
11. Water quality

11.1 Water quality characteristics

There are many characteristics which can be used to describe the quality of water in a river, including:

Physical: temperature, total dissolved solids (TDS), suspended solids, turbidity, colour and odour.

Inorganic: pH, hardness, conductivity, nutrients, heavy metals and trace elements.

Organic: biochemical oxygen demand (5 day and ultimate BOD_u), chemical oxygen demand.

Gases: oxygen O_2 , carbon dioxide CO_2 , hydrogen sulphide H_2S .

Biological: micro-organisms including *Escherichia coli* (*E-coli*), pathogenic organisms and algae.

Acceptable standards for water quality vary depending on whether water is to be used for domestic, agricultural or industrial purposes; or whether the aim is to maintain the biology of a river.

11.2 Types of pollutant

The following is substantially taken from Fischer, List, Koh, Imberger & Brooks (1979):

The following list is arranged in order of hazard, starting with the least dangerous

Natural inorganic salts and sediments: These materials are not toxic in small concentrations and only become possible pollutants in excessive doses. In the case of common salt in Australia, this is a very important case where what is least hazardous might be among the most environmentally damaging.

Waste heat: Once-through cooling systems for electricity generating plants use water for carrying away large quantities of low-grade waste heat. Aquatic life can be severely affected – as evidence, for example, the extensive investigations for minimising effects of waste heat from Huntly Power Station on the Waikato River in New Zealand.

Organic wastes: Domestic sewage containing ecosystem materials such as carbon, nitrogen, and phosphorous, can cause bad smells and nuisances. After treatment and dispersion (of varying degrees) it is considered acceptable to assimilate these materials into large water bodies. The biochemical oxygen demand (BOD) may be sufficiently reduced so that it can be satisfied by the natural dissolved oxygen in the water body.

Trace metals: These, often heavy metals such as lead, mercury, and cadmium, are naturally present in small amounts, but wastewater can have high concentrations.

Synthetic organic chemicals: These are slow to degrade in the environment and are often bio-accumulated in the food chain. Wastewaters may have high initial dilution, but the food chain can multiply the concentration by several orders of magnitude. Biological processes can do the opposite of the physical process of turbulent mixing which reduces the concentration.

Radioactive materials: Long term storage of these is necessary. In the northern hemisphere, salt mines are often chosen. The northern hemisphere also likes the look of dry parts of the southern hemisphere.

Chemical and biological warfare agents: These are designed to be toxic at very small doses. They have a habit of returning to damage the agents who used them (Agent Orange).

Regulatory systems usually distinguish between point and non-point sources of pollutants. A point source is usually the discharge from a structure which is designed for the outflow of wastewater. Exceptions include the accidental spill of oil from a ship and the release of radioactive wastes from a power plant. Most laws and regulations for water pollution control concern point sources. It is not usually possible to treat pollution from non-point sources. Examples include the runoff of salts and nutrients from agriculture, soil erosion, acid rain, and street drainage.

11.3 Impacts of human works

A partial list of damage caused by traditional approaches is:

- Human-made reservoirs may cause deterioration in water quality because of summertime thermal stratification associated with oxygen depletion in the lower layers.
- The reservoirs raise the head on groundwater which may cause it to seep to the surface and bring pollutants.
- Diversion of water for various uses or to other watersheds reduces river flow and its ability to provide flushing and to provide a satisfactory environment for organisms.
- Conveyances such as canals can transport large quantities of dissolved salts, sediment, nutrients and parasites to places that would not otherwise receive them.
- Agricultural drainage systems may accelerate the leaching of nutrients and salts from the land into natural hydrologic systems.
- Breakwaters for harbours interfere with natural circulation which could otherwise carry away

pollutants.

- Estuarine modifications can radically change circulation patterns with bad consequences for flushing of pollutants
- Most coastal protection works of a “hard ” nature cause environmental damage somewhere, even if they perform the local task they were required. Sea-walls and groynes often lead to the loss of sand from beaches, an environmental problem of another kind.

Sometimes it can be very difficult to turn around traditional culture, especially where another common pollutant, money, is concerned. Tradition is also a powerful factor. Morgan (1971) describes the entrenched culture of the US Army Corps of Engineers, responsible for many works in the US. Goldsmith and Hildyard (1992) describe at length the effects of dams around the world.

11.4 Transport processes

Advection: Transport by an imposed current system, as in a river or coastal waters.

Convection: Vertical transport induced by hydrostatic instability, such as the vertical flow above a plain on a hot day.

Diffusion (molecular): The scattering of particles by random molecular motions, which may be described by Fick’s law and the classical diffusion equation. Viscosity is an effect of molecular diffusion.

Diffusion (turbulent): The random scattering of particles by turbulent motion, considered roughly analogous to molecular diffusion, but with ”eddy” diffusion coefficients, much larger than

molecular diffusion coefficients.

Shear: The movement of fluid at different velocities at different positions.

Dispersion: The scattering of particles or a cloud of contaminant by the combined effects of shear and transverse diffusion (to be explained later).

Mixing: Diffusion or dispersion as described above; turbulent diffusion in buoyant jets and plumes; any process which causes one parcel of water to mingle with or be diluted by another.

Evaporation: The transport of water vapour from a water or soil surface to the atmosphere.

Radiation: The flux of radiant energy, such as at a water surface.

Particle settling: The sinking (or rising) of particles having densities different from the ambient fluid, such as sand grains or dead plankton.

Particle entrainment: The picking up of particles such as sand or organic detritus from the bed of a water body by turbulent flow past the bed.

For pollutant analysis, fluctuations and irregularities are just as important as the mean flows.

11.5 Tools for problem solving

Order of magnitude analysis

Fischer *et al.* (1979, p12) write: “For any mixing problem a skilful analyst should be able to work out a rough approximation for the solution within a fraction of an hour!”. Such a process is known as “order of magnitude” analysis. It is reminiscent of the wager that the physicist Richard Feynman

(Feynman 1985) used to make, that he could solve *any* physical problem to within 10% in one minute! Such problem-solving skills are important for environmental engineers. Problems can be broken up into sub-models. Much time and effort which might otherwise be wasted can be saved by this process.

Numerical techniques

A numerical calculation can be no better than the validity of the underlying approximations made when representing a complex process by mathematical equations. It is still necessary to make assumptions based on judgement and insight, and to leave out those processes which have little effect on the results.

A wide variety of numerical methods can be applied to mixing problems, which usually means the numerical solution of differential equations, whether ordinary or partial. Typically, finite difference or finite element methods are used, although the fundamental equation for transport by a flow where diffusion occurs, the advection-diffusion equation, shows a number of surprises and pathologies when numerical solution is attempted. Stochastic (“Monte Carlo” methods) may be used to simulate diffusion, which is the like simulating the like. In general, the methods which are most robust and successful are those where the solution method incorporates or mimics the *nature* of solutions.

Hydraulic models

These are necessary in some situations where the physical problem is sufficiently complicated. Also, they reveal physical phenomena which the relatively simple equations used cannot reveal.

Various phenomena revealed by experiments include: large scale vortices, internal waves and hydraulic jumps (caused by fluid stratification), multilayer shear flows, blocking, doubly-diffusive convection, *etc.*.

Field studies

In cases of dispersion of pollutants it is often difficult to model all the physical scales adequately. Field experiments are very important. Sometimes Lagrangian-type experiments, such as following drogues or drifters (or in the case of a famous experiment by Richardson, “two floating pieces of parsnip”) to track flow trajectories and dispersion. However, tracking is difficult, and fixed-location apparatus gives data at a reasonable cost.

Mixed approaches

For large complicated situations a careful interweaving of all the above is probably the best way to proceed. Each piece of a problem should be done in the most practical way – bearing in mind the aphorism that “there is nothing quite so practical as a good theory”. The final synthesis of a varied approach will undoubtedly be better than by depending on only one approach. Each different approach illuminates the others.

11.6 Diffusion and dispersion in waterways

Turbulent diffusion and dispersion

We consider flows which are reasonably steady (albeit turbulent) and have uniform geometry. For these cases, we can use a Fickian-type of law for diffusion due to turbulence. Initially as an introduction, let us consider a local velocity field which is turbulent. We will only consider the x component, so that we write

$$u = \bar{u} + u',$$

where \bar{u} is the time-mean velocity at a point, and u' is the fluctuating velocity, such that the time mean of u' is zero, $\overline{u'} = 0$. Similarly, we write an expression for concentration of a pollutant

$$c = \bar{c} + c',$$

and we want to calculate the flux of the pollutant, uc

$$uc = (\bar{u} + u')(\bar{c} + c') = \bar{u}\bar{c} + \bar{u}c' + \bar{c}u' + u'c'.$$

However, we do not want to study the fluctuating values of this, and so we take the time mean:

$$\begin{aligned}\overline{uc} &= \overline{\bar{u}\bar{c}} + \overline{\bar{u}c'} + \overline{\bar{c}u'} + \overline{u'c'} \\ &= \bar{u}\bar{c} + \bar{u}\overline{c'} + \bar{c}\overline{u'} + \overline{u'c'} \\ &= \bar{u}\bar{c} + \overline{u'c'},\end{aligned}$$

and so we have the result that the mean of uc is not the mean of u times the mean of c , but contains the extra turbulent transport flux $\overline{u'c'}$.

The turbulent transport fluxes such as $\overline{u'c'}$ have several attributes:

- They range in size from fluctuations the size of the flow geometry down to the smallest turbulent scale.
- They are random – individual fluctuations are not repeatable, but the statistical characteristics of those fluctuations are.
- The random nature of the flow results in intermittent but large spatial gradients in variables as packets of fluid with quite different characteristics are brought into contact by the turbulence. This enhances molecular diffusion.
- The continuous introduction of packets of high and low concentration by the turbulence will result in an overall dilution of zones of high concentration *via* turbulent mixing. This is *turbulent diffusion*, which is rather more important than molecular diffusion in river flows.

The energy to create turbulence is typically put into the system at scales the size of the overall geometry. Viscosity is the agent ultimately acting so as to dissipate the turbulent energy in the form of heat. It operates on the smallest possible scales of the flow field – at a molecular level. In between the creation and dissipation turbulent scales there is an orderly *cascade* of turbulent energy by which energy is nonlinearly transmitted from the large to small turbulent fluctuations or scales by a continuously decreasing sequence of turbulent eddies. This has been tersely described by L. F. Richardson, the father of computational fluid mechanics, paraphrasing Jonathan Swift:

Big whirls have little whirls that feed on their velocity,

And little whirls have lesser whirls and so on to viscosity - in the molecular sense.

With the exception of free jets such as smoke or exhaust stacks in the atmosphere, most flows encounter and are affected by boundaries. These cause the flow field and its turbulence characteristics to be different in all three co-ordinate directions. It is anticipated that the *eddy diffusivities* will be different in each direction. The main objective here is to be able to predict the eddy diffusivities in turbulent channel flow and the importance of their differences in magnitude on turbulent mixing in the channel.

Eddy diffusivities

Gradients of momentum and transport are sharper in the vertical and the transverse direction. An approximation obtained by Elder for the mean vertical eddy diffusivity $\overline{\varepsilon}_z$ is

$$\overline{\varepsilon}_z = 0.067 u_* h,$$

where h is the depth, and u_* is the shear velocity,

$$u_* = \sqrt{\frac{\tau}{\rho}} = \sqrt{ghS},$$

where τ is the mean boundary shear stress.

For the transverse eddy diffusivity $\overline{\varepsilon}_y$ Fischer et al. (1979) suggest

$$\overline{\varepsilon}_z \approx 0.15 u_* h,$$

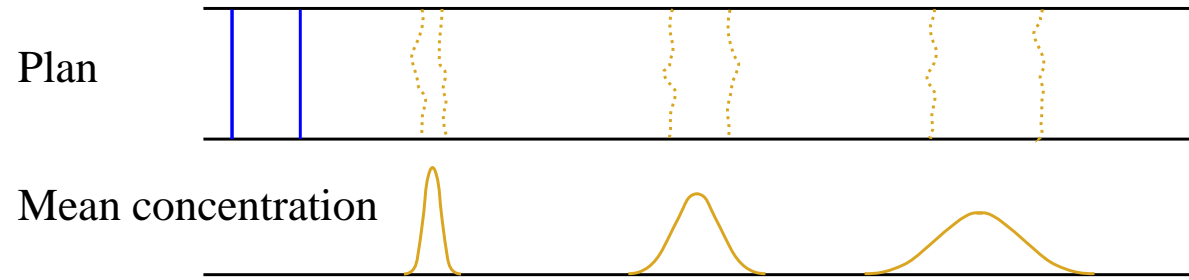
with a similar result for the longitudinal diffusivity $\overline{\varepsilon}_x$:

$$\overline{\varepsilon}_x > 0.15 u_* h.$$

The coefficients vary, depending on the channel or estuary type.

Dispersion

(a) Hypothetical uniform transverse velocity profile



(b) Realistic transverse velocity profile

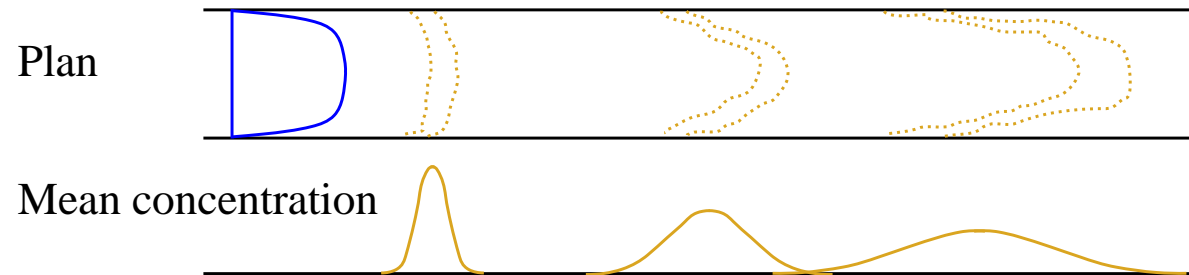


Figure 11.1: The role of the velocity distribution in enhancing dispersion

An important feature of turbulent diffusion in waterways is that the velocity distribution is not uniform across the stream. This has the ability to separate individual particles much more quickly than if just turbulent processes were at work, and for the effective diffusivity to be considerably greater. This is shown in Figure 11.1. In each of two cases shown, the top part shows an instantaneous snapshot of the pollution cloud in plan, and in the next part of the figure the mean

concentration distribution across the stream is plotted. Part (a) shows a hypothetical stream where the velocity is constant across the section. A puff of pollution introduced uniformly across the section is then carried downstream, and turbulent diffusion plays the role that we see, so that the concentration distribution is gradually diminished and widened. In Part (b) of the figure, however, we see what happens when there is a realistic transverse velocity profile. Some particles near the side do not travel as far as those in the middle, and the cloud of pollution becomes increasingly distorted, and the extent of the cloud can quickly become large. Now, taking the mean across the stream we see the results in the bottom part of the figure, where the mean concentration is now much lower, as is the lateral extent of the cloud. The *mean diffusivity* has been considerably increased by the velocity profile.

This phenomenon was first described by G. I. Taylor in 1953. This artifact of spatial averaging is known as *dispersion*. The basic operation involved is to obtain a partial differential equation which is derived in terms of area-averaged variables. By considering the sort of control volume we used earlier for the long wave equations, we can show that, for a concentration of pollutant c :

$$\frac{\partial}{\partial t} \int_A c \, dA + \frac{\partial}{\partial x} \int_A cu \, dA = 0.$$

Now, in a similar sense to what we did for time-fluctuating quantities we let

$$c = \tilde{c} + c'',$$

where \tilde{c} is the spatial average over a section, and c'' is the amount by which the concentration

varies from that average. Writing a similar expression for u , and substituting, we obtain

$$\int_A c \, dA = \tilde{c}A, \quad \text{and} \quad \int_A cu \, dA = \tilde{c}\tilde{u}A + \widetilde{c''u''}A,$$

giving

$$\frac{\partial}{\partial t} (\tilde{c}A) + \frac{\partial}{\partial x} (\tilde{c}\tilde{u}A) + \frac{\partial}{\partial x} (\widetilde{c''u''}A) = 0.$$

However, \tilde{u} is simply the mean velocity as we have already used it $\tilde{u} = U = Q/A$, and if we expand the terms in this equation and subtract the mass conservation equation

$$\frac{\partial A}{\partial t} + \frac{\partial}{\partial x} (UA) = 0,$$

then we obtain

$$\frac{\partial \tilde{c}}{\partial t} + U \frac{\partial \tilde{c}}{\partial x} + \frac{\partial}{\partial x} (\widetilde{c''u''}) = 0,$$

where we have neglected an area derivative in the fluctuating component term (area changes relatively slowly).

Taylor postulated (see *e.g.* Fischer et al. 1979) that $\widetilde{c''u''}$ can be modelled as

$$\widetilde{c''u''} = -\varepsilon_T \frac{\partial \tilde{c}}{\partial x},$$

where ε_T is the *dispersion coefficient*. Substituting, and neglecting derivatives of this quantity, we

obtain

$$\frac{\partial \tilde{c}}{\partial t} + U \frac{\partial \tilde{c}}{\partial x} = \varepsilon_T \frac{\partial^2 \tilde{c}}{\partial x^2},$$

the advection-diffusion equation, but where the coefficient of diffusion is the dispersion coefficient.

Fischer et al. (1979) and French (1985) give a detailed method for estimating ε_T . There is a simple empirical formula:

$$\varepsilon_T = 0.011 \frac{U^2 B^2}{u_* h},$$

where B is the top width, as used previously. This expression is “correct to within a factor of four”, which is considered acceptable ... For a narrow channel, a typical value (p423 of Streeter, Wylie & Bedford 1998) for a mean flow velocity of 0.1 m s^{-1} is $2.75 \text{ m}^2 \text{ s}^{-1}$, and for a wide channel a typical value is $275 \text{ m}^2 \text{ s}^{-1}$.