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The effects of hydraulic projects and their management on water quality

R. GRAS, J. P. ALBIGNAT & Ph. GOSSE
Electricité de France, Direction des Etudes et Recherches, Départment Environnement Aquatique et Atmosphérique, F-78400 Chatou, France

ABSTRACT Various types of hydraulic project are reviewed in order to examine the extent to which altering flow characteristics or other associated quantitative factors can effect water quality and more generally aquatic life. Particular attention is paid to the canalization of streams or rivers and to the construction of dams for navigation or electricity generation; a section covers reservoirs and pump storage stations and discusses their impact in the light of their characteristics and management. Some information is also given regarding estuarine or maritime projects, such as tidal power plants. The main water quality parameters are considered with special attention to thermal behaviour. Physico-chemical parameters are considered as well as those concerning aquatic flora and fauna (plankton and fish resources). Specific examples are examined for most of these types of project.

Effets des aménagements hydrauliques et de leur gestion sur la qualité de l'eau

RESUME Il est passé en revue l'ensemble des aménagements hydrauliques pour examiner comment les modifications des caractéristiques des écoulements ou des facteurs quantitatifs qu'ils entraînent peuvent influer sur la qualité de l'eau ou la vie aquatique d'une manière plus générale. Sur les cours d'eau, l'accent est porté sur les questions de canalisation, de construction de barrage pour la navigation ou la production d'électricité; un chapitre est consacré aux retenues et aux stations de pompage en mettant en évidence l'importance des conséquences sur la qualité de l'eau en tenant compte des caractéristiques de ces ouvrages mais aussi de leur mode de gestion. Quelques éléments sont enfin donnés concernant les travaux en estuaires ou en mer, en particulier les aménagements marémoteurs. Tous les paramètres de qualité d'eau sont considérés, mais une attention particulière est accordée aux régimes thermiques; des éléments sont donnés sur la physico-chimie, la faune et la flore aquatique: plancton et ressource piscicole. Pour la plupart de ces aménagements, des cas concrets sont examinés.

INTRODUCTION

It should be noted that hydrological studies used to focus on quantitative resources, and this emphasis may reflect the fact that questions relating to water quality were not always felt as acutely in the past as today by reason of the growing pollution of surface waters in recent years. Alternatively, this focus may have arisen because the consequences of developments in water resources management for water quality are not always immediately perceptible. For many water uses, such as electricity generation, irrigation or navigation, the quantitative aspects of water resources alone are of interest. For other uses, the qualitative aspect has to be examined in parallel with the quantitative aspect. This is true of the production of drinking water and the role of streams in the disposal of pollution. Some uses are linked to the water quality itself, for example in the case of tourism and leisure activities such as fishing, sailing and swimming.

The quality of water must meet certain criteria associated with the use in question. The criteria required are often conflicting for different uses, such as fishing and swimming, or even regarding the same use. For instance, in the case of fishing, water quality should allow a suitable fish production, both in terms of biomass and structure of the fish population, and the ecosystem therefore must be in good equilibrium. Cold streams are generally preferred by fishermen since this environment favours the presence of salmon type fish, but in contrast biomass production is low under such conditions. Other criteria must be taken into account for leisure activities. For instance, swimming requires a good bacteriological level and high water temperature, whereas an abundant plankton life, which is often linked with a high fish productivity, gives a colour and turbidity which swimmers find unpleasant. Furthermore, depending on the environment, high temperatures can favour the growth of harmful algal species, such as blue algae, which imparts a taste to drinking water or produces microcystis, toxic for swimmers.

The construction of a facility to change river flow alters water quality locally and, in general, throughout the zone in which hydraulic characteristics are modified. Considering biological aspects in addition to physico-chemical parameters, it is clear that apparently harmless developments can alter the ecosystem drastically. The present paper reviews the effects that various types of projects may have on water quality and aquatic life. Particular attention will be paid to activities which modify streams including canalization, construction of dams for navigation, electricity generation and regulation of rates of flow. Estuary or marine developments will be studied to supplement the discussion.

SUMMARY OF INTERACTIONS IN AN ECOSYSTEM

The association of living organisms, or biocenosis, with a specific physico-chemical environment, or biotope, forms an ecosystem (Fig.1). Three broad groups of living species can be distinguished in an ecosystem: autotrophic plants or the producers of the ecosystem, heterotrophic consumers, and decomposing organisms. The first group

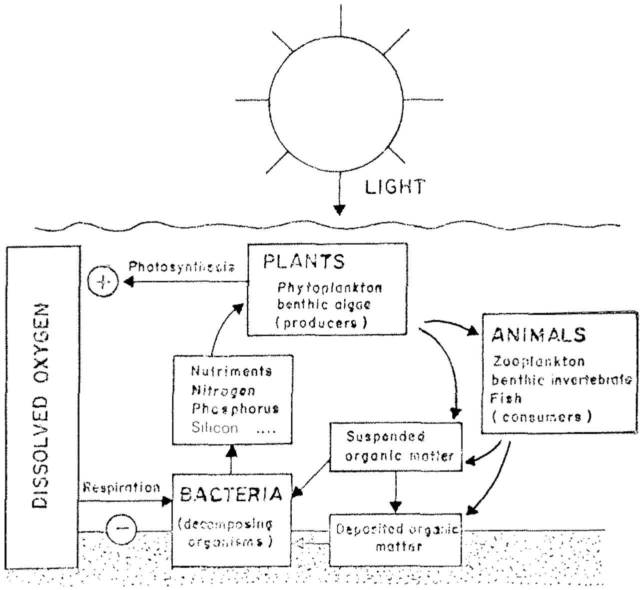

FIG.1 Functional diagram of an aquatic ecosystem.

comprises chlorophyll plants (phytoplankton or fixed plants) drawing on the energy generated by the sun and nutrients in the water for their growth and reproduction. Heterotrophic consumers are either grazing animals (assimilation of plants) or carnivorous animals (assimilation of plants-eaters or carnivores of a lower trophic level). The decomposing organisms are bacteria which mineralize organic detritus. Consequently, there are constant interactions between biocenosis and water quality. Phytoplanctonic growth, for example, will depend upon water turbidity or the quantity of phosphorus or nitrogenous nutrients, but a high phytoplanctonic concentration will lead to a high water turbidity, a decrease in dissolved mineral elements and an alteration to the diurnal cycle of dissolved oxygen or pH. Furthermore, the bacterial decomposing cycle (e.g. nitrification) not only depends on dissolved oxygen level but also influences it.

THE EXTENT TO WHICH PHYSICAL PARAMETERS ALTER WATER QUALITY AND THE ECOSYSTEM

Hydraulic projects alter certain physical parameters which have a substantial influence on water quality, and therefore, on the ecosystem. Despite the diversity of these projects, quite general laws can be established by studying the physical parameters changed and the consequences of this change for water quality. The discussion below is limited to the study of a few general parameters providing the best picture of water quality or aquatic life. Among these parameters, temperature and dissolved oxygen content are of predominant importance.

Changes in the rate of flow

A change in the rate of flow alters other parameters relating to flow or geomorphology, which are analysed separately. The rate of flow acts locally through the ability of the stream to dilute effluents, an increase in the rate of course reducing concentration by dilution. This is also true of the oxygen flux exchanged at the surface with the atmosphere or on the bed through the oxygen absorbed by sediments, i.e. sediment oxygen demand. In general, a change in the rate of flow changes water quality. In particular, an increase in the rate of flow in a more-or-less natural drainage basin increases the transport of suspended or dissolved substances. However, if the rate of flow is increased artificially by regulating reservoirs, the transport of substances may not be increased, either because sedimentation occurs in the reservoirs or because the water stored originally is less highly charged. However, fluctuation in the rate of flow can reintroduce suspension of mineral or organic sediments.

Modification of water velocities

From a physico-chemical viewpoint, velocity plays a major role in sedimentation mechanisms or the reverse mechanism of resuspension of deposits. In general, a decline in velocity favours sedimentation of suspended mineral and organic substances including plankton, and should therefore reduce turbidity. It should be noted that gaseous exchanges at the surface are directly linked to the relative velocity between air and water. A velocity decrease can reduce exchanges, in particular for oxygen. In practice, in lakes, reservoirs and slow streams, exchanges are mainly governed by wind speed, and an alteration in water velocity has a negligible effect.

The slowing down of streams can favour the formation of stratification in reaches which are deep enough, and the internal exchanges within the water body are reduced. This can promote the local growth of phytoplankton and can also induce anaerobic conditions in the vicinity of the bed. Fish populations are influenced by flow conditions, as high current speeds are beneficial to some species such as trout, etc., while other species (carp) prefer somewhat stagnant waters. The change in sedimentation acts on the benthic population and on the potential of certain zones as spawning grounds (Lim & Labat, 1982).

Change in depth

The depth of a stream conditions the thermal inertia of a water body. Assuming that the turbulence generated by the flow is sufficient to make the stream vertically homogeneous, increased depth reduces the daily temperature fluctuations caused by solar radiation or more generally by weather changes. At a seasonal level, the thermal behaviour is practically independent of average depth. Average depth can alter the oxygen balance of a stream since the oxygen flow exchanged at the surface is distributed over a different depth, and the same is true of oxygen losses from sediment oxygen demand and plant respiration. An increased depth will favour plankton growth to the detriment of benthic flora since less solar radation reaches the bottom. Another aspect to be borne in mind relates to fluctuations in level which are in general harmful for certain species of benthic invertebrates and can adversely affect spawning.

Changes in residence time

In practice, changes in residence time are a consequence of changes in the parameters discussed above. This physical parameter probably has the greatest influence on water quality, because time has a fundamental role in the kinetics of a suite of chemical and biological processes. Usually hydraulic projects increase the transit time of water in the zones concerned, except for example when low flows are increased. Depending on the initial state of the stream (which may be cold, warm or practically at natural local temperature, Gras *et al*, 1983) an increase in residence time changes thermal behaviour. The temperature moves closer to the natural local temperature, i.e. to the temperature of a stagnant water body of the same depth and subject to local meteorological conditions.

The dissolved oxygen balance can be substantially modified by residence time, especially in a relatively polluted environment. This balance results from a set of chemical and biological processes, including biological degradation of organic substances, benthic oxygen demand, gaseous exchanges at the surface, photosynthetic production of oxygen, the nitrogen cycle, etc., whose kinetics are influenced to a varying extent by time. In practice, it is impossible to generalize whether the increase in residence time produces a decrease or an increase in oxygen content. Increases in some zones and decreases in others may occur for the same stream. The increase in residence time can favour plankton growth. In extreme conditions, plant growth in primary production can change over from a system in which plants are attached to the bottom and banks, to a purely planktonic system.

Change in other geomorphological parameters

In practice, only the parameters listed above can change thermal behaviour. A change in other geomorphological parameters may affect the biology of the system and indirectly its physico-chemistry. An alteration of the nature of river banks and bottoms induces a major change in benthic flora and fauna, which are the initial links of the trophic chain and can consequently have an effect on the ecosystem as a whole. The modification of banks also plays a major role in fish reproduction. The construction of hydraulic projects in a stream often separates it into rather distinct reaches. The construction of successive obstacles limits or prevents the passage of migrating species. In the long run, this also causes more-or-less marked degeneration for essentially non-migratory species (SRAEL-QE, 1982).

ANALYSIS OF THE IMPACT OF HYDRAULIC PROJECTS ON WATER QUALITY AND AQUATIC LIFE

The indications given above will be useful for the analysis of the impact of some typical hydraulic projects. For some facilities, such as reservoirs, the analysis covers the way in which the operating mode can affect the quality of the reservoir water and the downstream section of the stream.

River facilities

Canalization of a stream The objective of canalization may be to maintain navigability. Canalization generally involves modifying banks, deepening certain zones and, often, creating reaches. It is thus to be expected that this type of development will have a relatively substantial impact (Chalon *et al.*, 1978). It is nevertheless necessary to indicate that the effect on thermal behaviour will often remain limited to a reduction in the amplitude of diurnal cycles and short term fluctuations (Fig.2), especially for lowland rivers which are already in equilibrium with local meteorological conditions. Since the rate of flow is not changed, the physico-chemical parameters will essentially be indirectly influenced by the action of the change in velocity and depth, for instance on

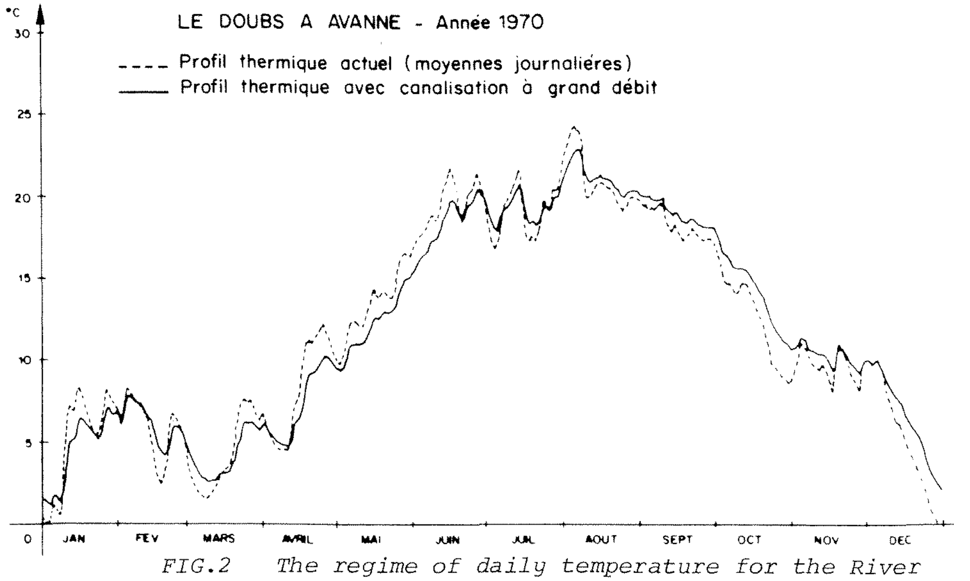

FIG.2 The regime of daily temperature for the River Doubs before and after canalization based on the results of a simulation model.

sedimentation and planktonic growth. In general, such a project promotes a changeover from a benthic to a phytoplanctonic system. Fish resources will certainly be highly modified, but with greater impact on the structure of population than on biomass production.

Weirs The construction of a weir involves the development along the valley of a generally shallow impoundment. No persistent stratification phenomena can be observed in such an impoundment, since the turbulences induced by wind and friction on the bottom mix the water sufficiently. Stratification can sometimes be observed for short periods at times of low wind and highly sunny spells during the low flow period. Weirs again lead to the modification of most parameters, including the rate of flow which sometimes changes during the day. This causes fluctuations of level in the impoundment and downstream which in turn may affect the life of benthic organisms. As in the case of canalization, there will not be much effect on temperature and physico-chemical characteristics. However, this type of project tends to favour planktonic to the detriment of benthic life, and it also induces major changes in fish population, due especially to the change in the sediment facies and to the barrier represented by the dam.

The management of a dam can greatly modify some quality parameters, especially dissolved oxygen. As mentioned earlier, the creation of a reservoir can limit gaseous exchanges of the water-air interface. However, when the water is released at the dam, reaeration can occur in the fall when the water is sub-saturated upstream from the dam. The reverse can also occur in exceptional periods when the water is over-saturated, for example by the occurrence of high production by photosynthesis on a fine summer day. In a highly polluted river, fish are more commonly observed downstream from the weir, partially because of a higher dissolved oxygen content. With certain facilities, the water can either be released at surface level or withdrawn from near the bottom. In the latter case, the benefit of reaeration by the fall is lost. The installation of turbines in a weir built for navigation can have negative effects on the oxygen balance of the stream, especially in an already highly polluted one (Fig.3).

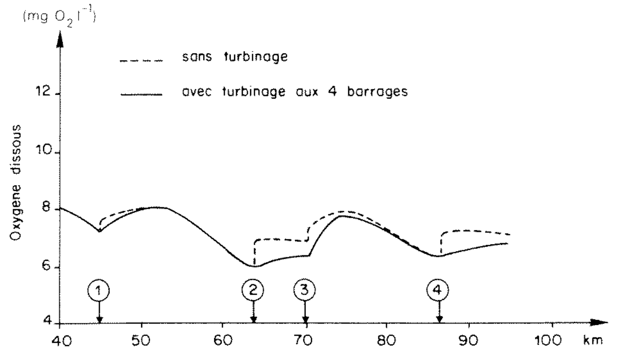

FIG.3 Longitudinal profile of the dissolved oxygen concentrations of the River Moselle before and after the installation of turbine equipment in the weirs based on the results of a simulation model.

By-pass reach When building hydraulic facilities, it is often necessary to by-pass certain sections of a stream. It is usual to maintain a low rate of flow, called the reserved flow, in such sections. This rate is generally set fairly arbitrarily so as to maintain a certain level of aquatic life. All the parameters analysed earlier are greatly modified and relatively thorough changes

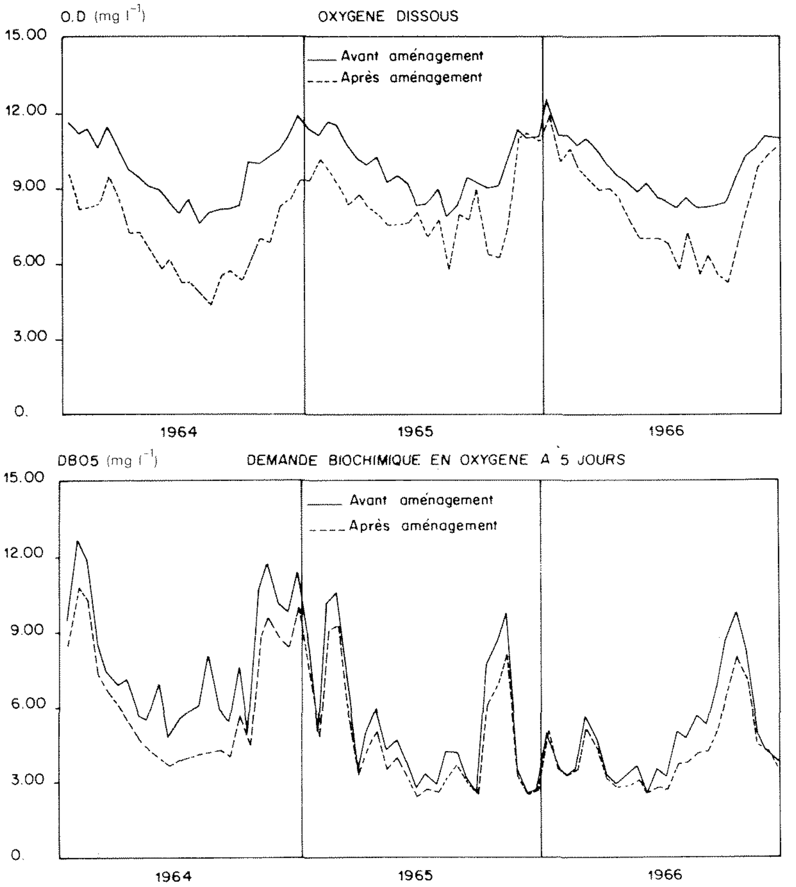

FIG.4 The regime of dissolved oxygen concentrations and of biochemical oxygen demand in the River Rhone before and after the creation of a by-pass reach based on a simulation model with a rate of flow of 10 $m^3 s^{-1}$ *and an initial organic matter load of 2000* $g\ s^{-1}$.

may thus be expected in water quality and aquatic life. It should nevertheless be underlined that the reduction in the rate of flow is local and has repercussions on the ability to dilute effluents released in the by-passed section (Fig.4). Therefore, the direct effects of the decrease in the rate of flow on the physico-chemical characteristics occur only in cases of discharges into the by-pass section. However, the physico-chemical quality of water may also be altered by the upstream development. Thermal behaviour can be variably modified according to the value adopted for the reserved flow. The depth and residence time of water have a major influence on temperature behaviour. Long residence times are associated with low depths, and the two parameters have a cumulative effect. The example in Fig.5 shows how the choice of the reserved flow can affect a parameter associated with thermal behaviour (the average temperature of the warmest 30 consecutive days) which plays a determining role in the structure of fish populations. Beyond a certain value, the

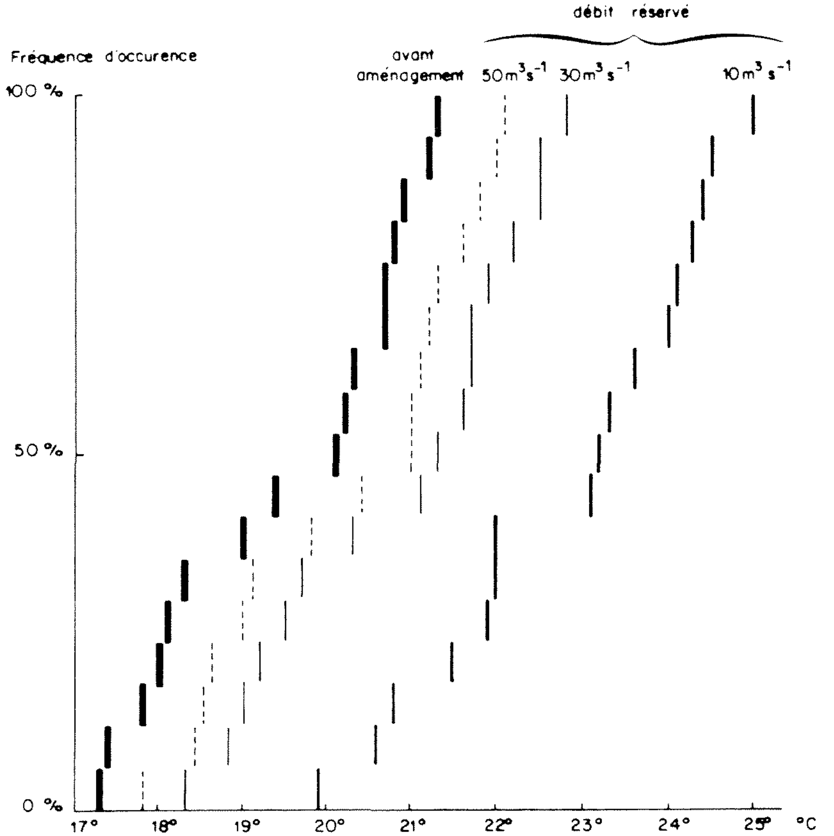

FIG.5 Frequency of occurrence of the average temperature of the warmest 30 consecutive days in the River Rhone (same reach as Fig.4) before the creation of the by-pass reach and for three values of the reserved flow (10, 30 and 50 m^3s^{-1}) based on the results of a simulation model.

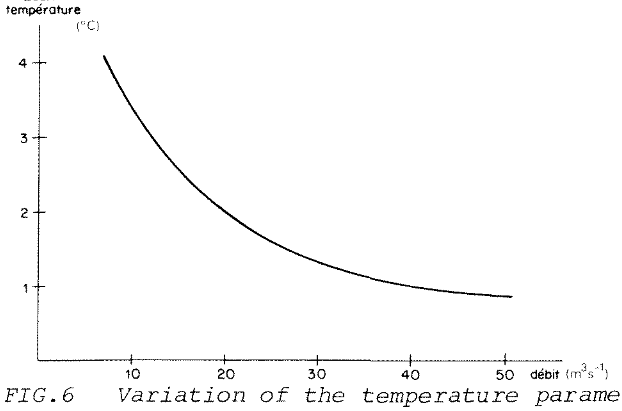

FIG.6 Variation of the temperature parameter shown in Fig.5 as a function of the rate of the reserved flow in a by-pass reach of the River Rhone based on the results of a simulation model.

increase in the reserved flow no longer has much influence on this parameter (Fig.6).

In contrast with the projects mentioned earlier, the conditions are not necessarily present here for a switchover from benthic to planktonic flora. The substantial decrease in rate of flow induces low depths for most of the time which allows the penetration of light to the bottom. Turbidity, of course, has an influence on the latter phenomenon, but the decrease in velocity should reduce it by increasing the sedimentation of suspended matter. However, where there is deposited material, there is also the possibility of resuspension during flood periods. The ecosystem is generally greatly modified by the construction of by-pass reaches. In order to safeguard certain fish species, special care must be taken, i.e. through choice of the reserved flow, by limiting fluctuations in the rate of flow, or by attempting to preserve an acceptable water quality through the management of upstream development and by creating passageways and fish ladders. Despite what has just been said, a by-pass reach is often the best safeguarded part of a developed section since the riverbed preserves its natural characteristics.

Development of banks by dikes It is sometimes necessary to develop banks, for example, to prevent high rates of erosion, to facilitate the flow in the flood period, or to improve the aesthetics of banks. In general, this has virtually no effect on the main physical flow parameters. The average flow velocity may sometimes be slightly increased, but this type of development also eliminates zones of low speed. This causes a reduction of deposition and more generally changes the banks facies. The effect on water quality remains very limited, except that suspended matter may be affected due to the slight change in water velocity. In practice, the impact consists of an alteration of the riverside benthic fauna and flora which perhaps causes a change in the trophic chain. Fish stocks could be affected by the elimination of spawning grounds and refuge zones, reed patches, etc.

Flow control Flow control consists of increasing low flow rates and limiting floods. The impact on water quality can be detected directly or may originate from the cumulation of the effects of several factors. An increase of the low flow would *a priori* appear to be favourable for a stream which receives many urban and industrial effluents, since concentrations are reduced at the points of injection. However, in practice, increasing the rate of flow reduces residence time between two points of injection, and the residual load in the downstream section, resulting from the kinetics of various processes (biodegradation, phytoplanktonic growth, etc.) may be higher (Fig.7). Therefore, an increase in the flow rate does not always improve the water quality of a polluted stream. For instance, Nihoul (1982) shows that the worst case of pollution downstream from a thermal discharge does not correspond to the lowest rate of flow. This also applies to the self-purification capacity of the stream. The effect of reducing high rates of flow will mainly concern sedimentation processes with resuspension of deposits.

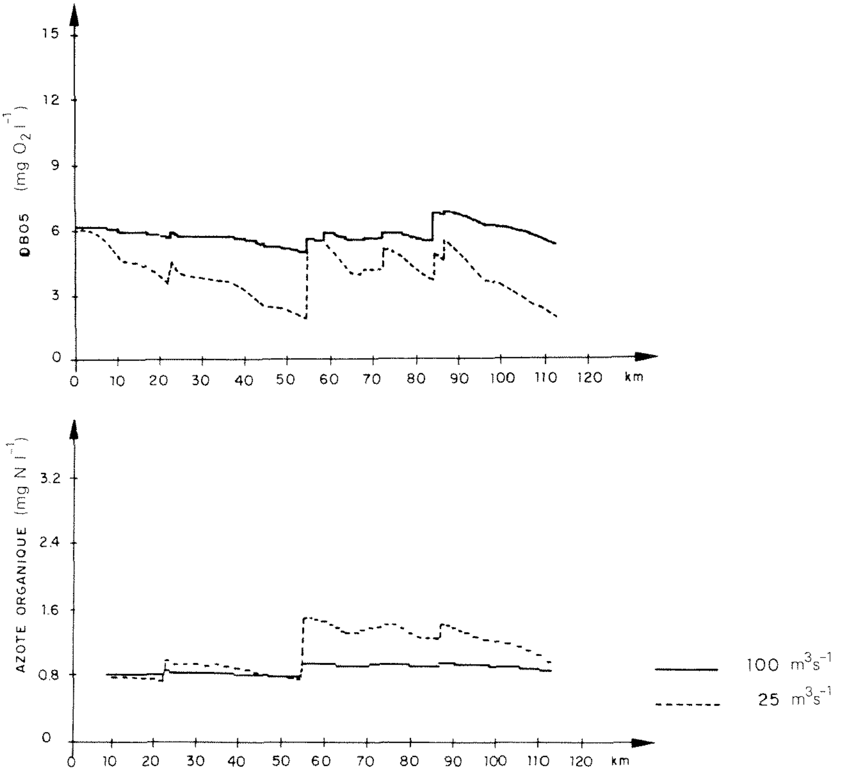

FIG.7 Longitudinal profiles of the biochemical oxygen demand and of organic nitrogen concentrations in the River Moselle for two values of the rate of flow (25 and 100 m^3s^{-1}) based on the results of a simulation model with the hypothesis that polluted discharges are not dependent on the rate of flow.

Creation of reservoirs

The creation of a reservoir in a drainage basin has a direct effect on the submerged part and an indirect effect downstream from the dam, involving modification of the rate of flow and the water quality. It is of interest to consider in broad terms the change induced by water impoundment. This change will be of most importance when the characteristics of the reservoir approach those of a lake, i.e. when water residence time is long. The strongest differences between a lake and a river are the river's capacity to renew water and the possibility of stratification in a lake. In this regard, a reservoir is an intermediate environment between a lake and a river. Depending on depth and residence time the reservoir will become more similar to one or the other of these two environments. The influence which the creation of a reservoir has on the water quality and aquatic life of a river will now be discussed.

Reservoirs with a short residence time When residence time in the reservoir is short (a few days), there is almost no stratification, except in special cases such as a deep reservoir with a cold inflow and with water withdrawal from near the bottom. The influence of reservoirs with short residence time on temperature consists of a reduction in short-term fluctuations (diurnal cycles, changes in meteorological conditions), but the alteration of water quality will mainly concern the sedimentation of suspended matter. A changeover from benthic primary growth to planktonic production may be observed and components of the oxygen balance can be slightly modified. Surface aeration will be reduced and benthic oxygen demand will depend on the nature of sediment deposits (in general, an increase in the value of this term can be expected). A rise in residence time, even for a few days, may have a marked effect on the biodegradation processes which involves an increase in the oxidation of organic matter including detritic plankton, although the latter will increase the quantity of organic matter to be degraded downstream.

Reservoirs with a long residence time When residence time increases, summer stratification is more easily developed. The water quality and the characteristics of the ecosystem as a whole move towards those typical of a lake. The surface layers become progressively isolated from the remainder of the water body as stratification is developed. Planktonic life takes over from benthic primary production. The sedimentation terms increase and the reservoir traps mineral and organic matter. Exchanges at the bottom take on greater importance and increased oxygen demand and possibly release of nutrients or heavy metals occurs when physico-chemical conditions become anaerobic. There is thus a thorough change in the water quality as well as in aquatic life as a whole, ranging from the initial links of the trophic chain to fish. Population structure will differ markedly from those of a stream, although this does not necessarily imply a reduction of biomass, in fact the reverse may occur (Brossard & Gallene, 1982).

Downstream as well, a marked effect on the water quality and aquatic life, at least in the vicinity of the dam, may be expected. In practice, the water quality in the reservoir like that of the water withdrawn, which consequently feeds the downstream section of the stream, depends on the management of the system:

(a) either through the design of the facility itself, including the level at which water is withdrawn and shape of the intake, which have an effect on the layers of water withdrawn, or,

(b) the quantitative management of water, including the period during which the reservoir is filled and the downstream rate of flow and fluctuation.

The role of the level of withdrawal has been studied for a 50-m-deep reservoir in which residence time is approximately four months. The effect on the distribution of dissolved oxygen content is given in Fig.8 for withdrawal levels near the bottom and 30 m above it. Similarly, Fig.9 shows the temperature, dissolved oxygen and phytoplankton contents of the water withdrawn from the dam at these two levels.

Pump storage stations In order to obtain the best use of a system consisting of thermal and hydroelectric power stations, it can be advantageous to store electricity in the form of potential energy by pumping water from a lower to an upper reservoir. At times of peak demand, the reservoir water is used to drive a turbine and returns to the lower reservoir. Various cases can arise, depending on whether the lower or upper reservoir already exists, and whether one or the other is an artificial basin, etc. The special feature of these developments is the regular exchange of water between the two reservoirs. This necessarily induces a marked reduction of stratification due to internal currents, especially in the zones near the water intake and discharge structures. In addition to this destratification, the sedimentation, phytoplanktonic

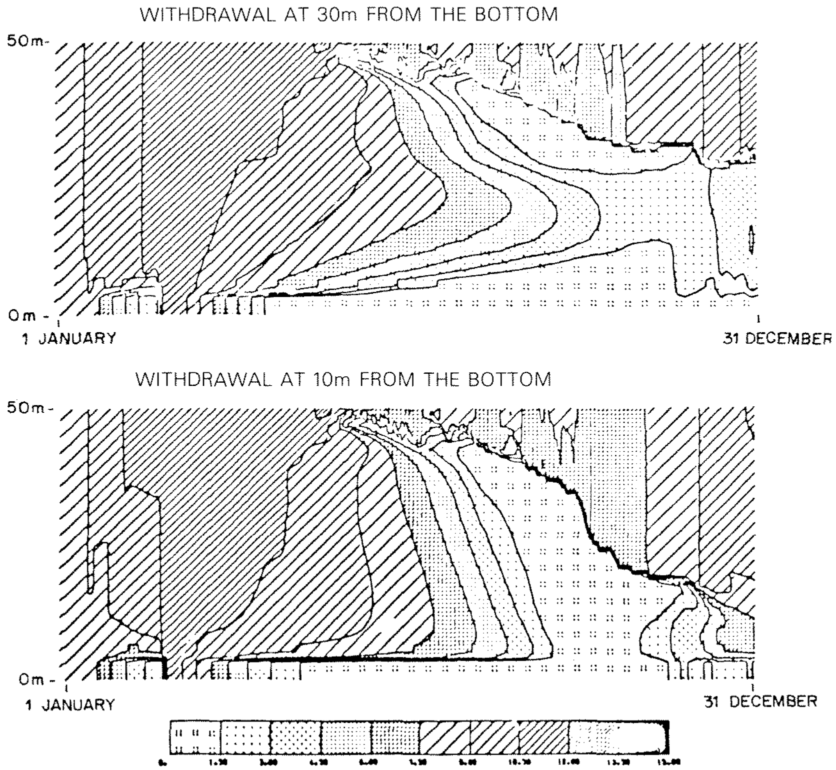

FIG.8 Isoconcentrations of dissolved oxygen (in a depth-time coordinate system) in a 50-m-deep reservoir for two levels of water withdrawal (10 and 30 m above the bottom) based on the results of a simulation model.

growth, and dissolved oxygen distributions will also be modified. Figure 10 shows the trend of stratification in the reservoir before and after entry into service in the pumped storage scheme of Redenat-Chastang (Enderle, 1982).

It is difficult to define the direction the changes will take in these circumstances, since they are highly dependent on local conditions, the shape of reservoirs, the quantity of flows transmitted, the level of the water intake structures, the speed of injection, etc. In the case of the Redenat-Chastang project, the entry into

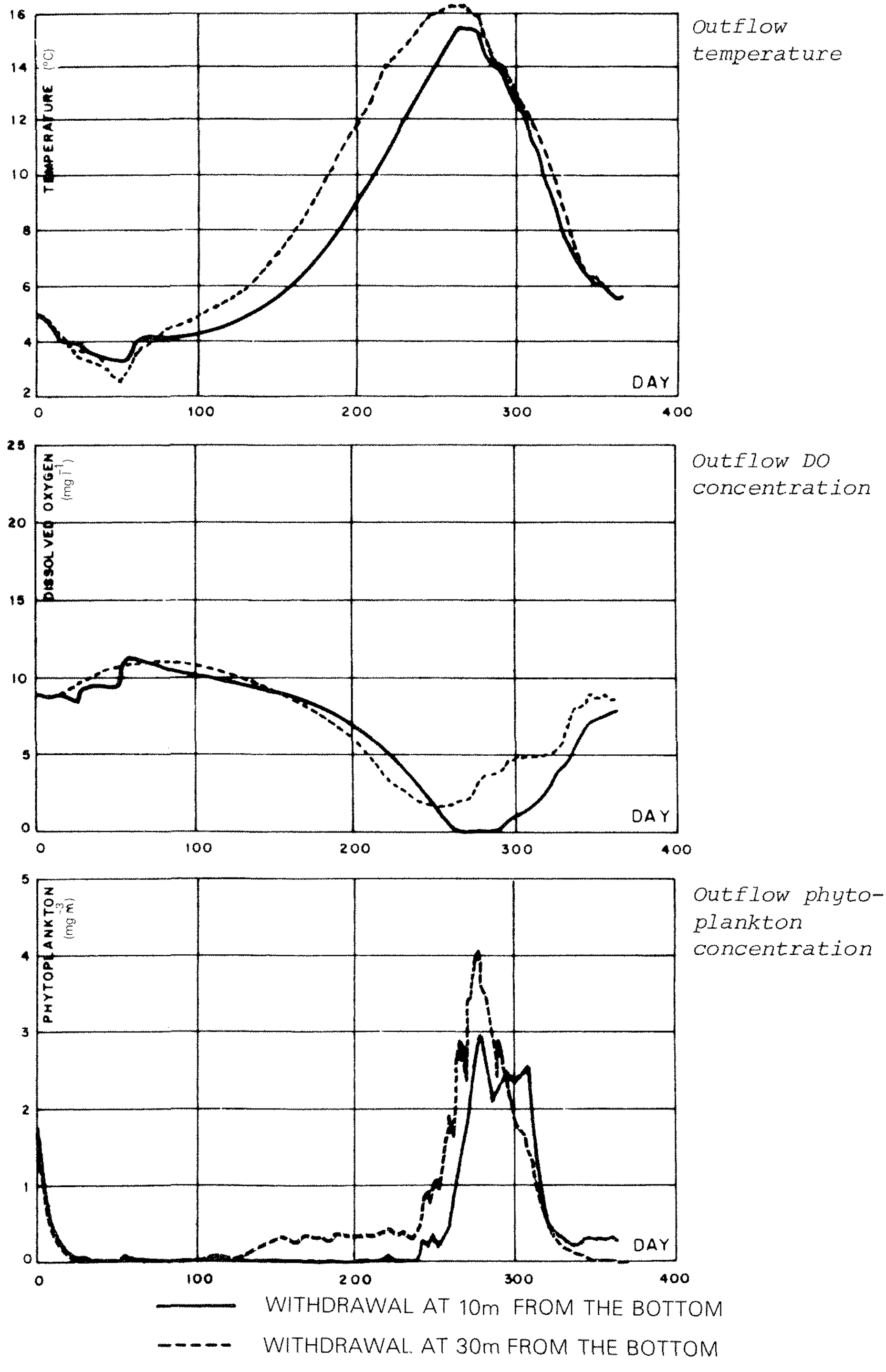

FIG.9 Regimes of temperature, dissolved oxygen concentration and phytoplankton concentration downstream of a dam for two levels of withdrawal (10 and 30 m above the bottom) based on the results of a simulation model.

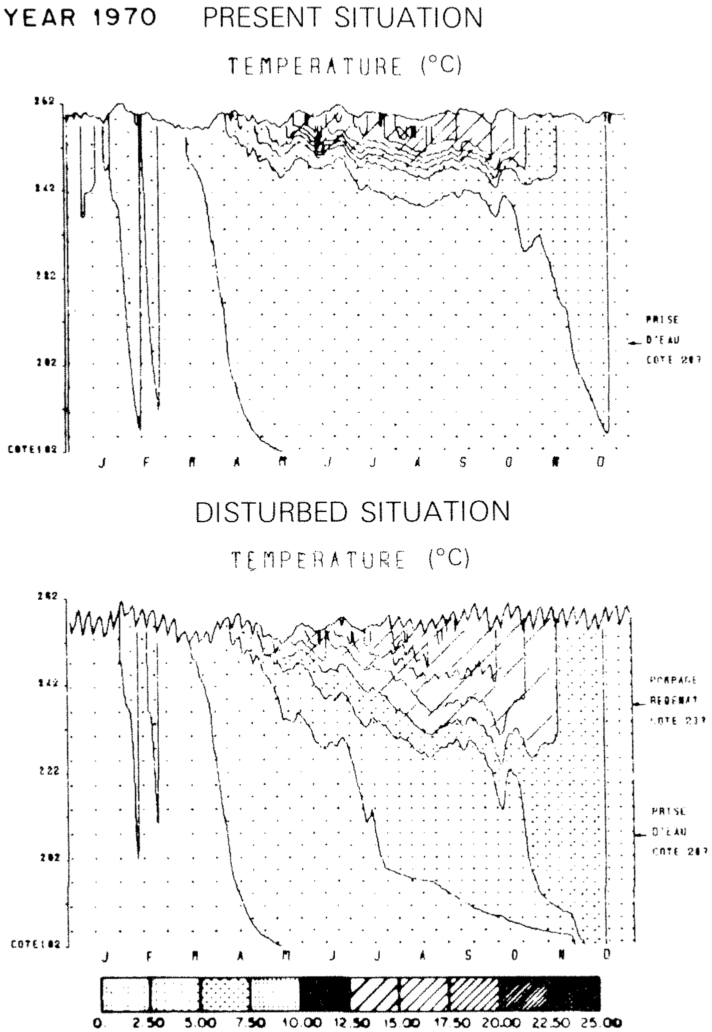

FIG.10 Regime of temperature in the Chastang Reservoir (depth-time coordinate system) before and after entry into service of the pumped storage station of Redenat-Chastang based on the results of a simulation model.

service of the pumped storage system is likely to increase phytoplanktonic growth. The circulation of water between the two reservoirs produces fluctuations in levels, which are sometimes high and have various consequences. These fluctuations can greatly increase turbidity by the regular erosion of the banks, although the action of the wind in causing surface agitation often plays at least as great a role in returning sediment to a suspended state. The regular effects of the fluctuations in water level on the fish population are considered to be potentially detrimental.

Small bodies of water in a drainage basin The development of numerous small bodies of water for tourism, fishing, navigation and swimming can greatly modify the water quality of a hydrographic system, or affect aquatic life. *A priori*, the effect of one small artificial lake may appear as negligible. However, in practice it affects sedimentation since the reservoir traps sediments which fix pollutants such as heavy metals and toxic substances. These can accumulate and may be released in bulk during flood conditions. These water bodies increase residence time in the drainage basin so, as seen earlier, the temperature changes, mainly increasing during the summer. The primary planktonic production increases and the water body may become a source seeding the downstream section of the stream. It should also be noted that these bodies are a barrier for migratory species which no longer have access to their spawning grounds. The reach effect tends to isolate fish stocks with damaging effects which possibly induce degeneration (SRAEL-QE, 1982).

Hydraulic projects in estuaries and in the marine environment

Hydraulic projects built in these environments are generally quite small in relation to the size of the water bodies in question. The fact nevertheless remains that these projects modify a certain number of parameters relating to the water quality locally and sometimes produce effects which are disproportionate to their size.

Construction of ports The construction of a port obviously changes the nature of the bottom and the currents. This generally affects benthic life, but has little effect on the water quality. The poor quality of water in a port is due to effluents and not to the presence of the port itself although its existence limits the dilution of effluents. The modification of currents sometimes induces deposition of fine sediment with associated pollutants.

Dredging waterways It can be observed that local turbidity increases after dredging. Dredging a waterway of course destroys local benthic life. In an estuary, the changing of depth can markedly alter the circulation of water and, for example, promote the penetration of salt water.

Tidal power plants The construction of a tidal power plant in an estuary alters water circulation markedly. The quality of water can be substantially modified, with changes in salinity and a reduction of turbidity (e.g. River Severn; Swan, 1980). The dissolved oxygen balance can possibly be altered by the change in the conditions for aeration at the surface, and also by the kinetics of degradation of telluric organic matter, especially fresh water phytoplankton entering the estuary. In contrast with the previous case, the entry of sea water into the estuary is slowed. Thermal behaviour is slightly altered, tending towards warming in the summer and cooling in winter. Aquatic life is undoubtedly modified, but the estuary remains a very productive zone.

Effect of upstream developments Construction of hydraulic projects on streams can have consequences as far as the estuary and even in the sea. In particular, flow control produces different sedimentary dynamics in estuaries. These problems are very complex and it is difficult to draw general conclusions (Brossard & Gallenne, 1982). In some estuaries receiving water carrying organic substances, for example the Escaut, Loire and Gironde estuaries, major reductions can be observed in the dissolved oxygen content during the summer. This drop in oxygen levels favours the release of different chemical components from sediments (NH_3, heavy metals, etc.). Maintenance of low flows can somewhat improve this situation.

More unusual phenomena may be associated with substantial releases of fresh but variably polluted water. These include the so-called "red tides" (Khalanski, 1983) which involve the development of toxic dinoflagellates (e.g. the Vilaine estuary) and sometimes result in high fish mortalities. The conditions in which such phenomena may arise are complex and involve the water quality and the meteorological conditions prevailing a few days before the appearance of the planktonic bloom.

METHODS FOR QUANTIFYING THE IMPACT OF A PROJECT ON THE WATER QUALITY AND AQUATIC LIFE

The above discussion has been mostly qualitative and must be viewed with caution since effects can vary substantially from one project to the next. In practice, these effects need to be further specified and various methods exist to achieve this. The most immediate method consists of comparing the facility studied or projected with another well known analogous facility, or one for which observations can be made. However, when the purpose is to estimate impact, a problem often arises by reason of the large natural fluctuation in both the physico-chemical and the biological parameters, which makes it illusory to directly compare the trends before and after development. The hydrological and meteorological conditions of the moment, and the conditions which have prevailed for a fairly long period before the observations, have a major effect on all these parameters. For instance, the mineral or organic content of a stream depends on the water quality in the upstream section and, therefore, on recent hydrological and meteorological conditions. It also depends on water input from the drainage basin, the ground water level, and therefore on the rainfall of earlier months. The effect of biological parameters can go back even further in time, especially for the higher links of the trophic chain. An exceptionally dry summer or very cold winter, for example, can have consequences on fish stocks for several years.

In addition to this method of analogy, mathematical tools have been developed to deal with these problems. This is a major branch of science which cannot be summarized in a few words, but some of the techniques are mentioned here, since they can provide explanations of the behaviour of global parameters such as temperature, dissolved oxygen, nutrients, phytoplanktonic biomass. Simulation models are available for these parameters, which either represent existing situations or explain the changes that would occur in the presence of a projected facility. The aim of these models, which are also referred to as "functional" models, is to portray the trend of ecological processes over time and in space. They are based on the definition of functional schemes which include transfers of substances and energy (Fig.1). In this type of model, a system of equations represents the growth processes (primary plant growth by photosynthesis) and transfers (transit through the trophic system, addition of organic substance and mineral nutrients, bacterial mineralization, water sediment exchanges, etc.). Most of these processes depend on temperature, and coupling biological models with thermal and hydraulic models allows the states of the system to be calculated in undisturbed conditions and those disturbed by a development. The models then quantify the impact of the development on water quality and the simplified ecosystem. Applications of such models are illustrated in several of the figures presented in this paper.

There are no such efficient tools available for calculating the higher links of the trophic chain, such as fish. It is possible, however, to make overall estimates of fish productivity from water quality parameters, and information is also available to determine the structure of natural populations. These last techniques are referred to as structural, since they also establish a relationship between the population composition and abiotic factors, such as temperature, chemical or hydromorphological parameters (Khalanski *et al.,* 1982).

CONCLUSIONS

Water resources are often considered only from a quantitative viewpoint but, in practice, many uses require that some characteristics of the water quality be taken into consideration. Sometimes, the qualitative aspects are even of primary importance. It is important to understand that the quality of water comprises not only physico-chemical but also biological aspects, and in practice these cannot be separated. Many physico-chemical transformations are associated with biological activities such as mineralization by bacteria, the nitrogen and carbon cycles, nutrient cycles in which plankton plays a major role, dissolved oxygen balance, etc.

All hydraulic projects, including those to meet quantitative needs (navigation, irrigation, flood control) have a definite effect on the quality of water. Appropriate design or good management of a facility can limit a particular effect on the water quality, although it is necessary to have criteria to follow. The criteria relating to water quality differ from one use to another, and even for the same application, various criteria may be in conflict. Mathematical models allow these problems to be analysed with respect to the estimation of effects, or to the improvement of the design and selection of proper management. Most of the time, however, the scope for adapting management in order to meet water quality criteria is limited.

Various types of development have been reviewed, specifying for each type the modifications which they may induce. Table 1 gives an indication as to the relative importance of the impact of various projects with reference to some specific characteristics of water quality. It is considered useful to include fish resources in the discussion since they provide an overall reflection of environmental quality. It should be observed that effects are not always proportional to the size of a development. For instance, it is a known

TABLE 1 The magnitude of impact of various hydraulic projects on some specific characteristics of water quality

Type of project	*Thermal*	*Physico-chemical*	*Plankton*	*Benthos*	*Fish resources*
STREAMS					
Canalization	+	+	+++	++	++
Weir	+	+	+	++	++
By-pass reach	++	+	+	+	++
Development of banks	-	-	-	++	+
Flow control	+	++	+	-	+
RESERVOIRS					
Short residence time	+	++	+	++	++
Long residence time	+++	+++	+++	+++	+++
Pumped storage station	++	++	++	+++	++
Small water bodies	+	+	+	++	++
ESTUARY AND SEA					
Construction of ports	-	+	-	+	-
Dredging waterways	+	+	-	++	+
Tidal power plant	+	++	+	+	+
Consequences of upstream developments	-	+	+	-	-

Magnitude of impact: - almost nil, + low, ++ average, +++ large.

fact that the construction of hydroelectric micro-stations has a definite impact on the fish stocks in a drainage system. However, the greatest change is undoubtedly caused by the creation of large reservoirs.

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