each case, a different methodology will be used. Spills can occur **instantaneously** and **continuously** over an interval of time. Additional coefficient as the **dispersion** might be needed to be calculated to evaluate the development of the plume along the stream.

A more complete description of the methodologies and equations involved in the process described before, can be found in Thomann & Mueller (1987), Lung (2001) and (1994).

6. References

Hino, M. (1994). *Water Quality and its Control: IAHR Hydraulic Structures Design Manuals 5*. Taylor & Francis. https://books.google.es/books?id=_gp_QgAACAAJ

Lung, W.-S. (2001). *Water quality modeling for wasteload allocations and TMDLs*. John Wiley & Sons.

Thomann, R. V, & Mueller, J. A. (1987). *Principles of surface water quality modeling and control*.

Yotsukura. (1968). *As Referenced in Preliminary report Techniques of Water Resources Investigations of the U.S. Geological Survey, Measurement of Time of Travel and Dispersion by Dye Tracing, Book 3, Chapter A9, By F. A. Kilpatrick, L. A. Martens, and J. F. Wilson, 1970.*