FRESHWATER BIOLOGICAL ASSOCIATION

CLOUDING: THE ISSUE.
An appraisal of the effects
of turbidity in aquatic systems
by C.S. Reynolds

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TO SEVERN TIDAL POWER GROUP

Dear Sirs,

This report is submitted in fulfilment of the original requirements specified in your task-brief 3.1(iv)a5 and order number T.0073. Revision of the draft submission has taken account of the reviewing panel's additional stipulations. It is intended to be informative, giving so far as possible an overview of current understanding of the causes and consequences of suspended particle-loads in aquatic systems. It does not pretend to be exhaustive in its cover of the literature and not all the generalizations need apply directly to the Severn Barrage but it has been written in awareness of the conditions anticipated within the impounded system. In line with the contractual brief, it seeks to review:

(a) The distribution of the particulate structure of turbidity, the constitution and sources of particles causing turbidity and the factors which influence the fluctuations in their abundance.

(b) The interrelations between turbidity and water quality parameters.

(c) The effects of turbidity on primary and secondary biological production.

Owing to the Association's primary experience being mainly in freshwaters, the report is inevitably biassed towards the behaviour of turbidity in lakes and rivers. Moreover, in instances where specific data on estuaries are less extensive, the extrapolation from freshwaters is often necessary. We append a number of recommendations where we feel that information specific to the materials and processes dominating the Severn Estuary may prove important to the design and eventual operation of the barrage.

For, and on behalf of the Association

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November 1988

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ABSTRACT

This review considers the wide diversity and provenance of particulate materials in water. In addition to the quantities introduced into aquatic systems, the turbidity that is imparted depends upon its longevity in suspension which is itself a function of entrainment by the motion and the size range of the particles. Turbidity is an optical property and, accordingly, the differential effects of suspensoids on the absorption and scattering of incoming irradiance are compared. Principal effects upon the water quality operate via the planktonic primary production to influence the balance of gaseous exchange. The nature, quantities and behaviour of particles also directly affect the tenability of turbid environments to a range of invertebrates and fish. Unanswered questions relevant to the behaviour of a Severn Barrage and impoundment of tidal water are identified.

1: INTRODUCTION : THE PROBLEM OF TURBIDITY

Turbidity is a visual property of liquids. The word implies a sullied, cloudy appearance and a general lack of clarity. The effect may be due, in part, to substances dissolved in the water, such as humic derivatives. However, turbidity is generally understood to be due to the presence of solid matter held, to a greater or lesser extent, in suspension. Such matter is extremely diverse in its nature and origin, in the average size of the individual particles, their abundance and longevity in suspension and it may be considered to embrace living organisms as well as inert material. The universal property of suspensoids is that they interfere with the direct, straight-line transmission of light, through two principal mechanisms: light-scattering and light-absorption (Kirk, 1985). Besides impacting upon the aesthetic appearance of lakes, rivers and seas, suspended materials may significantly modify the potential of the environment to support plant growth and are thus intimately involved in the exchange fluxes of dissolved gases (especially oxygen and carbon dioxide). On the other hand, suspensoids may provide a substantial solid surface, upon which various sorption phenomena can occur and certain microorganisms can grow. Large quantities of suspended matter will have adverse effects upon predatory invertebrates, fish and even diving birds and mammals that depend mainly on visual contact in encountering their prey; species adapted to rely more upon tactile and olfactory senses, however, may be selectively advantaged in turbid environments. Water containing a high content of mineral suspensoids may bring about undue wear to pumping machinery with which it comes into direct contact. So far as possible, the following sections address these topics in turn. Some conclusions are drawn in the final section, though specific recommendations concerning the design and operation of the barrage can only be provisional at this stage.

2. THE ORIGIN AND NATURE OF SUSPENSOIDS IN NATURAL WATERS

2.1 Basic properties of particles

According to Kirk's (1985) definition, adopted above, the size spectrum of particles contributing to turbidity of lakes, rivers and seas spans perhaps 12-orders of magnitude (see Fig. 1). The upper extreme is chosen to embrace such 'particles' as dead trees or whales, assuming that waterlogging of their tissues imparts to the structure some degree of isopycny (i.e. having the same density) with the suspending medium. The lower size extreme is at the scale of individual molecules. Between the extremes, the range embraces: a series of fractions of 'mineral' particles, from boulders, gravels, sands, silts and clays, originally deriving from the progressive erosion of terrestrial land-surfaces and transported, with varying efficiency, by flowing water into streams and rivers, but includes material re-worked and resuspended from earlier deposits by channel processes, wave action and internal scour; a diverse array of organic detrital particles and aggregates, deriving from the decay and decomposition of not only aquatic organisms but also terrestrial and aerial biota brought in via the watershed; dust, soot and other anthropogenic particles, deposited directly from air on to water; a further component is the biotic plankton, comprising living bacteria, algae and animals which are adapted to pass part or all their lives in free suspension in open waters.

The same selection of material covers a wide range of densities. Depending upon their elemental composition and crystalline structures, the mineral particles typically vary between 1500 and 5500 kg m^{-3}. Components in organic detritus (carbohydrates, proteins and lipids) have densities generally ranging from 800-2500 kg m^{-3}, so that the densities of individual particles will depend upon the balance of substances present and also the water content. Indeed, living tissue (protoplasm) generally has a density of between 1020 and 1050 kg m^{-3}. However, many species of planktonic organisms (diatoms, coccoliths, crustacea) in particular, are invested with calcareous or siliceous skeletons which increase their average densities, (perhaps to 1400 kg m^{-3}) while others (especially cyanobacteria, some copepod crustacea) maintain gas- or oil-containing organelles which, incidentally or otherwise, may lower average density to less than that of estuarine waters (in the range 1000-1030 kg m^{-3}).

2.2 Suspension and entrainment

It is appropriate at this stage to define what is understood by the term "suspension". Except for the very smallest particles ($< 10^{-6}$ m: colloids and below) and those larger particles which are exactly isopycnic, the difference in their density ρ_a, relative to that of the surrounding water, ρ_w will determine that they have an overall tendency to gravitate either downwards (if $\rho_a > \rho_w$) or upwards (if $\rho_a < \rho_w$). Thus, their suspension is, itself, a relative condition. Their buoyancy, or the lack of it, is expressed by an intrinsic velocity capacity, and is measured in (e.g.) meters per second (m s^{-1}). The intrinsic settling or flotation velocities ($\pm \underline{w}_s$). Small spherical particles, at least, conform to Stokes' Law, which may be represented mathematically by the equation

$$\underline{w}_s = \frac{\underline{gd}^2 (\rho_a - \rho_w)}{18 \eta} \qquad (1)$$

where $\underline{d}$ is the diameter of the particle (in m), $\underline{g}$ is gravitational acceleration (9.81 m s^{-2}), η is the absolute viscosity of water (10^{-3} kg m^{-1} s^{-1}).

The literal interpretation of equation (1) is that for particles of the same density, their intrinsic velocities vary as the squares of the diameters, either sinking ($\underline{w}_s$ positive) or floating ($\underline{w}_s$ negative) in relation to the adjacent water. Particles which are subspherical will generally move at lower velocities than the corresponding spherical particle of the same volume and density but by a constant shape-dependent factor, Φ, known as the 'form-resistance' of the particle. The limiting condition of the Stokes Equation (1) is that as the particle moves relative to the water, the flow of water over its surface is laminar, i.e. generates no turbulence. Turbulence of the flow over the particle is measured by the dimensionless Reynolds Number of the particle (Re) derived from the equation:

$$\underline{Re} = \underline{dw_s}\ \rho_w/\eta \qquad (2)$$

given $\underline{d}$ = diameter and $\underline{w_s}$ is the settling velocity, ρ_w is the density of the water and η its viscosity as introduced.

Empirical solution of (2) shows that Reynolds Number of denser particles increases sharply ($Re > 0.5$) when their diameters exceed 10^{-4} m (100 μm). Above this limit, the departure of the actual settling velocity from the value predicted by the Stokes equation (1) becomes increasingly significant (see Fig. 2), the settling particle generating increasing frictional drag. Nevertheless, the curve is asymptotic so the general rule that $\pm W_s$ increases with increasing particle size is not violated while the density difference with the medium is preserved.

The reciprocal of settling (or floating) velocity, distance per unit time, is a column clearance time, $\underline{t}'$ (i.e. the time taken to travel the full vertical depth of the water). Thus

$$\underline{t}' = \underline{h}/\underline{w_s} \qquad (3)$$

where $\underline{h}$ is the column height in m; $\underline{t}'$ is then given in seconds. It is clear that, other factors being equal, larger particles will clear a static water column, of fixed depth, $\underline{h}$, proportionately faster than smaller ones of the same density.

Natural water columns of seas and lakes are, however, rarely static. Convection (caused by alternate heating and cooling at the surface), inertial currents due to the rotation of the Earth (Coriolis' Force) and, especially, wind-stress at the surface set up a variety of internal motions in the water column which may be considered to be, to differing extents, turbulent. In rivers and small, highly flushed lakes, downhill transport of the water introduces analogous effects. In estuaries, turbulence is augmented considerably by tidal ebb and flow cycles particularly where, as in the Severn estuary, the tidal range (in the order of 10 m) is exaggerated by funneling. If we consider a particle settling through a parcel of water which is itself in upward motion, with a velocity exceeding w_s the particle will experience a net upward trajectory. In a free-turbulence field, then, settling particles are constantly re-introduced near the surface, so that although there is no change in their intrinsic settling velocities and the net tendency for the particles to settle out is unaltered, the time taken for a population of particles to do so is lengthened. The elimination of the particles follows an exponential decay curve, analogous to dilution, with fewer and fewer particles available to redispersion through time (see Fig. 3). Of an original population (N_o) of uniform particles, uniformly distributed in a freely mixed turbulent column (h_m), those remaining at time t' is then given by:

$$N_t = N_o . e^{-1} \qquad \text{(4; Smith, 1982)}$$

The population remaining at any given time t is in direct proportion, i.e.

$$N_t = N_o \; e^{-t/t'} \qquad (5)$$

Substituting for t' from (3),

$$N_t = N_o e^{-w_s t/h} \qquad (6)$$

Equations (5) and (6) are particularly instructive in two respects. One is that it shows maintenance in the circulation is proportionately prolonged the greater is the ratio of depth (h) to settling velocity (w_s). The second is that the delay in clearance rate caused by mixing of the water columns is a constant independent of the turbulent intensity. The exponential curve (Fig. 3) describing the proportion of particles remaining in suspension is, of course, non-vanishing, but is (e^{-1} =) 0.37 at t^1 and 0.05 (i.e. 95% of the particles settled) after a time equal to $3t^1$.

Both deductions depend upon the assumption of full *entrainment* of the particles in the turbulent flow field. Reynolds (1984) argued that although entrainment of particles with significant density difference from water is never complete, it was approached when the vertical turbulent velocity fluctuations in the eddies ($\underline{w}'$) exceeded $\underline{w}_s$ by one to two orders of magnitude. More recently, Spigel & Imberger (1987) have set the limiting condition for effective entrainment of particles when $\underline{w}_s < 15\ w'$.

Comparing likely values of $\underline{w}_s$, predicted from equation (1), with quite modest turbulent velocities such as those generated at water surfaces by light winds of 1-3 m s^{-1} ($\underline{w}' > 0.01$ m s^{-1}; Arai 1984) or by current velocities in deep, smooth rivers of > 0.1 m s^{-1} ($w' > 0.003$ m s^{-1}; Smith 1975), it becomes clear that particles in the size range $10^{-3} - 10^{-2}$ m with a density difference of $(\rho_a - \rho_w)$ of not greater than 1650 kg m^{-3} may be considered to be effectively entrained in natural waters and, hence, from the point of view of the present discussion, to be described as being in suspension. Proportionately larger or denser particles may be entrained at the greater current velocities (1-2 m s^{-1}) associated with tidal flow in the upper Severn Estuary (Dr J. West, pers. comm.).

2.3 Maintenance and persistence of suspensions

Following this reasoning, it is possible to construct a phase diagram (Fig. 4), describing particles in terms of their sizes and densities and to superimpose current velocity isopleths which will represent the limit of entrainment (as defined by the criterion of Spigel & Imberger, 1987) and the boundary with disentrainment. This figure thus represents the physical properties of the suspensoids that will constitute turbidity in aquatic systems. By far the most important mineral particles will be the scale of clays; silts, free waterborne industrial and mining fragments (e.g. ash, pulp-fibres, coal dust will be maintained only in high currents and fluvial spates); sands and fine gravels are also liable to entrainment by tidal motion in the Severn Estuary. Organic detritus should be properly included, although its further decay and disintegration will modify its entrainment properties. Living planktonic organisms are, by definition, to be included, even those flagellates and limbed animals with a capacity to swim in a controlled fashion in static water: the maximum swimming speeds that these organisms can attain (generally << 1 cm s^{-1}, or 10^{-2} m s^{-1}) are still inadequate to overcome the dominant scales of motion in natural waters. Larger swimmers, which may be taken to include the majority of fish, squid and decapod crustacea, except during their very young, planktonic stages, may be safely excluded from this definition of suspension.

2.4. Resuspension

The behaviour of small particles in relation to a given turbulent flow-field is made more difficult to predict by temporal variability in the turbulent energy and its potential erosion of previously sedimented material. Owing to frictional resistance of the sediment surface, current velocities are effectively reduced to zero in the boundary zone adjacent to the sediment surface. In addition, a boundary of viscous mud may resist erosion of the bed: the enhanced density of this particle-rich fluid restricts vertical transfer of momentum from the overlying waters; the density gradient increases the definition of horizontal shear. Increased velocities in the open turbulence field compress the boundary shear and may begin to move larger particles projecting above the ambient sediment surface and, perhaps, resuspend finer materials. At any given steady state, the particulate make-up of the sediment surface will tend to comprise those particles beyond the capacity of the field to resuspend. This rise must be tempered by the property of cohesiveness. Sandy and pebbly sediments can be considered to be non-cohesive. i.e. particle behaviour is dominated by individual properties, with little mutual attraction. Increased turbulent activity may work this material into ripple marks, ridges or dunes and only in extremes, wash it away. On the other hand, clay - and finer salt - particles though individually capable of being re-entrained, tend to cohere and, collectively, offer a surface that is resistant to erosion to a far greater extent than the size-settling properties would suggest.

Cohesiveness may be increased in fine deposits with a sufficient organic content to permit the development of bacterial and zoological films which tend to bind particles together. Once erosion has started, however, the cohesion may be lost and particle resuspension becomes quite rapid. Freshly re-entrained material may be transported elsewhere, where progressive loss from suspension and re-settlement must begin anew. Attempts have been made to relate the erosion of fine, cohesive material to the so-called voids ratio (roughly, the degree of sediment compaction) but the definition of effective particle size for cohesive materials remains a serious problem.

Empirical solutions of the approximate relation between particle size and the critical velocity for the onset of erosion have been derived from the results of laboratory experiments. Fig 5 shows the critical velocities for sediment grains of density 2650 kg m^{-3}, as derived by Sundborg (1956); the difference between 'consolidated' and 'unconsolidated' deposits is unspecified; and the critical velocities of organic particles will be proportionately lower (by an order of magnitude or more; cf. Fig 4). Nevertheless, it is evident from Fig 5 that the range of current velocities experienced in the Severn Estuary (up to 2 m s^{-1}) will potentially augment the suspended load by re-entrainment of larger silt and sand from the bottom and by disintegration of consolidated deposits.

Other circumstances under which significant resuspension of fine material is expected to occur can be cited. The first is in shallow upper estuarine sediments scoured by enhanced river inwash (velocities exceeding 0.1 m s^{-1}). The second is due to wave action around the estuarine margins, where the depth of water is less than half the wavelength of wind-driven waves: sands and gravels may be driven into small dunes but the clay- and silt particles are drawn away in the turbulent flow. The third case is where sediments are disturbed by biogenic forces burrowing animals and bottom swimming fish which will throw up finer materials into the ambient flow field. However, these are probably minor components of the general resuspension mechanisms operating in the Severn Estuary, which are dominated by tidal energy.

It is emphasised again that, within this definition of suspensoids, persistence in a given column of water is nevertheless finite, while a given set of hydrological conditions obtains. Abrupt increases in current velocity, wind stress and wave penetration will re-entrain sedimented particles, especially from shallow areas. Conversely, sedimentation increases wherever the motion of the water weakens (in bays, backwaters and at depth). This behaviour is responsible for a wide range of depositional phenomena, like delta formation, braiding of river channels, current sorting on shorelines and 'focusing' of deep lacustrine sediments (Lehman, 1975) along velocity gradients. At the essential time-scale of tidal movements (roundly, 6 h between high- and low-tide) no steady state is anticipated with respect to net deposition or net sedimentation. Over longer time scales, the perceived steady state is of an energetic estuary in which prolonged suspension of abundant form particles is favoured. This deduction corresponds with unpublished evidence made available to the author by STPG that the Severn Estuary is unusually deficient in extensive deposits of unconsolidated sediment when compared with other less-energetic, large estuaries. The extent to which the reduction in the tidal energy in the upper (landward) estuary after closure of the barrage, especially during future neap tides, will modify the depositional environment and, ultimately, the clarity of the water requires further investigation.

An additional criterion for the persistence of suspensoids is their maintenance in a mutually dispersed state. Aggregation of particles into larger flocs provides new Stokesian properties ($\underline{d}$ is increased in Equation 1), though the inevitable inclusion of water within the floc structure means that the density difference ($\rho_a - \rho_w$) of the 'new' particle will have been reduced; i.e. $\underline{w}_s$ is not increased in direct proportion to $\underline{d}^2$. Dispersion of small particles is generally attributable to the dominance of their surface electric charges (the electrophoretic or zeta potential) which, for a given suspensoid in a solution of given ionic strength, will be uniformly positive or negative. When (e.g.) river borne clays are discharged into sea water, having a different ionic composition and strength, the zeta potential also changes to the extent that mutual repulsion of different particles may well be overcome and their aggregation by collision is no longer resisted. Such behaviour influences the longitudinal gradients in turbidity content observed in estuaries and to the cohesiveness, or otherwise, of the sedimented material e.g. Sundborg (1956). Changes in the distribution and intensity of salinity gradients in the barrage, post-closure, may be expected to modify.

2.5. Seasonality and spatial variability of turbidity

Taking an overall view of the catchment-river-estuary system, providing a broad spectrum of geological composition, geomorphological landform, geophysical process and geographical arrangement, general patterns of behaviour of water-borne particulates may be characterised.

(i) Suspended sediment import. The major primary source of suspensoids in upper estuaries derives from the erosion of unconsolidated deposits in the river catchment area. Loose particles may be removed from points in the catchments located even above first-order drainage channels, by surface overflow during wet weather. The same particles may eventually reach the sea, through a succession of one or more high-discharge events, in the latter instances, at least, being moved downstream within the channel. Increasing depth, mean velocity and duration of flow downstream determine that relative suspensoid transport is more prevalent and persistent in the lower catchment. The concentrations of material carried in this way, however, have much to do with their availability in the catchment (exposed surfaces, e.g. ploughed land, quarries, industrial and mining spoil, civil engineering projects and the volume of net run off per unit land area. 'Natural' estuarine turbidity due to 'mineral' material tends to be higher in catchments in which arable farming and extractive industries are prevalent than areas dominated by permanent grass or woodland and to be considerably enhanced during high-rainfall, high net run-off events. Accordingly, the greatest increase in turbidity is likely to occur during the first heavy rainfall of autumn and following a summer season of net soil-moisture deficits. Subsequent events during a wet autumn or winter may continue to sustain high turbidity loads through the winter. Conversely, reducing discharges during spring and summer (primarily due to higher evapotranspiration from the land and increased soil water deficits rather than to an absolute seasonal decline in rainfall) introduce, re-suspend and transport lesser concentrations of particles; the reduction represents a weakening of erosive power and competence which is not a linear function of velocity but is, rather, the product of several higher order relationships. It is emphasised that turbidity changes with seasonally varying discharges do not conform to unique mathematical relationships, even for a particular river, for some hysteresis is expected in a cycle of rising and falling discharge. When different rivers are compared, it is evident that swift-flowing rivers draining upland catchments dominated by hard rocks and thin soils and which receive high annual precipitation now carry little fine material (owing presumably to dilution and past removal of particulates) are generally much less turbid than those draining fertile lowlands. Though their headwaters rise in the highlands of Central Wales, the Severn and several of its major tributaries (e.g. Wye) also traverse lowland areas characterised by intensive agriculture, populous towns and centres of industrial activity: the river water entering the Severn Estuary, in the order of 3 x 10^9 m^2 ann^{-1} and importing in the order of 10^6 t suspended solids (i.e. at concentrations averaging 0.1-1.0 kg m^{-3}), must be considered to be, at most times, 'turbid'.

Estuaries may also import suspensoids from the open sea. Typically, of course, even coastal waters disperse and dilute particulate loads relatively efficiently and, perceptibly, are usually much less turbid than river waters.

Two processes could facilitate possible landward import of material in estuaries: disentrainment from seawater into subtidal troughs and in shallow, sheltered bays at high tides; erosion of sea-bed deposits near the estuary mouth and transport on the incoming tide. Neither would be necessarily significant in the Severn Estuary, owing to the energy associated with tidal movement; indeed, the contribution of bed material from the Bristol Channel to the sediment load in the estuary is considered to be 'negligible' (STPG, Sediments Review Paper).

A third import mechanism arises from direct erosion of the estuary coast itself. Absolute rises in post glacial sea level and relative rises due to enstatic movement of the land continues to the present day: it has been estimated (STPG, Sediments Review Paper) that landward encroachment of the estuary removes some 0.3×10^9 kg of estuarine shore material annually, about two-thirds of which is fine-grained and contributed to the suspended load. This erosion will be greatest at peaks in the tidal cycles (spring tides) and abetted by wave action driven by on-shore westerly gales. Further rises in mean level in the estuary will contribute to this process, this is relevant to the elevation of landward post-barrage level, even if tidal range and wave intensity is reduced.

(ii) Estuarine retention and resuspension. It has already been noted that the predominant processes of resuspending particles in estuaries are the reworking of deposited material by the action of undercurrents associated with incoming tidal surges, assisted by wind-driven wave action on shallow deposits. In either case, the condition depends upon the penetration of the protective boundary layer by the force of the generated motion. In turn, the relative recruitment of particulate material is, in part, dependent upon the manner in which the tidal energy is dissipated and the extent of shallow water subject to wave-break.

The morphometry of the Severn Estuary is such that incoming tides are funneled towards the head and compensated by a relatively free rise over the tidal range. Reported maximal flood-tide velocities (STPG data) are in the order of 2-3 m s^{-1}; ebb velocities are less, generally < 1 m s^{-1}. Maximum velocities are also lower during neap tides but are still in the order of 1 m s^{-1}. The differences between velocities at the surface and just above the estuary bed are generally < 0.5 m s^{-1}. Turbulence associated with these currents (section 2.2, Figs 4, 5) are likely to contain a broad spectrum of particles of $< 10^{-3}$ m in diameter.

Similarly, the open aspect of the estuary to the direction of prevailing winds must provide abundant opportunity for the resuspension of particulates by wave action on shores and marginal shallow water. Wind runs based on averaged measurements at Rhoose Airport (near Barry, S. Glamorgan) indicate a predominance of winds from the west that, for 95% of the time, blow at between 2.5 and 10.5 m s^{-1} (with an ambient mean of 5.5 m s^{-1}). However, the area of the estuary so affected will remain a relatively small proportion of the total; incidences of resuspension due to wave action would not be expected to increase as a consequence of barrage formation other than as a consequence of rise in water level. An unknown quantity is whether impoundment of sediment-rich river water will offer a greater amount of particulate material in the same areas of wave-erosion. Again, the contribution may prove to be relatively minor but it is worthy of further investigation.

(iii) Retention and loss of suspensoids. The impact of frequent episodic recruitment of particulate suspensoids upon ambient turbidity levels is also influenced by the rates of loss of the material to the sinks. Two main mechanisms may be distinguished, though they are practically interrelated. Loss from suspension, in the sense of disentrainment and re-settlement of particles, is a function of the temporal and spatial weakening of the turbulent energy relative to the settling velocities of particles ($\underline{w}_s:\underline{w}'$; section 2.2).

Accordingly, coarser material will be rapidly redeposited away from wave-washed shores and during 'slack water' between tides. Finer material will be entrained for longer and further and be lost from suspension much less rapidly; the opportunity to do so will be greatest in deep and non-turbulent estuarine troughs. A further consideration here is the likely prevalence of density stratification with depth: vertical separation into distinct hydraulic layers imports to each a unique $\underline{h}$-value (Equation 3) and sinking loss exponent (Equation 6) while the stratification persists. Data presented elsewhere (STPG, Stratification Report) anticipate some density stratification persisting through neap tidal cycles.

For much of the finest material ($< 10^{-5}$ m; Fig 4), the time scale of turbulent fluctuations in relation to column clearance times determine that relative sinking loss is negligible, i.e. suspension is effectively indefinite (cf. Fig 2). The time scale of retention of this material within the estuarine water is dependent upon the second of the two mechanisms: the rate at which the particle-rich water is diluted out of the estuary by tidal exchange with particle-deficient sea water and by the net displacement by river flow. Crude comparisons of the volume of the upper estuary (above the proposed barrage) with the hydraulic exchanges suggest theoretical times in the order of days (less than a lunar tidal cycle). This time scale will be lengthened as a consequence of barrage formation, rendering post-barrage turbidity levels more persistent.

The ambient levels of turbidity in estuaries depend upon spatial and seasonal variability in the balance between import, resuspension and voiding of particulate loads. At a given location, this balance is affected by small-scale processes (local currents, scour channel irregularities, semi-diel tidal cycles (ebb and flow), semi-lunar changes in tidal range (neap/spring), approximately annual fluctuations in fluvial sediment-loads, all superimposed upon a geological scale of estuarine evolution. The balance also varies with depth of water and distance from the estuary head, as well as with the modifying effects associated with islands and promontories. Stochastic events may intervene in the ambient "steady-state" at every level - wind fluctuations, severe storms and (presumably) geological events.

In the Severn Estuary, long-term monitoring of turbidity levels (e.g. Hydraulics Research, 1980) confirm a general seaward diminution of suspensoids from the order of 0.1 to 1 kg m^{-3} at Avonmouth, to < 10 g m^{-3} towards the open Bristol Channel. Peak concentrations are registered in the region of Sharpness (of the order 1-10 kg m^{-3} on spring tides, falling to 0.1-1 kg m^{-3} at neaps (Kirby, 1986). Enhancement of suspended solid loads due to high river flows and storm events are detectable as far downstream as Avonmouth (STPG, Sediments Review Paper).

(iv) Plankton. The autotrophic component of the planktonic community (phytoplankton) is ultimately dependent upon the underwater light energy available to support it. At the same time, phytoplankton itself represents part of the particulate load, so that, potentially, the capacity of a body of water to support net phytoplankton increase is the point at which the plankton is effectively light-limited. In general terms, the phytoplankton-carrying capacity of the water is the difference between the self-shaded limit and the "shading" due to the non-living particulate components. The amounts of plant nutrients (phosphorus, nitrogen, silicon, a.o.) may impose a lower biomass threshold, as may the balance between net growth and net consumptive losses (respiration, grazing, outwash). Notwithstanding, the eventual capacity is complementary to the level of non-living turbidity and the rates at which it can be attained. Phytoplankton in rivers, lakes and coastal waters tends to be at its least abundant in winter and to have its greatest potential for abundance in summer, when the water is warm, the radiation income is greatest and, as observed above, non-living turbidity is low. The optical properties of 'turbid water' are therefore crucial and are considered in the next section.

2.6. Summary.

Particulate matter in water is extremely diverse in composition, provenance, size and density. Turbidity depends upon those particles which remain entrained in the motion of the water, whether this is due to gravitational currents wave-action or induced turbulence. The typical velocity scales of estuarine water movements, entrain clay and silt particles, and at times transport or rework larger particles. Fine organic detritus and the living organisms of the plankton may be considered to be entrained suspensoids and, hence, recognised as contributing to turbidity. The quantities of these materials entering or enhanced in estuaries depends upon the nature of the catchment and the seasonality of inflowing discharges. In estuaries much of the non-living turbidity owes to the resuspension by tidal energy of fine suspensoids, offset by redeposition in deep or stratified water and its displacement by tidal exchange. Persistence of turbidity is influenced by the variability in fluid motion of water, in the exposure of sediments and in the ionic strength of the suspending medium. The upper potential for biological primary production is limited by the extent of shading by turbidity.

3. EFFECTS OF SUSPENSOIDS ON THE PENETRATION OF SOLAR RADIATION

3.1 Optical properties of water

As stated at the outset, turbidity is recognized by its impact upon the optical properties of the fluid medium, in particular, its clarity. The definable properties of pure water include a quantifiable capacity to transmit light. The intensity of a beam of monochromatic light passed through a layer of pure water is weakened with the distance travelled, owing to two simultaneous effects: photons are removed by absorption; and they become more diffuse, due to scattering. The fractions of the incident flux which are absorbed and scattered, divided by the thickness of the layer, are respectively referred to as the absorption coefficient (a) and scattering coefficient (b). The sum of the quantities (c) is the beam attenuation coefficient. The attenuation is cumulative and exponential with distance; all three measures are therefore conveniently expressed in natural logarithmic units m^{-1}. Because the energy of photons varies inversely with the wavelength of the light beam, attenuation is not uniform across the visible spectrum (see Fig. 6).

The presence of solutes and particulate material in the path of the light beam will alter the shape of this attenuation spectrum by interfering with both absorbance and scattering properties of water in a way which increases c and, hence, reduces the straight line transmissibility of the water. The values of a, b and c remain properties of the liquid in question and are not dependent upon the intensity of the incident light.

Transforming this simple conception of what are really very complex physical principles (for thorough treatments, see Preisendorfer 1976; Kirk, 1983) to the optical properties of natural waters, the light source, the solar radiation flux, entering the water body exclusively across its surface, is progressively attenuated with increasing depth. An underwater light field is set up, the characteristics of which vary with water depth, with the angle and intensity of the surface-incident radiation and with the optical properties of the water. Beyond acknowledging that the proportion of the incident irradiance crossing the surface is a function of its reflectivity (which is < 3% for unpolarized light on a flat surface at incidences from vertical to 50° from zenith but which increases rapidly at angles > 70° from zenith, i.e. sun < 20° above horizon), we should direct our attention to the underwater attenuation. At any depth, $-z$ m beneath the surface, there is both a downward irradiance component, $I_d(z)$ and a (usually) smaller upward component, $I_u(z)$, due to upward backscattering. As I_d weakens with depth, so does I_u. So long as the attenuation properties are uniform with depth, then the rate of diminution of I_d at a given wavelength is approximately exponential with depth, and is expressed in terms of a vertical attenuation coefficient at that wavelength (ϵ). Thus, at z:

$$\epsilon\ (z) = \frac{1}{I_d(z)} \quad \frac{dI_d\ (z)}{dz} \quad = \frac{d\ \ln I_d\ (z)}{dz} \tag{7}$$

whence,

$$I_d\ (z) = I_d\ (0).e^{-\epsilon\ z} \tag{8}$$

where I_d (0) is the downward irradiance flux just beneath the surface. Whereas I_d varies with wavelength (Fig. 6), it is usually convenient to average the vertical attenuation coefficient, ϵ, across the visible spectrum (400-700nm). The attenuation due to backscatter at depth z is in proportion to the ratio $I_u(z)/I_d(z)$.

It is possible to determine the turbidity (T) at 90° of a given suspension by nephelometry (in empirical Nephelometric Turbidity Units, or NTU) and to estimate b, the scattering coefficient (units : m^{-1}) by a factor estimated to lie between 0.92 and 1.10 (Kirk 1985); assumption of numerical equivalence is considered acceptable. For the appropriate waveband, the coefficient of absorption, a, of a filtered isolate can be measured spectrophotometrically. Then we can assume that $\epsilon = c = a + b$.

Alternatively, in situ approximations of the underwater light field generally rely upon curve fitting to photometric measurements of $\underline{I}_{\underline{d}}$ within a given waveband at successive depths, $\underline{z}$, and calculating the slope ϵ, on the basis

$$\epsilon = \ln[\underline{I}_{\underline{d}}(\underline{z})] - \ln[\underline{I}_{\underline{d}}(\underline{z} + 1)] \qquad (9)$$

Simultaneous measurements with a horizontal beam transmissometer are supposed to provide an estimate of the total light absorption at successive depths; subtraction of $\underline{a}$ should then yield an estimate of $\underline{b}$. In highly turbid waters, however, accumulated errors of measurement of $\underline{c}$ render such determinations unreliable. This limitation should be borne in mind if critical quantities are required or if any form of deterministic simulation is constructed.

A crude estimate of ϵ is based upon the use of a Secchi disc: this simple device consists of no more than a white or quartered disc, either 200 or 300 mm in diameter which is lowered into the water until it just disappears from the view of an observer. "Calibration" of the depth of disappearance, $\underline{z}_{\underline{s}}$, against the mean $\epsilon_{400-700}$ for the visible spectrum is said to yield conversion factors of 1.4 to $1.7/\epsilon$ or against the waveband of least attenuation (ϵ_{min}, usually the spectral band 480-580 nm), 2.0 to $2.3/\epsilon_{min}$.

Whichever of these methods are adopted, a series of determinations through time may be quantified against the variability in the attenuation coefficient. If, for example, the background extinction of the water were constant, then the increment in attenuation should be proportional to the amount of material in suspension, i.e.

$$\epsilon \propto \epsilon_{background} + f.\epsilon_s \qquad (10)$$

Where f = the population of particles and ϵ_s is the particle-specific absorption. The problem arises that ϵ_s values differ for the different kinds of suspensoid we have identified and several kinds will be present simultaneously and in variable mutual proportions.

3.2 Irradiance attenuation in natural water bodies

Kirk (1983, 1985) reviews the attenuation profiles of a large number of lakes and seas with a wide range of absorption properties. His comprehensive analyses distinguish waters wherein the absorption coefficients are dominated by dissolved colour - usually humic materials or Gelbstolf (= "yellow substance"), by photoplankton and by inanimate tripton (non-living particles and organic debris). Absorption scans to illustrate different components of absorption are represented in Fig. 7.

The highest clarity waters are the open oligotrophic oceans, notably the Central Pacific waters: their absorption properties are not dissimilar from those of pure waters (Fig. 7a cf Fig. 6). Lake waters that are heavily stained with humic derivatives absorb strongly at the shorter visible wavelength (i.e. they absorb mainly blue- and UV-light and appear to be coloured yellow-brown. Kirk's (1985) data for Corin Reservoirs (ACT) provide a suitable example (Fig. 7b) perhaps representing peat-stained waters of temperate moorlands as well as coloured waters of tropical and subtropical continental waters. Lowland lakes with a lower organic content have a background colour nearer to that of pure water; here (Fig. 7c) absorbance may be dominated by inwashed and resuspended tripton, but where nutrients are available to support it, phytoplankton may account for an increasing share of the absorbance. In the example given, the chlorophyll *a* component was 47 mg m^{-3} and was dominated by diatoms; the absorption due to unit chlorophyll varied between 0.025 m^{-1} (mg chl *a* $m^{-3})^{-1}$, i.e. 0.025 mg m^{-2}, at the chlorophyll absorbance peaks (440, 665 nm), and 0.007 mg m^{-2} at about 585 nm. Absorbance spectra of algal pigments vary with species, due to different specific composition and relative chlorophyll content. They also depend upon a packaging effect; pigment spread through a fine, attenuate filament intercepts more photons than the same pigment held in a spherical shape. Averaged across the visible spectrum, algal chlorophyll has a specific attenuance (ϵ_s) of between 0.004 (spherical cells

$< 5 \times 10^{-6}$ m in diameter) and up to nearly 0.02 $m^2\ mg^{-1}$ for some filamentous species.

Non-living material may transmit, refract, reflect or extinguish light that it intercepts. Numerous examples of absorption spectra in particular turbid lakes are available (one of which, for Lake George, a clay-rich lagoon in ACT, Australia, is given in 7d). No general relation has been derived, as no 'independent' variable has been defined. The same weights of clays or sands or organic debris per unit volume have different net effects upon light transmission, dependent upon particle size and shape, and the same variable properties, together with differences in colour and density, apply to any one descriptive category of material. What can be stated is that the efficiency of absorbance (Q_{abs}) of a given substance is related to the cross-sectional area of the particle $[\pi(d/2)^2]$ for a sphere of diameter d and the efficiency of its scattering (Q_{scat}) corresponds to the fraction of the cross-section of the beam occupied by particles divided by the cross-section of particle. The sum corresponds to the efficiency of attenuation, Q_{att}. Q_{att} is described by a complex relation, owing to van de Hulst (1957),

$$Q_{att} = 2 - \frac{4}{\_}\sin \_ + \frac{4}{\_}(1 - \cos \_) \qquad (11)$$

where $\ = (4\pi d/2\ )(m - 1)$, $\ $ = the photon wavelength and m is the refractive index of the material. For a non-absorbing particle, $Q_{scat} = Q_{att}$; the scattering efficiency of non-absorbing particles with a refractive index of 1.17 (a typical value for colourless minerals suspended in water) are plotted against diameter in Fig. 8a. Scattering is very low for particles less than 1×10^{-6} m in diameter but rises steeply to a maximum at 2 μm, before stabilising at an efficiency of 2.0. What can also be stated is that the upwelling radiation reflected back from variable amounts of clays and silts in suspension in Mississippi reservoirs increases as an approximately linear function of the weight of material in suspension, especially in the waveband 700-800 nm (Fig. 8b: from Ritchie *et al*. 1976).

It is thus apparent that coarser clays and fine silts ($\underline{d} \sim 2x10^{-6}$ m) attenuate light more efficiently than either larger or especially much finer particles and that the turbidity created by any given type of particle is proportional to the total mass per unit volume of water.

An approximate relation may be proposed to determine the attenuation properties of non-living particulate matter in terms of its concentration in a form that enables direct comparison with those of phytoplankton. Supposing that clay and silt particles in the size-range $\underline{d}$ = 2 to 10 μm have a mass 2.5 x greater than algae of identical volume, then the mass-specific coefficient of light attentuation will be 0.4 times that of the same mass of fresh algae. Approximately 0.5% of the fresh algal mass is due to chlorophyll, the attenuation coefficient of which is put at 0.01 m^2 (mg chl $\underline{a}$)$^{-1}$, or 10 000 m^2 kg^{-1}. i.e. 10 000 m^2 (200 kg live alga)$^{-1}$, or 50 m^2 (kg alga)$^{-1}$. Thus, the attenuation due to clay particles approximates to 20 m^2 kg^{-1}. Then the vertical attenuation due to clay particles, uniformly present at a concentration of 1 kg m^{-3} is roundly, (1 kg m^{-3} x 20 m^2 kg^{-1} =) 20 m^{-1} and comparable to that due to an algal concentration equivalent to 2 g m^{-3} chlorophyll $\underline{a}$.

3.3 Irradiance penetration

We may now make some assessment of the light fields in water bodies. The most useful parameter would be a value of how far into water the light will penetrate. With an exponential relation, zero light is approached asymptotically. We must therefore elect a definable light level to analogize to depth of penetration. Limnologists like to define the base of the illuminated layer as the depth reached by 1% of the immediate subsurface irradiance. This has the advantage that the latter may be back calculated from attenuation coefficients but 1% of bright tropical sunlight, some 425 W m^{-2} (equivalent to 1.95 m mol photon m^{-2} s^{-1}) is scarcely comparable with 1% of < 100 μ mol m^{-2} s^{-1} experienced (say) on an overcast midwinter morning at higher latitudes (see, for instance, Reynolds 1987)[1]. In the next section, reference will be made to net photosynthetic oxygen generation, which has a threshold level, dependent upon species, temperature and light history, in the range 2-20 µmol photon m^{-2} s^{-1}. Taking the geometric mean of this order of magnitude, we may nominate 6 µmol photon m^{-2} s^{-1} as an appropriate base. Rewriting equation (8) we can readily calculate the absolute depth of the lightfield (or euphotic layer) as

$$\underline{z}_{eu} = (\ln I_0 - \ln 6)/\epsilon^* \qquad (12)$$

where ϵ^* is the sum of the attenuation coefficients due to water, colour, phytoplankton and non-living particulates, each averaged (for convenience) across the spectrum.

$$\epsilon^* = \epsilon_w + \epsilon_c + \epsilon_{chl} + \epsilon_p \qquad (13)$$

Fig. 9 presents some actual profiles of light under measured surface irradiances available in the literature. The inset bars represent the apportionment of the attenuation components. The examples are intended to illustrate extreme cases but they serve to show quite clearly how suspended clays and large populations of phytoplankton can impact upon the depth of underwater light penetration. Apart from twilight hours, the variation in the penetration of light in clear waters will not be obvious to the casual observer and the diel variation becomes less the more turbid is the water: they simply appear murky throughout. The striking point is that in the range of turbidity equivalent to $\epsilon^* = 0.5$ to 2 m^{-1} (i.e. 25 to 100 g m^{-3} suspended solids), the reduction in potential light penetration is very marked; for values $\epsilon^* > 2$ m^{-1} the depth of effective light penetration is unlikely ever to exceed 2 m depth.

[1] 1 mole of photons, or 1 einstein, is equivalent to 6.023×10^{23} photons. Full tropical sunlight is therefore 1.175×10^{-20} photons and about 0.47 of total solar radiation.

3.4 Summary

The optical properties of water are governed by simultaneous interactions between absorbance and scatter of light. Particulate matter in water interferes with both components. Natural water colour and phytoplankton cells absorb light energy unequally across the spectrum; some non-living particulates alter the scatter and back-reflection properties. Attenuation is very dependent upon the size of particles, being greatest for particles about 2 µm in diameter. Larger particles cause less attenuation per unit mass. Attenuation by a given type and size category of particles is in linear proportion to the dispersed mass present.

4. THE EFFECT OF SUSPENSOIDS ON COMMUNITY METABOLISM

4.1 The light profile and photosynthesis

There is a large literature on the photosynthetic capacity of phytoplankton, in terms of temperature, instantaneous irradiance, and the species composition of the phytoplankton. Photosynthesis is the essential basis of autotrophic growth and is the beginning of the major food chains. This section is concerned primarily with the photosynthetic by-product, the generation of oxygen. In essence, inorganic carbon is fixed as carbohydrate, releasing oxygen in equimolecular proportions.

$$\mathrm{CO_2 + H_2O} \underset{\text{Energy}}{\qquad\qquad} \mathrm{[CH_2O] + O_2} \qquad (14)$$

The oxygen is released into the medium in solution and provides a source of respiratory reactant for all forms of life in the water, i.e. releasing the energy stored in the organic food. By analogy, oxygen is consumed and carbon dioxide gas is discharged. In addition, oxygen is directly involved in many chemical oxidation processes and in the heterotrophic bacterial pathways leading to the breakdown of organic substrates. High concentrations of suspended particles provide a vastly enhanced cumulative surface area for the attachment of bacteria, thus raising the potential heterotrophic O_2 consumption. Where waters metabolise more organic matter than they generate, net photosynthetic oxygen production is vital to offset biochemical consumption and to avoid the consequences of anoxia: the build-up of metabolites of anaerobic bacterial activities, including hydrogen sulphide, ammonia and methane. Without oxygen, active animals cannot long survive. It is scarcely surprising that all water managers are anxious to keep their waters 'sweet' and to monitor closely the biochemical oxygen demand (BOD) in their charge. 'BOD' is conveniently quantified as the consumption of oxygen by the raw water, stored in the dark at 20C for 5 days. Thus, for a given water body with a given BOD, a major metabolic criterion will be whether sufficient photosynthetic oxygen is generated to supplement exchanges of atmospheric oxygen at the surface.

This simple requirement must be tempered by the fact that the experimental measurement of photosynthetic oxygen generation corrects only for consumption as dark respiration. The oxygen produced in the light may be just as rapidly consumed by the algae if their growth is limited by (say) lack of nutrient: carbohydrate is not accumulated in the cell indefinitely but is respired at an accelerated rate (or photorespired), consuming oxygen in the process. Moreover, short-term day-time, *in situ* measurements of photosynthesis can rarely be multiplied up directly to give 24-h or even day-time integrals of oxygen production in the lake.

In view of this caveat, it is advantageous to compare backcalculations of net oxygen generation from phytoplankton growth rates under ideal culture with the more direct measurements *in situ*.

When plotted against photon flux densities, photosynthetic rates are found to rise linearly at first before plateauing at a temperature-limited maximum; some fall-back (inhibition) occurs during sustained periods at high intensities. As an illustration, two plots are represented in Fig. 10a, being derived from FBA data for the freshwater diatom, *Fragilaria crotonensis*, at 5, 10 and 20C. The characteristic shape of the "P vs I" curve varies with species and their light histories but can be defined in terms of the plateau values (P_{max}), the intercept, which is negative, being equivalent to dark respiration (R), the point of inflection in the P vs I plot (by extrapolation, I_k) and the angle (α) of the slope between P at $I = 0$ and P at $I = I_k$, i.e. $\alpha = P/ I$. (Fig. 10b).

Translating to an imaginary water column with the exponential attenuation of downwelling irradiance inset in Fig. 10c, the curve of light-limited P on z is also exponential. The plot also marks the corresponding specific dark rate of respiration and the depth, z (I_k), below which photosynthetic rate is light-limited. The area integrated under the curve in Fig. 10c is equivalent to that enclosed by the trapezium in Fig. 10b, and defines the areal specific rate of photosynthesis. In terms of I,

$$\Sigma P = P_{max} \times \tfrac{1}{2} [(0 \text{ to } I_o)\ (I_k \text{ to } I_o)] \qquad (15)$$

In terms of depth,

$$\Sigma P = P_{max} \times z(0.5 I_k) \qquad (16)$$

The units of ΣP in Eq (16) are mg O_2 (mg chl a)$^{-1}$m^{-2} h^{-1}. Given P_{max} at 20C = 10.4 mg O_2 (mg chl a)$^{-1}$m^{-3} h^{-1}, I_k = 0.12 m mol photon m^{-2} s^{-1} and $z(0.5I_k)$ is at 2.7 m (Fig. 10c), ΣP = 28.1 mg O_2 (mg chl a)m^{-2} h^{-1}.

Cultured strains of the same freshwater *Fragilaria* sp., maintained under conditions of continuous saturating light and nutrients at 20C, achieve maximum recorded rates of cellular increase of 1.38 (± 0.09)d^{-1} (Reynolds 1983), i.e. the equivalent of two cell divisions every 24h, or a doubling of biomass every 12h. Put another way, 1 unit of new carbon is fixed for each unit of carbon present as biomass at the start of the 12h. If we assume a typical cellular ratio of carbon to chlorophyll (50:1), the net rate of new carbon production is 50 mg C (mg chl a)$^{-1}$ (12h)$^{-1}$, and the *net* generation of oxygen is 133 mg O_2 (mg chl a)$^{-1}$ per cell division. A near-surface population would thus generate a net maximum production of 7.9 mg O_2 (mg chl a)$^{-1}$ m^{-3} h^{-1}.

4.2 Oxygen generation capacity of natural waters

To gauge the effect of turbidity on oxygen generation, we may construct a series of scenarios of net planktonic photosynthesis. The simplest deduction would be for a water of high clarity (ϵ_w = 0.2 m^{-1}) at the latitude of the Severn Estuary under a cloudless sky at the summer solstice (day length 16h); let us also assume that the temperature is 20C. The mean daily light income to the water would be not more than 58 mol photon m^{-2}, or 1 m mol photon m^{-2} s^{-1} (z_{eu} = 25.6 m; Fig. 10). The concentration of phytoplankton is, by definition, low, ≤ 1 mg m^{-3}; the net oxygen generation over 24h is represented in Fig. 11a, equivalent to a total of 1 mg chl a m^{-3} x 10.4 mg O_2 (mg chl a)m^{-3} h^{-1} x 16h x 14.1 m 2.35 g O_2 m^{-2} d^{-1} (≡ 0.83 mg O_2 l^{-1} during a 5-d BOD). This capacity is reduced by lower insolation levels and lower water temperatures. The behaviour of a similar chlorophyll concentration in a water column of similar optical properties obtaining near the winter solstice (8h day, 5C) under overcast skies (assumed to reduce light income to 0.3 of the potential) is shown in Fig. 11b: $\underline{I}_k$ moves proportionately nearer the surface, the oxygen production is reduced to 26 mg O_2 m^{-3} d^{-1}, or 0.17 g m^{-2} d^{-1} for the whole column. The third example (Fig. 11c) represents the vernal equinox (12h day, 10C, with sky 50% cloud cover; light income 0.65 of potential); oxygen is now generated at a calculated rate of 58 mg O_2 m^{-3} d^{-1} or 0.86 g O_2 m^{-2} d^{-1}.

The principal effect of increased turbidity is to restrict the depth of the layer wherein net photosynthesis is possible. If the increase in suspensoids were due exclusively to enhanced populations of phytoplankton, the reduction in the depth of the photosynthetic layer is countered by the potential of the greater near-surface concentration. Fig. 11d takes the equinoxial condition adopted in Fig. 11c but the water now contains 80 mg chl a m^{-3} which increases the attenuation coefficient to 1.0 m^{-1} and brings $\underline{I}_k$ much closer to the surface. Near-surface photosynthetic oxygen generation is 4.6 g O_2 m^{-3} d^{-1} or 13.8 g O_2 m^{-2} d^{-1}. Increasing phytoplankton still further (480 mg chl a m^{-3}) so $\epsilon^* \rightarrow 5.0\ m^{-1}$ yields the profile in Fig. 11e. In the top few centimetres, net daily oxygen production may be as high as 27.6 g O_2 m^{-3} d^{-1} but the now very restricted light penetration (0.5 $\underline{I}_k$ is at 0.6 m) keeps the column productivity down to 16.6 g O_2 m^{-2} d^{-1}.

The final graphs in Fig. 11 attribute the bulk of the turbidity to non-living tripton; thus, Fig. 11f assumes conditions similar to Fig. 11d, save that the attenuation (1.0 m^{-1}) is due to inert particles (∿0.5 kg m^{-3}) plus only 20 mg m^{-3} of productive phytoplankton. The productive potential drops to 1.15 g O_2 m^{-3} d^{-1} or 3.46 g O_2 m^{-2} d^{-1}. 20 mg chl a m^{-3} in the presence of turbidity complementing an attenuation of 5 m^{-1} generates the curve in Fig. 11g. The maximum productivity is little changed with respect to Fig. 11f (1.15 g O_2 $(m^{-2})^{-1}$ but the net oxygen generation is contained above 0.6 m; total column generation would be around 0.7 g O_2 m^{-2} d^{-1}.

While photosynthetic oxygen production potentially augments atmospheric interchanges (especially with agitation and good vertical mixing) of organic waters sufficiently to prevent anoxia developing, it is clear that high concentrations of tripton substantially reduce that potential. Because they also reduce the downward transfer of heat energy, high concentrations of turbidity render the water more likely to stratify and so impart a higher mechanical-energy requirement to keep them mixed to depth. In other words, turbidity not only interferes with oxygen generation at depths greater than 2-3 m but also increases the likelihood of anoxia in unmixed bottom waters. In this way, turbidity contributes to the vertical segregation of water masses to the extent that different layers may develop their capabilities to self-purify, particularly if there is a simultaneous high organic load. In a shallow estuary, potentially well-mixed by tide and sustained wind-action, persistent turbidity does not necessarily precipitate environmental problems so much as to raise the probability that they might nevertheless occur under certain hydrographic conditions of reduced fresh water inflows or of a relatively stratified column.

4.3 Summary

Suspensoids, other than living phytoplankton, reduce the potential of a water column to generate oxygen, owing to interference with the underwater light field. In addition, microbial decomposition of organic material may increase the oxygen demand and, hence, distort the metabolic equilibrium of the aquatic system as a whole. Turbid interference with vertical heat transfer may significantly raise the external mechanical energy required to keep the water from stratifying and isolating bottom water prone to the rapid development of anoxia.

5. EFFECTS OF TRIPTON TURBIDITY ON AQUATIC ANIMAL COMMUNITIES

5.1 General Remarks

In addition to their impact upon the all-important availability of oxygen to aquatic animals, suspended particulates influence the function and structure of the communities in a variety of ways, which, moreover, are not all necessarily negative. The effects are interactive in the sense that selection against a particular group of organisms at one trophic level may work to the advantage of other species at the same trophic level and, in turn, alter the impact upon organisms at another trophic level. The following consideration is based upon experiences in freshwaters and is not intended to provide a comprehensive overview of all possible effects on all estuarine species. Rather, it illustrates the general consequences by reference to a single broad category - that of the pelagic invertebrates (zooplankton) and the fish to which they might fall prey (thus representing their resource base). By way of a preamble, it is as well to provide a brief statement about the key processes, illustrated where appropriate by examples.

Again, the first step must be the distinction between particle types and sizes. A general hypothesis might be that high turbidity loads interfere with primary photoautotrophic production and accordingly limit the amount of potential food generated to the food chain. On the other hand, bacterial production, supported by alternative immediate energy sources (organic detritus) may offset this deficiency; at the same time inorganic particles enhance the surface area available to colonisation by attaching, non planktonic bacteria. Organic particulates might be considered especially beneficial in this respect, by simultaneously providing an enriched source of degradable substrate to bacteria and a direct source of food to detrital filter-feeders. In either instance, variation in the size-ranges of the particles present may limit the types of organisms they can physically support or which are able to ingest the particles directly. As noted already, size is also relevant to the longevity of the particles in suspension. The reciprocal process, the amount of material sedimenting, has analogous repercussions for the invertebrates of the bottom-dwelling benthos: deposition of organic detritus and bacterized mineral particles represents the resource base of a host of benthic-filtering species, provided that the deposition and subsequent mobility of silts and sands neither prevents the intake of adequate amounts of food particles (either by diluting their abundance or clogging the filtering mechanisms) nor prejudices the mode of attachment. In this way, it is possible to understand why the more mobile of the estuarine benthic species - including malacostracans (shrimps, crabs, amphipods), annclids (ragworms) and mud-dwelling bivalves (especially cockles and razor-shells) - should be so relatively common in sandy or silty deposits of tidal and sublittoral flats receiving significant organic inputs, why oysters and the more delicate, sedentary fan-worms are prevalent in areas of cohesive sediment and fine suspensoids and why well washed stony or rocky outcrops are essential to the persistance of attaching barnacles and mussels. In turn, the distributions of relevant predators, including demersal and benthic fish, and the preferred haunts of the various estuarine bird species (waders, oyster-catchers) are ultimately responsive to the nature and behaviour of the dominant suspensoids, through their influence upon the distributions of their preferred foods. All these effects may be modified by the sorption on to particles of toxic chemical contaminants.

5.2 Zooplankton

In freshwaters, fairly clear distinctions have been made among the functional feeding strategies of the elements of the principal components of the planktonic fauna. Whereas heterotrophic protozoans are particularly associated with bacterized aggregates of organic particles and, among the rotifers, both filter-feeding on small particles and selective browsing on certain specific food organisms have been identified, the major crustacean representatives (copepods, cladocera) show quite distinctive food-gathering traits. These include: non-selective filter-feeders, limited only by the size ranges of food particles available (mainly living and detrital), such as members of the Daphniidae; more selective raptorial herbivores, which differentiate and locate preferred particles (*NB* Calanoid copepods); and animals (e.g. Chydorids) which locate, attach to and then browse upon the algae, bacteria and protozoa that grow on the surfaces of the larger suspensoids. So far as an estuarine barrage is concerned, these freshwater species might be expected to be relatively the more abundant, or to give place to brackish-water counterparts. Sediment-rich lakes and rivers tend to be inhabited principally by calanoid copepods (*NB* *Diaptomus* spp.); high concentrations of non-nutritive mineral particles apparently tend to select against cladocera in rivers and towards copepod-dominated assemblages. Few filter-feeding species of crustacea pass more than their larval stages in the inshore marine plankton, which is dominated by browsers. The principal planktonic feeders in estuaries are often calanoid copepods like *Eurytemora* and some *Acartia* spp. Cladocera are only likely to dominate if the particulate fraction is made up of living algae and organic debris and in adequate quantities (> 0.5 g C m^{-3}). Large concentrations of particles which are neither organic nor principally comprise living organisms of filterable size (60 µm) tend to favour calanoids; the size of population supported, however, is related to the concentrations of primary foods that are present. If high mineral turbidity restricts *in situ* production of photoautotrophic algae, and a lack of organic substrates limits the growth of bacteria, then the biomass of calanoids and of the zooplankton generally will be correspondingly restricted.

5.3 Fish

Most freshwater- and many marine-species of fish feed in the water column, around rooted plants and on the substratum, upon foods that generally they locate primarily by sight. The key surface for respiratory oxygen exchange is the gill which, to function adequately, comprises closely stacked gill lamellae (filaments). The life-cycles are completed through egg-laying, usually on plant, rock or bottom substrata. Based on the review and illustrations of Bruton (1985), the most likely effects of suspensoids upon fish populations, summarised in Fig. 12, are:

(i) reduction in photosynthetic activity of primary producers reduce the base of food resource available to the food chain culminating in the fish;

(ii) restriction of habitat (for food) and shelter (for breeding) provided by rooted vascular plants.

(iii) reduced visibility of pelagic food

(iv) reduced availability of benthic food, due to smothering?

(v) clogging of gill filaments

(vi) reduced predation risk, especially from birds.

Only (vi) is considered advantageous to all species; however, those least disadvantaged by the other mechanisms may actually benefit competitively. Clearly (i) does not apply when planktonic algae constitute the main source of the turbidity but high concentrations of plankton do restrict the ranges of benthic macrophytes and macroalgae (potentially represented in estuaries by *Zostera* and certain seaweeds). Neither will (i) be important in organic environments if food chains may be predominantly based on bacterial production.

In spite of these caveats, the interaction between fish and suspensoids is rather more complex than has been implied. Bruton (1985) reviews several case studies, mainly drawn from African lakes, but including one on Natal river estuaries. All concern highly turbid systems but the responses of the fish populations are not always similar. High suspensoid loads undoubtedly cause a reduced growth rate, a decrease in size at breeding maturation and a movement of large fish to inshore feeding grounds. In reviewing the experimental evidence for the effects of suspensoids, Bruton (1985) highlighted the impact of sedimenting turbidity on egg and larval survival, and the anoxia generated

6. GENERAL STATEMENT

This review has addressed the topic of turbidity, mainly by reference to its consequences in freshwaters; it has taken limited cognisance of studies specific to the Severn Estuary and Bristol Channel, neither has it attempted to build an appropriate bibliography for the region. Nevertheless, it is possible to offer a few pointers as to information which may need to be sought or, where appropriate, newly investigated:

(i) Logic dictates that the post-barrage lake will not, de facto, receive any higher external loads of suspensoids, although coastal erosion attendant upon a raised mean level will generate added suspended loads. However, particle-rich water will be retained within the barrage for substantially longer periods, as a consequence of reduced tidal exchanges, which will also dilute present salinity levels. Further data on fluvial loads and dispersal rates downstream are desirable, as are some experimental data on particle aggregation. Density stratification may be more prevalent, favouring increased sedimentation in deeper water.

(ii) We are unaware of any systematic attempts to determine the nature of the primary suspensoid load (though we suspect it is dominated by clays and fine silts brought in at high fluvial discharge). The relative composition of organic material in the sediment will have a profound influence upon the biological systems of the barrage 'lake', either directly, as substrate for heterotrophs, or indirectly through altered gaseous exchange.

(iii) The structure of the present fauna of the area to be impounded should be investigated and perhaps compared with that in locations selected to have as nearly as possible, the physical/chemical characters anticipated in the impounded area.

(iv) Optical and BOD properties of the estuary should be established between the present tidal limit and 30-50 km beyond the seaward limit of the proposed barrage; this will provide a more comprehensive base for modelling the impact of post-barrage turbidity in the Severn Estuary.

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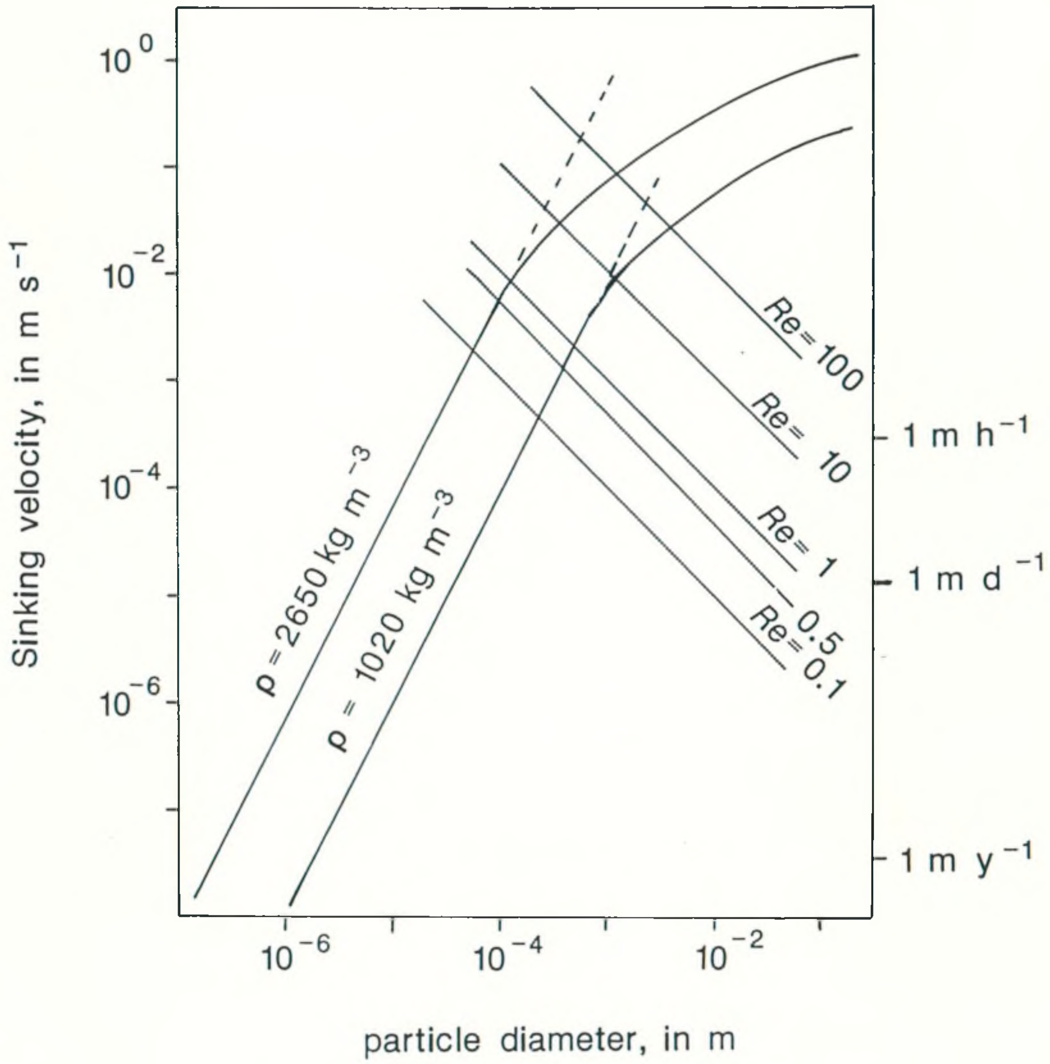

Fig. 2. The relation between sinking velocity of particles of selected densities (ρ = 1020 and 2650 kg m^{-3}) and their sizes. The lower parts of the fitted regression correspond to size-determined velocities under conditions of laminar flow over the particle. At faster velocities, the flow becomes turbulent (increasing Reynolds Number, Re) and begins to dominate the settling velocity (Re > 0.5).

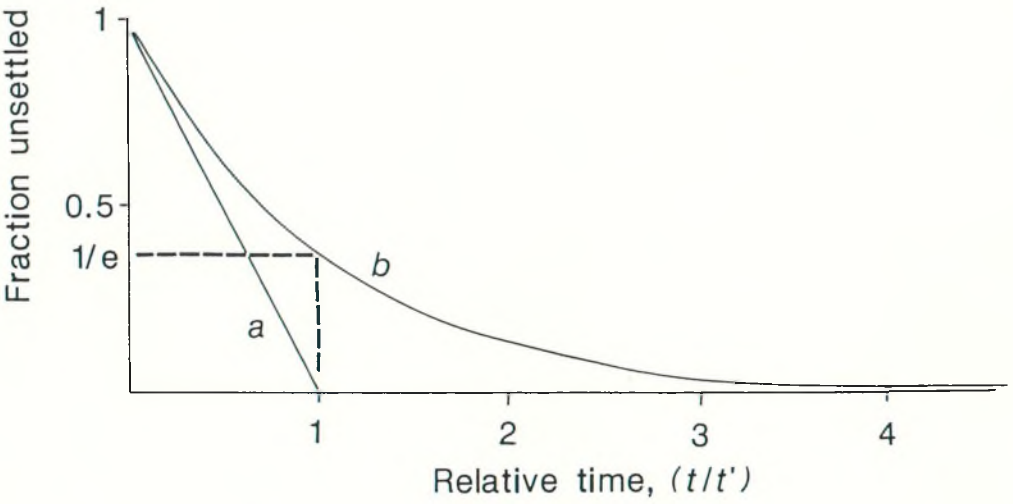

Fig. 3. Changes in the mean concentration of identical particles initially dispersed under (a) static conditions and (b) entrained in continuous mixing flow in a tubular column $\underline{h}$ in height; $\underline{t}'$ is the time taken for all the particles to clear the column, with a settling velocity of $\underline{w}_s$. ($\underline{t}' = \underline{h}/\underline{w}_s$). If all conditions are satisfied the fraction unsettled at $\underline{t}'$ under mixed conditions is always 1/e (= 0.368).

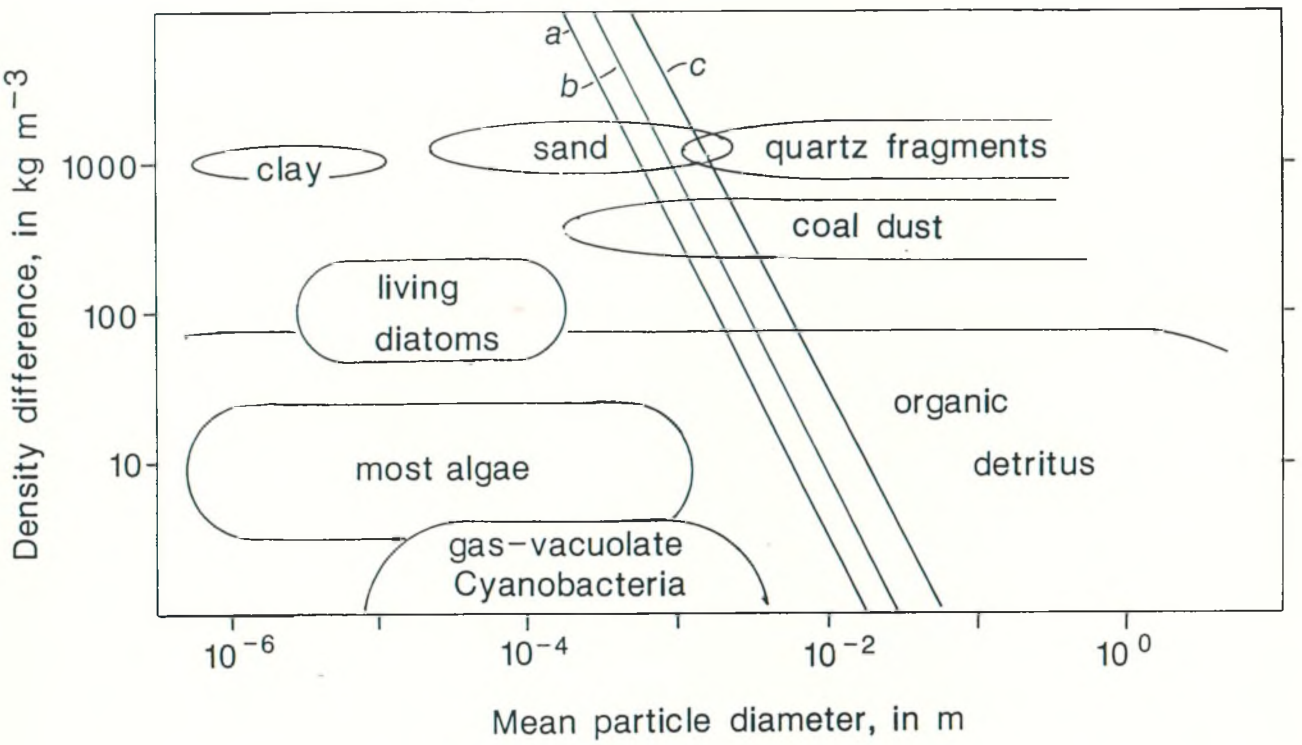

Fig. 4. Entrainment of particles as a function of size and density difference. The entrainment condition is satisfied only to the left of the three diagonal lines: a corresponds to the entrainability of particles by near-surface turbulence generated by a wind speed of 3 m s^{-1}; b is the corresponding solution for a 20 m s^{-1} wind; c is that due to a current of 1 m s^{-1} in a rough channel.

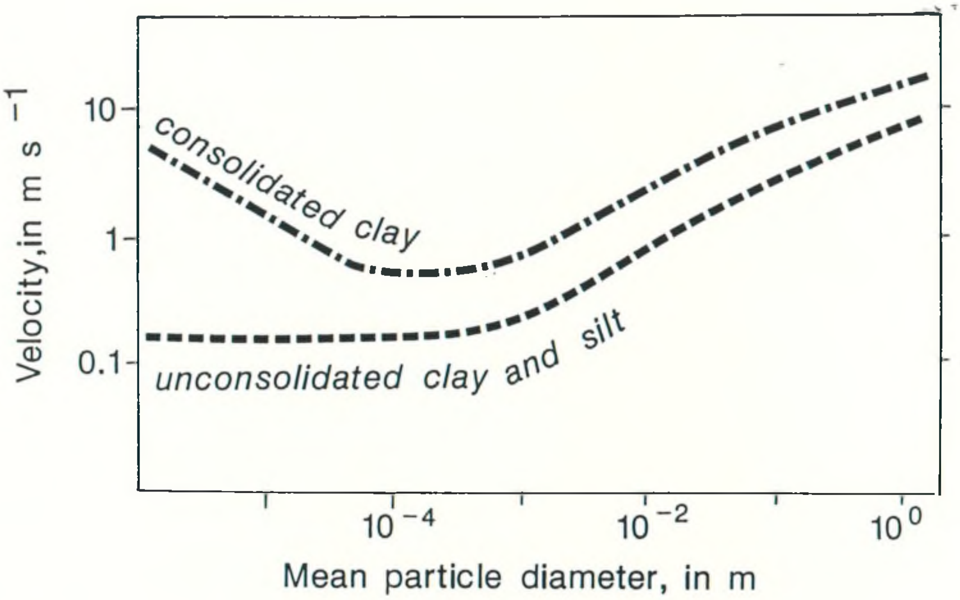

Fig. 5. The critical velocity, in m s^{-1} for the onset of erosion of uniform material of density 2650 kg m^{-3}

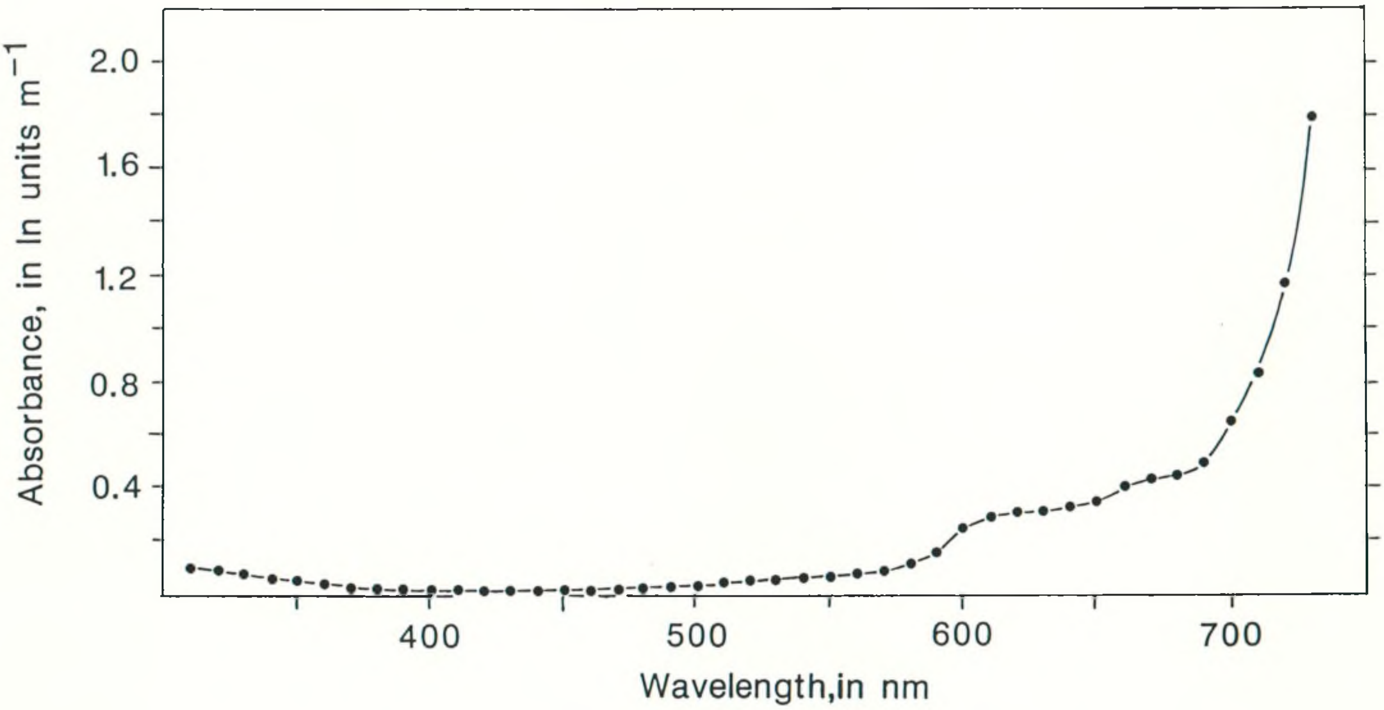

Fig. 6. The absorption spectrum of pure water in the visible and near visible wavebands.

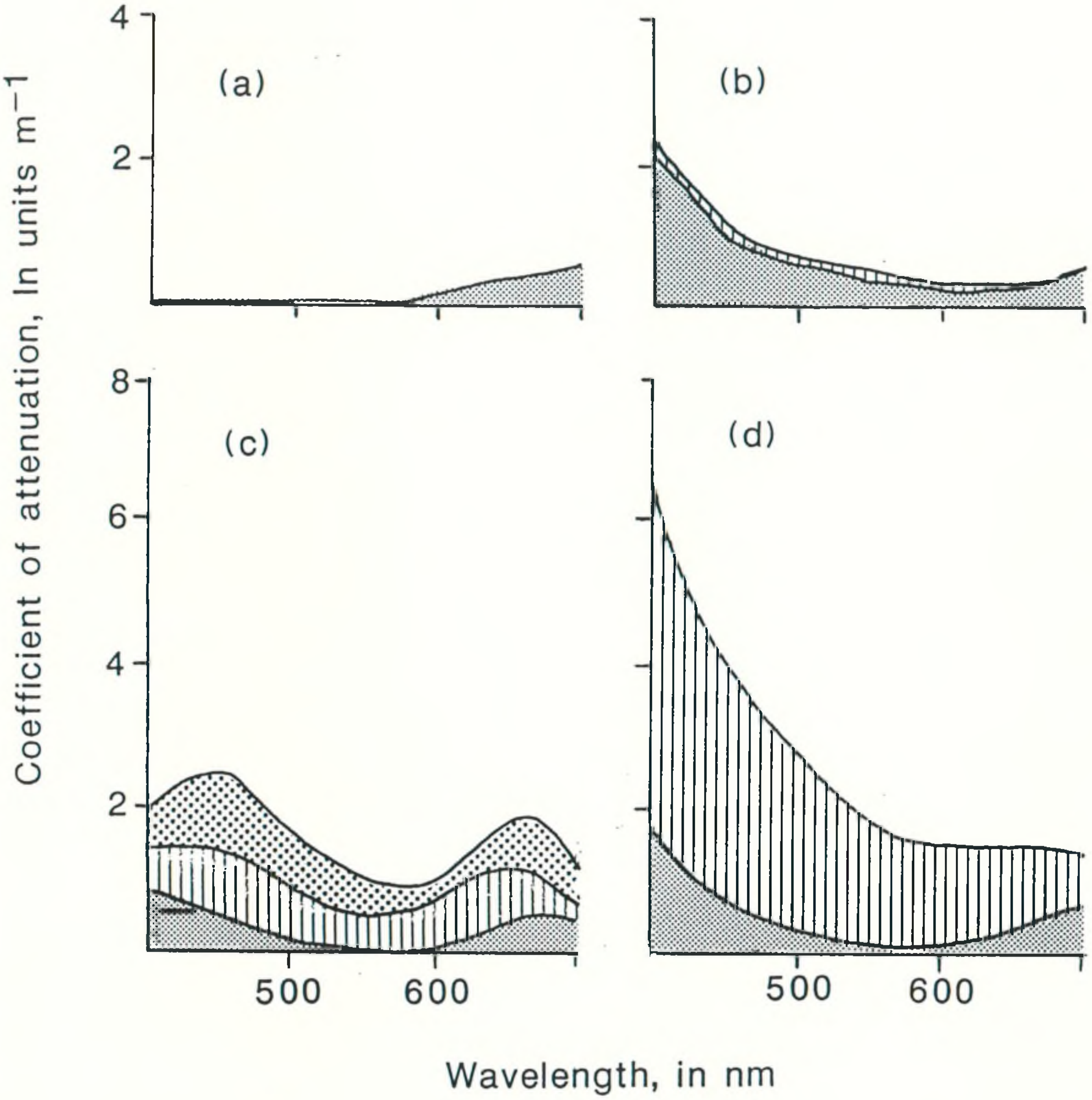

Fig. 7. Examples of attenuation spectra of some natural waters, to show effects of different components: (a) clear oceanic water from Jervis Bay (cf. Fig. 6); (b) a highly coloured water, Corin Reservoir, ACT, Australia; (c) a water with a high algal content, Crose Mere, England; and (d) a water rich in fine clay, Lake George, New South Wales. Fine stippling represents proportion of attenuation due to colour; vertical hatch to non-living tripton; coarse stipple to phytoplankton.

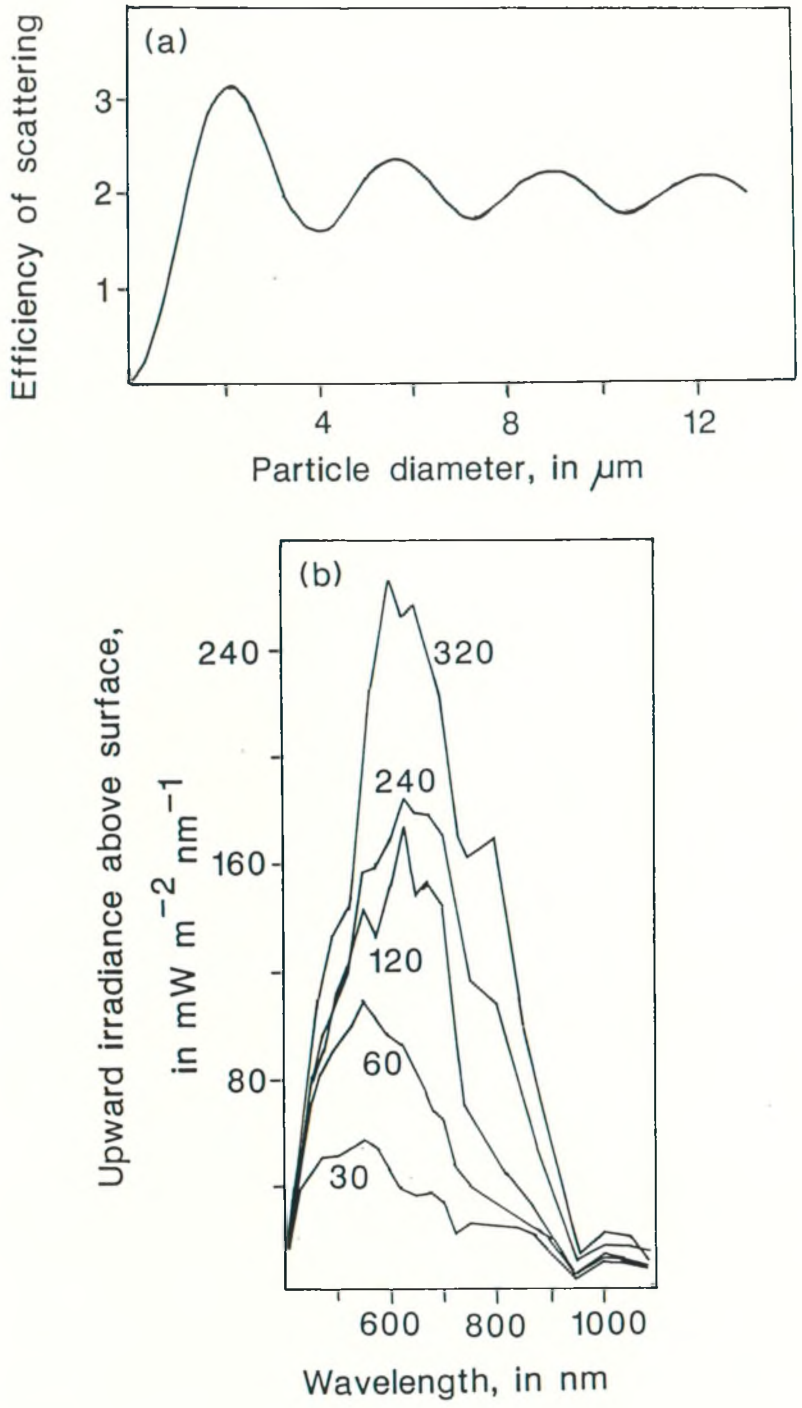

Fig. 8. Scattering of irradiance by particles: (a) scattering efficiency of individual non-absorbing spheres as a function of size, from equation of van de Hulst (1957), given a refractive index of 1.17; wavelength of light, 550 nm. (b) Spectral distribution of upwelling (backscattered) radiation from fresh water containing various masses of fine suspended solids (30-320 g m^{-3}). Data of Ritchie et al. (1976).

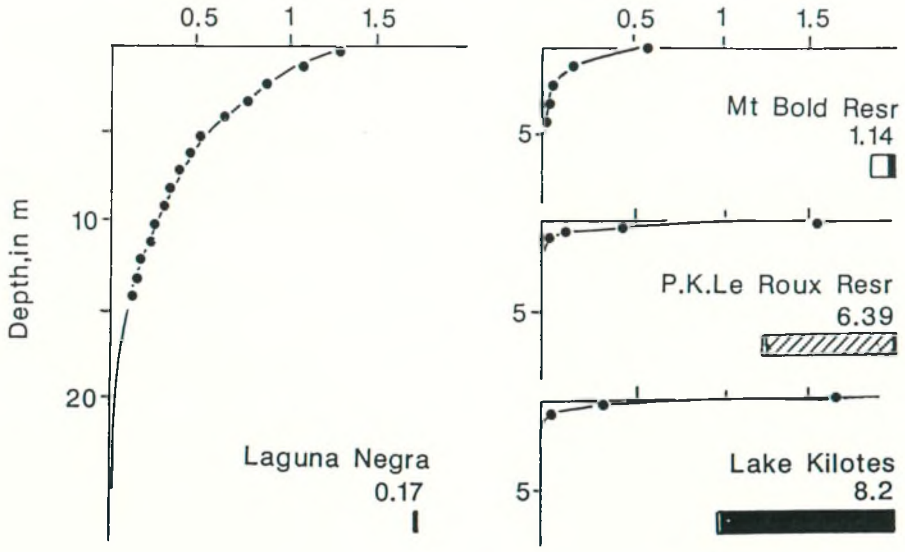

Fig. 9. Light penetration in some natural lakes and reservoirs, with the attenuation coefficient and its partitioning between water colour (unshaded), tripton turbidity (hatched) and phytoplankton algae inset.

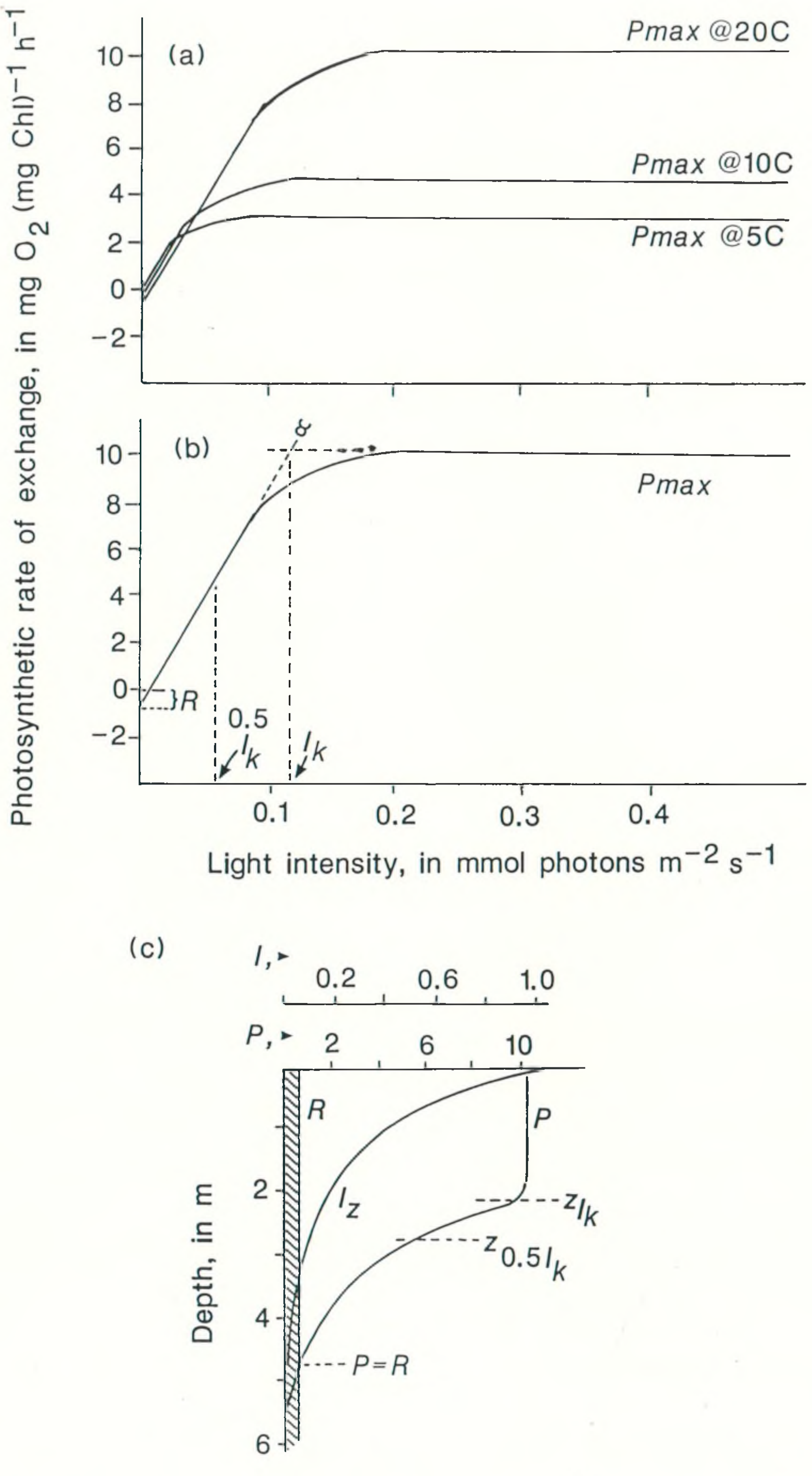

Fig. 10. Photosynthetic oxygen generation: (a) Dependence of chlorophyll-specific photosynthetic rate on light and temperature; (b) the 20C curve replotted to show important quantities, I_k, $0.5I_k$, the slope, α, and the dark respiration rate, R; (c) the 20C P curve (in mg O_2 (mg chl)$^{-1}$ h^{-1}) replotted against underwater light gradient (I, in m mol photon m^{-2} s^{-1}) to show the depths of I_k and $0.5I_k$ and where $P = R$.

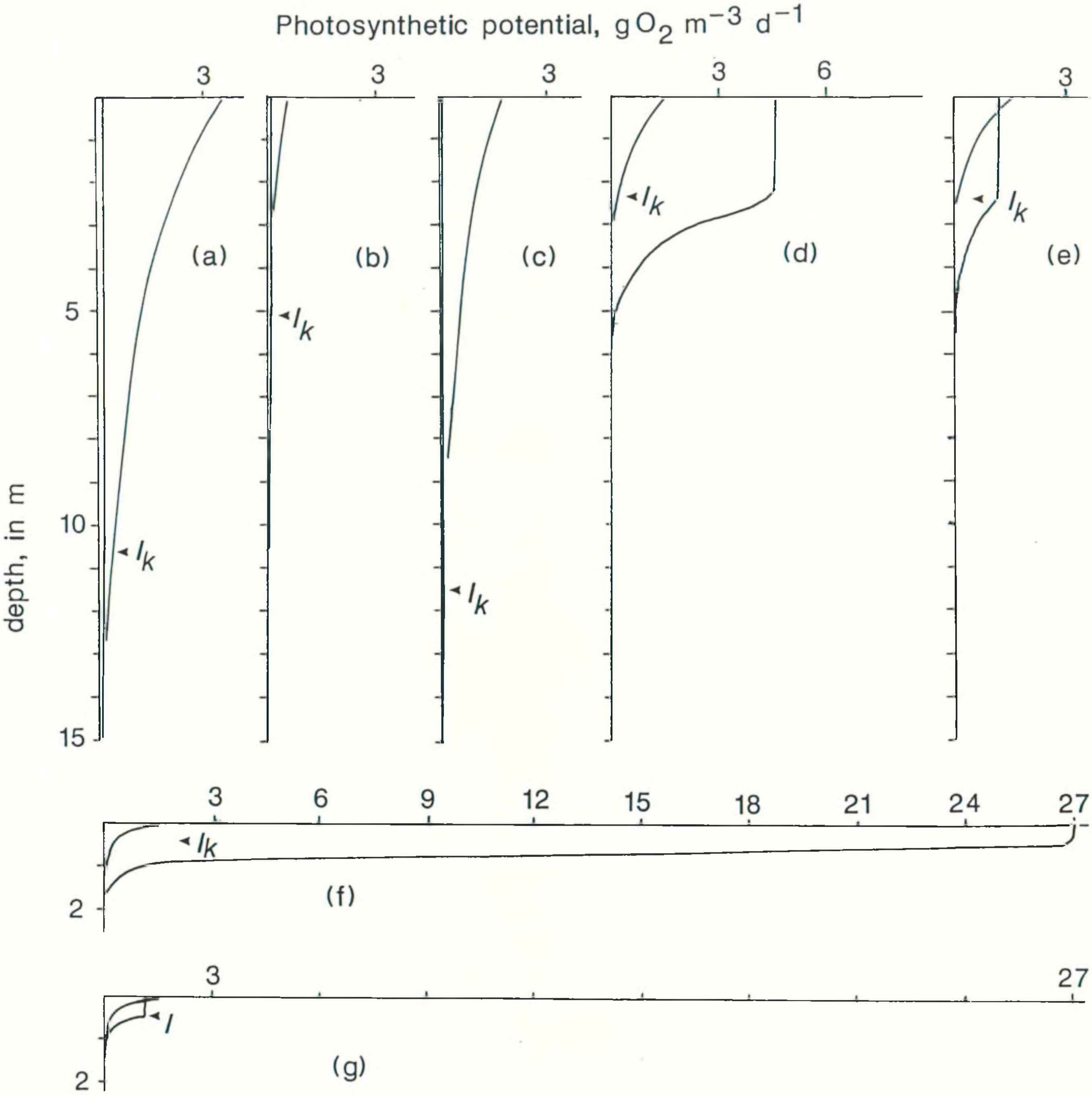

Fig. 11. Daily integral curves of photosynthesis given selected environmental conditions: (a) temperature 20C; daylength: 16h; cloud: 0; total light 58 mol m^{-2} d^{-1}; chlorophyll: 1 mg m^{-3}; $\varepsilon = 0.2\ m^{-1}$; (b) temperature 5°; daylight 8h; cloud: 100%; total light 3 mol m^{-2} d^{-1}; chlorophyll, ε unchanged; (c) temperature 10°; daylength 12h; cloud: 50%; total light 24 mol m^{-2} d^{-1}; chlorophyll, ε unchanged; (d) temperature 10°, daylength 12h; cloud: 50%; total light 24 mol m^{-2} d^{-1}; chlorophyll is 80 mg m^{-3}; $\varepsilon = 1.0\ m^{-1}$; (e) As 11(d) but $\varepsilon = 1.0\ m^{-1}$ while chlorophyll is only 20 mg m^{-3}; (f) As 11(d) but chlorophyll is 450 mg m^{-3} so $\varepsilon = 5.0\ m^{-1}$; (g) As 11(d) but $\varepsilon = 5.0\ m^{-1}$ while chlorophyll is only 20 mg m^{-3}.

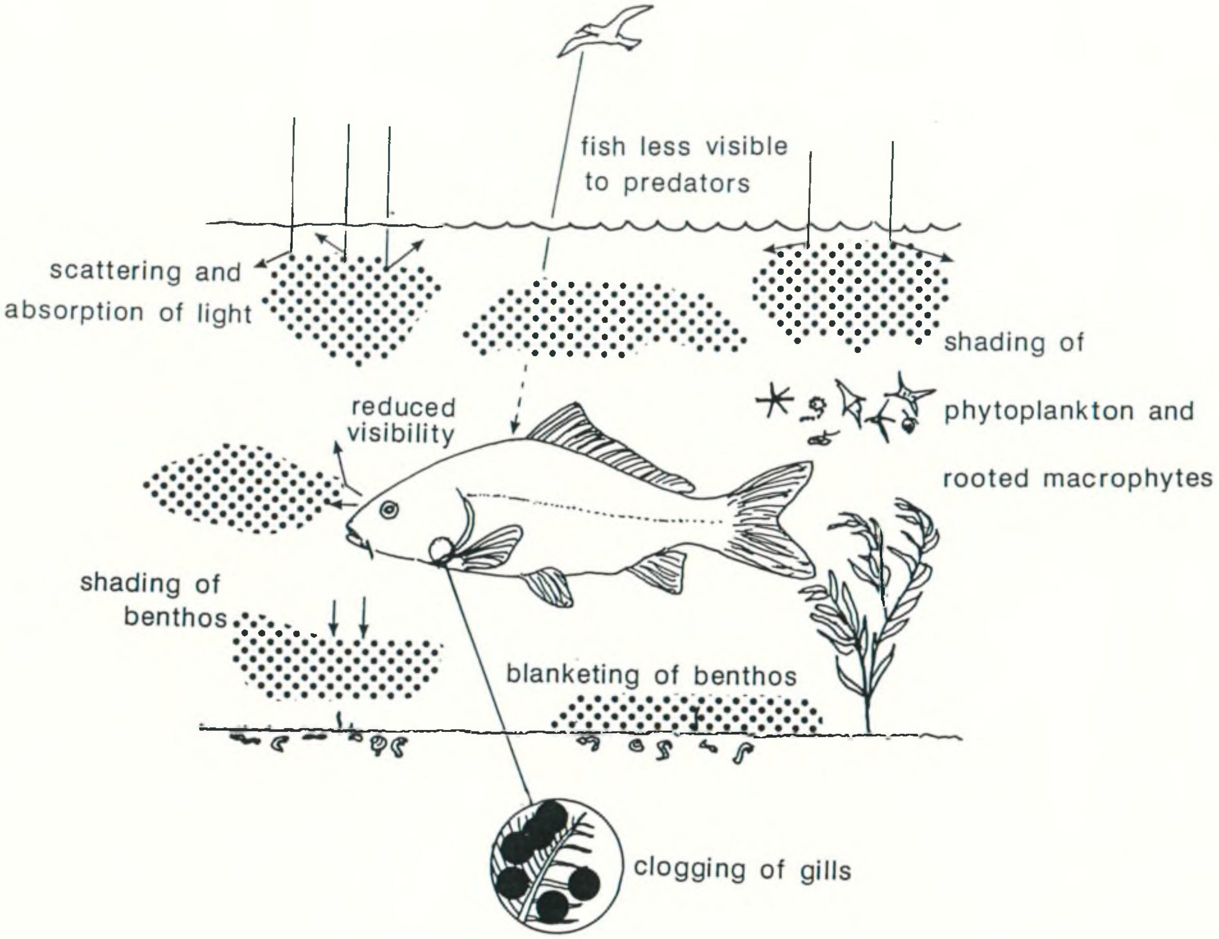

Fig. 12. Principal effects of turbidity on fish: apart from direct effects of gill clogging and reduced visibility of food, heavy turbidity reduces growth of macrophytes (source of shelter, food and breeding), phytoplankton (primary food source for invertebrates) and may limit the availability of benthic foods. Turbidity does protect fish from predators.