Cumulative impact of reservoirs on the aquatic environment. Joint scientific appraisal. Summary report

Nadia Carluer, Marc Babut, Jérôme Belliard, Ivan I. Bernez, Delphine Burger-Leenhardt, Jean-Marcel Dorioz, Olivier Douez, Simon Dufour, Catherine Grimaldi, Florence Habets, et al.

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CUMULATIVE IMPACT OF RESERVOIRS ON THE AQUATIC ENVIRONMENT

Joint scientific assessment

SUMMARY REPORT

May 2016

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Joint scientific assessment

CUMULATIVE IMPACT OF RESERVOIRS ON THE AQUATIC ENVIRONMENT

Summary Report

May 2016

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INTRODUCTORY CHAPTER

I.1 BACKGROUND

I.1.1 Context and aims of the assessment

This joint assessment study covers the **cumulative impact of reservoirs*[1] on the aquatic environment.**

It is part of the joint framework of **French reforms of abstractable volumes** and **of impact assessments** for projects for works, structures or developments, implemented in application of the National Environmental Commitment Act (known as the Grenelle II Act) of 12 July 2010 (Decree of 29 December 2011[2]). In some cases, application of the abstractable volumes reform, based on the Water and Aquatic Environments Act of 30 December 2006, could lead to the creation of new infrastructure for water storage, i.e. reservoirs, in particular as part of territorial development plans. The impact assessments reform means that the construction files submitted by applicants for reservoirs shall take into account the cumulative effect of planned works. Furthermore, certain strategic water management plans (SDAGE) have made provisions asking government services to ensure that the cumulative impact of all reservoirs present on a basin is taken into account when a project is examined. In this case, checking the compatibility of the project with the SDAGE plan requires an assessment of the cumulative effects of reservoir project(s) with those that already exist on the basin involved.

However, there is currently no national-level methodology covering this question of the cumulative impact of water storage structures on a single catchment area. In this context, the French Ministry of the Environment, Energy and the Sea (MEEM), assisted by Onema, asked Irstea to perform a joint scientific assessment study, in partnership with INRA, on the cumulative impact of reservoirs on the aquatic environment. This assessment, performed using a multi-disciplinary approach and mobilising experts from several research bodies and academia, aims to list, and where necessary elaborate, aspects of operational methodologies to improve the quality of examination procedures. A list of the experts involved is given in Appendix II.

At the turn of the millennium, an inter-agency study was performed on the impact of small artificial ponds* on environments (CACG, Hydrosphère and Géosys, 2001). It included a relatively comprehensive survey of existing knowledge on reservoirs and led to certain proposals, both for assessing the effect of small bodies of water on the aquatic environment and for mitigating this effect; this study remains largely valid. Nevertheless, some aspects of the context have changed since this study. In particular, the Water Framework Directive (WFD) was adopted in 2000, the French Water and Aquatic Environments Act passed in 2006, and the two reforms mentioned above were implemented (see Section I.2 regarding changes in the statutory context). This substantiates the need for a new look at the issue, in particular by including the concept of ‘good status’ of the aquatic environment introduced by the WFD. Furthermore, fifteen years on from this study, the survey on knowledge and available methods should be updated.

In this introduction, some background on the use of small reservoirs worldwide and in France is first presented. This is followed by an overview of the current French legal framework for the creation of reservoirs, and a look at the rules in place abroad for small agricultural reservoirs, using the example of a few countries affected by this issue. The areas covered by the assessment are then specified, with a presentation of the approach used, introduced by a quick summary of the main results from an exploratory phase that preceded this assessment and better defined the issues to be investigated.

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[1] Terms marked with an asterisk* are defined in a glossary at the end of the report.

[2] Decree 2011-2019

I.1.2 Uses and trends in small reservoirs worldwide

Water storage has increased greatly worldwide since the 1950s, in particular for irrigation needs. In 2003, there was 6,700 km^3 of stored water. In 2010, estimates based on data analysis, Geographical Information Systems (GIS) and statistics, considered that the surface area of agricultural reservoirs covered at least 70,000 km^2, which represents 0.1 to 6% of arable land on earth, with several million small reservoirs[3]. The USA alone had 2.5 million small agricultural reservoirs and Australia over 2 million with a total capacity of about 10% of that stored in large reservoirs in the country. In terms of density, values of between 0.15 and 6.1 reservoirs/km² were found in Australia for fairly recent years, depending on source and catchment area size, which is the same order of magnitude as for a US catchment area.

Small reservoirs are often for agricultural purposes, mainly irrigation and watering livestock. These reservoirs collect and store rainwater to secure the means of subsistence and increase crop yields. They are known to be essential tools for overcoming the vagaries of weather and thereby stabilising crop yields. Agricultural use of reservoirs varies: for example, in Australia, these small structures are mainly for watering livestock, while irrigation reservoirs are larger. Similarly, reservoirs are used for watering livestock in upland pasture areas. However, irrigation remains the main agricultural use of reservoirs, although some authors note that, particularly in India, these reservoirs provide other services at the same time: watering livestock, water reserves for firefighting, improvement of the local micro-climate, flood control, washing clothes, fish farming and bathing.

The number of reservoirs has greatly increased over recent decades. In 35 years, the number of such reservoirs in Australia has been multiplied by 2 to 10 depending on the catchment area studied (i.e. 5 to 22% per year), while an annual increase of 1 to 3% has been cited for the US and up to 60% or more in India.

Varied, and often interconnected, factors explain this rapid development of small reservoirs, usually for agriculture. In particular, droughts and economic pressures on the food and agriculture sectors have been identified as drivers. This trend has often been supported or encouraged by government incentive programmes. However, agricultural use of reservoirs could be abandoned over time. This is especially true in the context of growing urbanisation.

Box 1: Some figures on reservoirs in France

To our knowledge, the only attempt to systematically characterise the occurrence (number, surface area, volume and use) of small reservoirs at the national level in France was performed at the turn of the millennium as part of the inter-agency study on the impact of small artificial ponds (less than 1 million m^3) on environments (CACG et al., 2000). Given the difficulty of achieving a consistent and adequate set of data for the whole country despite the diversity of sources used, the study concluded that each *département* should produce an inventory of all bodies of water in its territory. Some *départements* have done this, or are in the process of completing it, but there is no consolidated national database. Figures given here are mainly based on extrapolations performed in the inter-agency study from gathered data. As an initial approach, it is assumed that the orders of magnitude remain correct, although the study showed strong dynamics of reservoir creation in certain *départements* over the period studied (1995-2000). The study revealed high variability in the density of reservoirs at the municipal level, with 2200 municipalities (i.e. nearly 7% of national territory, a figure stated to be probably underestimated) having a density greater than 0.2 reservoirs/km². The whole "fleet" was estimated at 125,000 structures with surface areas of between 200 and 300,000 ha, with a total volume of approximately 3.8 billion m^3. Nearly 50% of reservoirs counted had a surface area of less than a hectare, while 90% had a volume less than 100,000 m^3 with a depth of less than 3 m in 50% of cases and less than 5 m in 90% of cases. For bodies of water for irrigation, the mean volume was around 30,000 m^3. Table 1 gives a summary of the distribution of reservoirs by use and region.

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[3] The distinction between small and large reservoir is discussed in Section I.3; to give a sense of scale, the limit is around a few million m^3.

Table 1: Main uses of small bodies of water in France (based on the inter-agency study, 2000).

Uses	% in staff	% area	The most concerned regions
Irrigation	15	15	South-West, West
Fish farming	12	30	Centre, Rhône-Alpes, Lorraine and Limousin
Sport fishing and leisure	11	20	Bourgone, Pays de la Loire, Limousin, Auvergne and Bretagne
Leisures activities and enjoyments	62	35	Pays de la Loire, Bretagne, Centre, Limousin

Note than in certain regions, reservoirs for leisure activities or fish farming occupy a comparable or greater surface area than those for irrigation or low-flow period support. However, the question of assessing the effect of constructing new reservoirs currently most often regards those for irrigation or substitution (see Box 3 for definitions).

The maps in Figure 1 illustrate both the density of reservoirs on catchment areas which already have many, for example in Gers *département* and on the Doux catchment area in the north of the Ardèche *département*, and the significant effort made by certain departmental government services in putting reservoir data into databases.

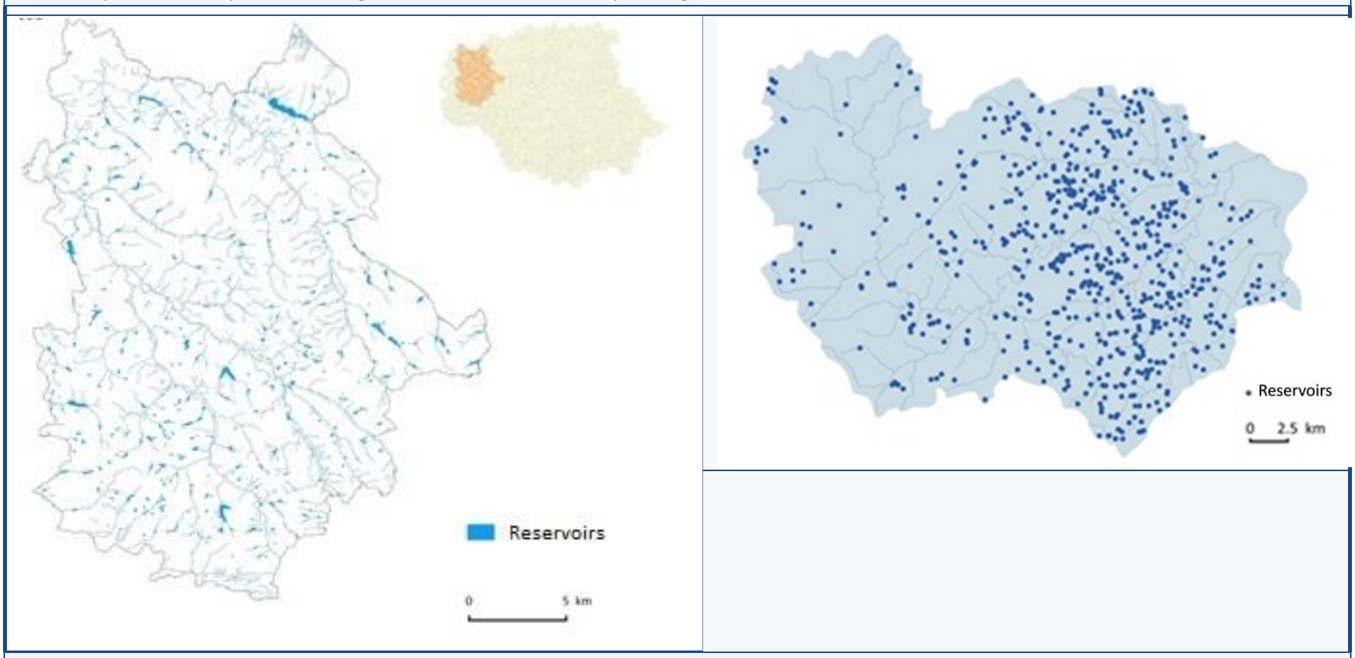

Figure 1: Examples of reservoir locations. Left: detail view of the locations of bodies of water in north-west Gers *département* (Source: Gers DDT); Right: Doux catchment area (Source: Ardèche DDT).

I.2 FRENCH LEGISLATION WITH REGARD TO RESERVOIRS AND QUANTITATIVE MANAGEMENT POLICY

As per Article L. 214-1 of the French Environmental Code, **the construction of new reservoirs is governed by the Water Act nomenclature**[4] which determines the examination procedure to which any development project is now subject (declaration/authorisation, i.e. whether subject to an impact paper or an impact assessment), based on its size and its effects on the water resource and aquatic environments. This nomenclature has been provided by the legislator to ensure balanced and sustainable management of water resources. Thus, the creation of a water body*, regardless of its status, is now subject to declaration or authorisation, in particular based on surface area thresholds determined by several clauses of the Water Act nomenclature. According to Clause 3.2.3.0, any water body, permanent or otherwise, with a surface area greater than or equal to 3 ha is subject to an authorisation procedure; if its surface area is between 0.1 and 3 ha, it is subject to declaration. However, these thresholds may be modified in some specific situations.

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[4] Decree 93-743 of 29 March 1993 pertaining to the nomenclature of operations subject to authorisation or declaration in application of Article 10 of Water Act 92-3 dated 3 January 1992.

I.2.1 Legislation on quantitative management and its association with reservoirs

The French water and aquatic environments Act of 30 December 2006 (known as the LEMA Act), introduced legislative measures aiming for sustainable management of water resources and reversal of chronic disequilibria, via the "abstractable volumes"[5] reform. In particular, the Circular dated 30 June 2008[6] specifies the details of this reform. Among other things, it specifies that water agencies, supported by the catchment area DREAL bodies, should provide the Prefecture(s) that coordinate the basin with a list of basins in quantitative deficit[7]. This list must then be made consistent with the SDAGE plans. A water resource is considered to be subject to balanced quantitative management when, statistically, in eight years out of ten on average, the maximum permissible or declared volumes and flow rates in this resource, regardless of uses, can be fully abstracted from it while ensuring proper functioning of the corresponding aquatic environments. This is the concept of **abstractable volumes**[8]. Proper functioning of these environments can be ensured via compliance with low-water regulating flows (DOE[9]), where they exist in SDAGE or SAGE plans.

The **restoring balance** procedure must be undertaken or pursued on all basins that are out of quantitative equilibrium. This Circular dated 30 June 2008 thus specifies general objectives for the restoration of quantitative equilibriums:

- assessment of overall abstractable volumes by the basin's water agencies and DREAL bodies where there is no local water commission (CLE);
- undertaking a programme of reviewing abstraction permits as soon as abstractable volumes are known, so that the total permitted volume is at most equal to the abstractable volume by the end of 2014, 2017 or 2021 depending on basin;
- distribution of water abstractions for agricultural irrigation may be delegated to a single joint management body (OUGC) that groups irrigators over a suitable area, in particular where there is a water distribution area (ZRE).

The Circular of 3 August 2010 pertaining to the restoration of quantitative equilibriums with respect to water abstractions specifies that returning basins with a large deficit[10] to quantitative equilibrium is based on a set of measures that aim to encourage water conservation and, **under certain conditions, to create new resources, i.e. reservoirs.**

The environmental conference of September 2013 specified that from now on, **only substitution reservoirs that are part of a territorial development plan may be subsidised by water agencies.** These territorial development plans aim for balanced management of water resources, without deteriorating the chemical and ecological quality of aquatic environments, and must be the result of a consultation involving all local stakeholders.

I.2.2 Taking the cumulative effects of reservoirs into account as part of the reform of impact assessments

Whether the reservoir creation project is subject to declaration or authorisation procedures, the applicant must file an impact paper with government services which includes an analysis of all the effects of the project with regard to the objectives of balanced and sustainable management of water resources. An impact assessment may be required, either systematically in the case of projects subject to authorisation under certain clauses of the Water Act nomenclature, or after preliminary checking called "case-by-case examination".

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[5] The Circular of 30 June 2008 defines abstractable volume as the volume that the environment is able to supply under satisfactory ecological conditions, i.e. those compatible with the basic guidelines set by the SDAGE plan, and where relevant, the general aims and rules of the SAGE plan.

[6] Circular of 30 June 2008 pertaining to restoration of quantitative equilibriums with regard to water abstraction and joint management of irrigation abstractions.

[7] A basin in quantitative deficit is in a situation where there is a mismatch between resource availability and abstractions. In such areas, it is necessary to restore quantitative equilibrium, to ensure compliance with objectives for the status of surface water bodies and groundwater while seeking sustainable maintenance of the main uses.

[8] Abstractable volume should be understood as the volume that can really be abstracted from the environment over a given period: in the case of reservoirs, with the exception of low-water substitution reservoirs, their filling conditions are to be considered and not the way the stored water is used.

[9] Low-water regulating flows are set to satisfy all uses in eight years out of ten on average and to achieve good water status.

[10] Discrepancy between abstractable volume and the volume abstracted in the driest year out of five on average greater than a threshold of the order of 30%.

The Decree dated 29 December 2011[11] covers the reform of impact assessments for projects for works, structures or developments which became applicable on 1 June 2012. This reform aims to better take the cumulative effects of projects into account. As per Articles R. 122-4 and R. 122-5 of the Environmental Code, **an impact assessment must, in particular, include an analysis of the cumulative effects of the project with other known projects.** Known projects are projects made public which, when the impact assessment was filed:

- were subject to an impact paper under Article R. 214-6 and to a public enquiry;
- or were subject to an impact assessment under this Code and for which an Opinion of the relevant government administrative authority responsible for the environment has been made public.

It is the applicant's responsibility to identify known projects using the national register of impact assessments.

A reservoir project must be compatible with the SDAGE plan, and the SAGE plan where one exists, which is the case when the project does not contravene the guidelines or basic principles of these documents. Furthermore, many SDAGE plans have provisions asking government services to ensure that the cumulative impact of reservoir projects is taken into account when a project is examined. Similarly, SAGE plans may have specified rules aimed at operations which could have significant cumulative impacts in terms of abstractions in their perimeter.

Box 2: SDAGE plans for 2016-2021 with provisions regarding the cumulative effects of reservoirs

Overall, the SDAGE plans for 2016-2021 concerning the Rhone-Mediterranean, Loire-Brittany and Adour-Garonne basins have provisions not only on the cumulative effects of reservoirs but also more general provisions regarding this idea of cumulative impact, in particular taking the "avoid-reduce-compensate" sequence into account.

The Rhone-Mediterranean SDAGE plan for 2016-2021 includes provision 6A-14 "Manage the cumulative impacts of bodies of water" which specifies that the creation of a water body must not compromise short and long term achievement of environmental objectives in the affected catchment areas, the resilience of aquatic environments, the objectives of blue-green infrastructure, and certain uses which strongly depend on the sanitary quality of water.

The Loire-Brittany SDAGE plan for 2016-2021 also has provisions that take into account this idea of the cumulative impact of reservoirs, including provision 7D - "Modify the spatial and temporal distribution of abstractions, via winter storage" which foresees that these developments, and their accumulation with existing structures on the same catchment area, could have impacts on environments which should be anticipated.

Finally, the Adour-Garonne SDAGE plan for 2016-2021 also has specific provisions to identify the territories affected by a high density of small bodies of water, and to reduce the cumulative impacts of bodies of water. In particular, provision D12 "Identify territories impacted by a high density of small bodies of water" plans for the identification by 2018 of the catchment areas affected by a high density of bodies of water, where it is necessary to limit the proliferation of small bodies of water.

I.2.3 Insight into the taking into account of small agricultural reservoirs in foreign legislation via a few examples

Although partial, the information gathered regarding reservoir legislation in several foreign countries where this issue is significant (Australia, New-Zealand, USA, UK and Spain) highlights significant differences with the French context along with some similarities. In most cases, the cumulative impact of these reservoirs is not covered in the documents consulted. Overall, reservoir management in these countries is performed at the regional level, or at the state level, with legislation covering these small agricultural dams* varying between regions or states.

Australia, which is particularly affected by increasingly frequent long periods of drought, has seen a sharp increase in the number of small farm ponds since the turn of the millennium, as for most other countries covered in this section. Consequently, the Australian government has opted for water resource management that aims to reconcile all water

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[11] Decree 2011-2019

uses in the regulated areas, and includes the water markets system in particular. This economic instrument, which is also used in California and Chile, ultimately remains quite marginal in Australia, as it only represents 5 to 10% of volumes abstracted each year, even in droughts. Furthermore, taking the need to preserve the environment into account, associated with awareness of the deterioration of aquatic environments, has led the federal government to focus on the Murray-Darling basin, which constitutes the agricultural region of south-west Australia, where water needs are highest following the extension of agriculture. Water abstraction quotas have therefore been revised downwards to the benefit of the environment. The Australian federal government is now moving to a policy of reducing water quotas, and generally limiting agricultural reservoirs on the Murray-Darling basin.

In the United States, small agricultural reservoirs are also very numerous and their construction is increasingly controlled in some States, including California. Californian water markets play a role that is even more marginal than those in Australia, as they only represent 3% of annual volumes consumed. Preservation of aquatic environments has developed in this country, in particular thanks to management of environmental flow rates at the level of large infrastructure.

In New Zealand, small agricultural dams have seen rapid growth due to ever increasing water demand, in particular associated with intensive agriculture, which is the main driver of economic development. As the exact number of small agricultural reservoirs is not well known, the regional councils of Auckland and Northland have launched surveys of these structures. Currently, 98% of abstractions of 5L/s or more in New Zealand are measured and recorded. The water management policy implemented in New Zealand supports this infrastructure, which secures access to water, but at the same time ensures its development is monitored.

In England and Wales, environmental agencies manage licences for “abstractions and impoundments”. Thanks to this licensing system, these two European nations monitor how, where and when water is abstracted. They use the Catchment Abstraction Management Strategy (CAMS) procedure, which uses environmental flow indicators to assess the quantity of water available for abstraction on a catchment area.

While not comprehensive, these few examples of foreign reservoir legislation, which cannot be transferred into French law, tend to show that France has a relatively developed legislative base framing the construction and management of reservoirs and that the results of this assessment could ultimately interest other countries.

I.3 AREAS COVERED BY THE ASSESSMENT

The assessment covers the effects of reservoirs on the aquatic environment. Given the evident complexity of the subject and the high expectations expressed at the operational level, a survey of the international literature, which serves as a basis for any joint scientific assessment study, was preceded by an **exploratory phase** (see the note on the assessment framework in Appendix I). This provided a survey of the knowledge and methods mobilised in France, based on an analysis of the available **operational literature**, and clarified the areas to further investigate in the assessment[12]. For this assessment, this involves a survey of international academic literature on the knowledge, concepts and tools available to cover the cumulative effects of reservoirs. A later stage should lead to the proposal of aspects of methodologies to cover the issue operationally, and the possible identification of research needs.

The types of effect[13] covered here are those associated with the hydrology and hydrogeology of a catchment area, sediment dynamics and hydromorphology, physical and chemical changes in water quality, and various biological compartments: fish, invertebrates, vegetation, i.e. the organisms present in the reservoir impact areas and rivers. The effects of reservoirs must therefore be examined via the various **functional characteristics** associated with rivers, which can be grouped into four main categories. This term covers the dynamics of water flow, flows themselves and associated concentrations of matter (suspended solids, nutrients and contaminants). It also includes the characteristics of physical

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[12] http://www.developpement-durable.gouv.fr/Expertise-scientifique-collective,46310.html (in French)

[13] In practice, it would appear that the term **effect** designates the results of a process from a cause with no sense of value judgement, while the term **impact** is associated with a value judgement (positive or negative impact) and therefore assumes the specification of assessment criteria and thresholds to judge whether the impact is positive or otherwise. In this report, which focuses on the influence of reservoirs on environments, the two terms are used interchangeably, with the term effect usually used in the first sense of “result, consequence of any agent or phenomenon”.

(river bed, reservoirs etc.) or biological compartments of the river, and the interactions between these various components. The various **functional characteristics** associated with these various aspects of the river are examined, i.e. the flows, concentrations where relevant, changes, and the influence on other compartments, whether physical or biological. These various types of effect are considered over various time and space scales. Birds are not specifically studied as they are not strictly dependent on a corresponding reservoir or river, and would require a wider scope of analysis. Finally, climate change is not explicitly considered, although the predictable change in water storage capacities is closely linked, at least in certain geographical areas, and it may also ultimately affect the ability to fill such structures. However, the cumulative effect of reservoirs on greenhouse gas emissions is covered.

The notion of cumulative effects has been defined legislatively in Section I.2.2; here it is considered as covering all effects caused by all reservoirs considered, over all variables envisaged. In Chapter II, it is seen that several different definitions of this concept are possible, of varying scope.

Social and economic aspects, while they have been partially considered as aspects of context, in particular as part of field trips undertaken during the exploratory phase, are not part of the scope of this assessment. In particular, it does not cover the question of whether or not the construction of a reservoir is justified from a socio-economic standpoint.

One of the difficulties associated with studying reservoirs is the diversity of structures for which this term can be used, whether with regard to the associated uses, how they are supplied, how water is returned, the quality of water collected, or other characteristics of their environment. This diversity further increases when considering all the current reservoirs on a given basin, as the spatial distribution of the various types of reservoir can be in highly varied configurations. The effect of an individual reservoir on various compartments of the aquatic ecosystem depends, in particular, on its use(s), how it is supplied and how it returns water. Following the exploratory phase, **a typology associated with each of these aspects was proposed**. It is presented in Box 3 and serves as a reference for the rest of the document. However, it should be noted that the information available in the articles and documents consulted is not always adequate for assigning the objects studied to any one of these categories with certainty.

Box 3: Types of reservoirs

Uses

As an initial approach, three categories of use can be distinguished **1** – that which does not consume water, but returns the intercepted water directly to the river throughout the year, **2** – that which does not consume at annual level, but significantly affects the flow regime by storing and releasing the water taken in, and **3** – that which actually consumes water. It should be noted that uses 1 and 2 mainly influence the hydrological regime via evaporation, and sometimes infiltration.

Uses in the first category include leisure (landscape attraction, bathing, boating, fishing, and hunting ponds*) and fish farming. They do not consume water but may have effects on water quality for example. Hydropower typically falls into the second category. Some industrial abstractions may also fall into this category, depending on whether or not they return most of the water abstracted to the environment. **Return / resupply** reservoirs, which serve to resupply the river during the dry season and support low-water flows, can also be included in this category. The third category includes all uses that abstract water and do not directly return it to the river: drinking water[14], irrigation, watering livestock, and snowmaking. In general, reservoirs may have multiple uses. Return / resupply reservoirs may sometimes end up in this category, as the water they return to the river is sometimes re-abstracted for irrigation.

Supply method

Here, 5 types of reservoir are distinguished, depending on their position with respect to the river and how they are filled (see Figure 2). Supply method and uses are not strictly independent. The types are presented below in order of increasing connection to the hydrographic network. **Substitution** designates the practice that abstracts water during low-stress periods (generally in autumn-winter) to store it in a reservoir, which is then used in summer and thereby reduces abstractions from the environment in the low-water period. A **reservoir** stores water which flows by gravity, while an **artificial pond** is filled by pumping.

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[14] It is generally considered that drinking water abstractions are quantitatively restored at 80%: not always into the same environment or at the same time, and generally with a significant deterioration in quality.

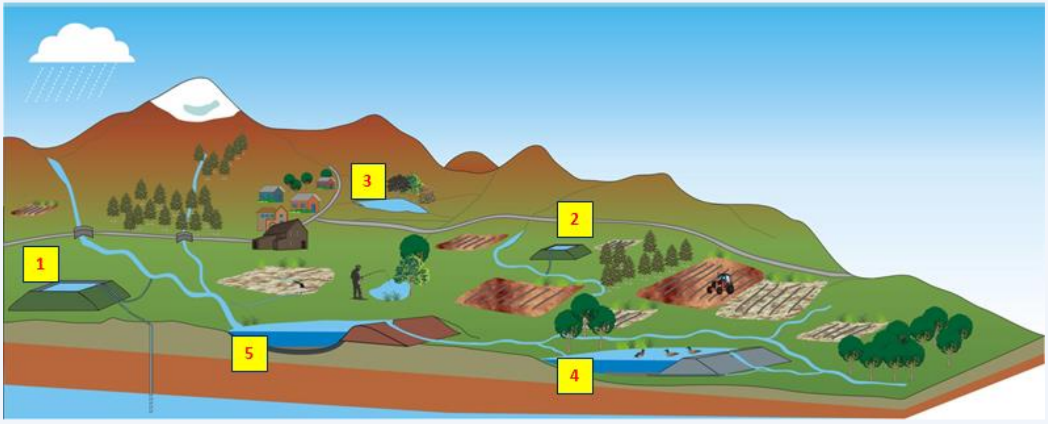

Figure 2: Location of reservoirs depending on their supply method (Source: F. Peyriguer (Irstea) based on O. Douez (BRGM)).

1. **Artificial pond** supplied by pumping **groundwater**. This is an artificial pond disconnected from the surface hydrographic network, supplied only by pumping in a nearby aquifer.
2. **Artificial pond** supplied by pumping in the **river.** This is also disconnected from the surface hydrographic network; it is supplied only by pumping in the river.
3. **Hillslope reservoir.** These reservoirs are supplied **by runoff water** and normally **disconnected from the hydrographic network.** Because they are located in talwegs to intercept more runoff, it is possible that structures considered as hillslope reservoirs could be installed **on springs or drain groundwater**: in such cases they are in fact reservoirs on rivers, and should be subject to the legislation for this type of structure (in particular minimum flow rate).
4. **Diversion reservoir.** Such a reservoir is similar to an artificial pond supplied by pumping in the river (**2**), but here it is gravity fed. However, when full, such a reservoir is rarely fully disconnected, and often only a minimum flow rate, sometimes piped from upstream of the reservoir, ensures river continuity.
5. **Dam reservoir.** This type of reservoir is located on a river: unless a specific minimum flow device is installed (with an upstream intake) all water that joins the downstream river has passed via the reservoir.

Some reservoirs can be supplied by urban stormwater or treated wastewater from sewage treatment plants or industry; they are not specifically covered here.

The requested assessment theoretically covers all types of reservoir, in particular with no explicit maximum capacity, but without covering very large structures. To give a sense of scale, the inter-agency study mentioned above was limited to reservoirs with a volume less than one million m^3, supplied by surface water. Conversely, Bergkamp et al[15], in a report on the effect of dams on ecosystem functions, defined large structures as those having a dam height greater than 15 metres or a height of between 5 and 15 metres and a volume greater than 3 million m^3. This is the maximum order of magnitude considered in this assessment, without being an absolute limit if the knowledge or data available for larger reservoirs appeared relevant. Re-supply reservoirs are at the limit of this size range, often having a volume greater than a million m^3, and are therefore only partially covered by the assessment. In terms of surface area, the reservoirs considered therefore range from several tens or hundreds of m² to around 10 hectares.

Table 2: Themes covered and types of reservoir considered in the assessment

Themes covered	Hydrology hydrogeology	Physical and chemical characteristics (temperature, oxygen, nitrogen, phosphorus, heavy metals, pesticides, greenhouse gases). Water quality	Sediment transport. Hydro-morphology	Ecology (in particular bio-indicators, vegetation, macro-invertebrates, amphibians and fish)
Types of reservoir Uses considered	Mainly fishing, leisure, fish farming, irrigation and ornamental	~~Re-supply reservoir (of large size)~~	~~Reservoir for snowmaking. Very few references. Deserves its own assessment~~	

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[15] Bergkamp G., McCartney M., Dugan P., McNeely J., Acreman M., (2000). Dams, Ecosystem Functions and Environmental Restoration, WCD Thematic Reviews, Environmental Issues II.1. World Commission on Dams: 187.

Supply method	Pumping groundwater (substitution reservoir)	Pumping in the river (substitution reservoir)	Runoff, spring (hillslope reservoir)	Diversion reservoir	Dam on a river

I.4 APPROACH ADOPTED FOR THE JOINT SCIENTIFIC ASSESSMENT STUDY

I.4.1 Lessons learned from the exploratory phase

This initial step, which surveyed the operational literature, showed that at **the scale of a single reservoir**, much data and knowledge was already available for covering the effects of large reservoirs, in contrast to small reservoirs, and particularly hillslope reservoirs, for which data was much scarcer. However, the analysis showed that data was often qualitative, or the context of the reservoir insufficiently described for the factors that determine how the system functions to be adequately characterised and for it to easily transfer or reuse the knowledge in a context other than that in which it was collected.

With regard to **cumulative effects**, hydrology and hydrogeology currently seem to be areas most suitable for coverage, via modelling in particular. However, the type of modelling to be implemented is yet to be specified, in particular depending on the needs identified in the assessment of the effect of reservoirs on other system variables (sediment transfer, physical and chemical characteristics, and ecology). As a vector, hydrology largely governs these other components, but the key parameters are not necessarily the same for all these components. The following can be cited as obvious examples: high flow rate for sediment transport and hydromorphology, characteristic flow rates during critical periods for aquatic organisms (low-water, breeding season etc.), and flow rate seasonality for physical and chemical water quality. Furthermore, certain methods, which make the link between habitat deterioration and deterioration of the hydrological regime associated with an accumulation of reservoirs, can already be used to partially assess the effects of hydrological modifications on aquatic organisms. However, these are mainly aimed at low-water periods and fish farming habitats, and only cover cumulative effects as the sum of individual effects: they should be supplemented to take into account interactions between ecological conditions, hydrological and physico-chemical conditions, and the likely resulting threshold effects for biological compartments. Finally, this stage has shown that certain biological metrics are sensitive to the presence of reservoirs: they can therefore be used to perform diagnostics of the initial state before a reservoir is constructed, or even to discuss the acceptability of certain reservoirs. However, they do not yet allow for a predictive approach, which would forecast the expected impact of one or more new reservoirs on certain biological compartments.

From an operational standpoint, this initial phase has shown the need for those responsible for assessing the cumulative impact of reservoirs to **have access to data in a form that is easily queried and used.** This would appear to be an indispensable prerequisite to implementation of suitable methods for the issue, which must be based on a set of consistent and adequately precise data to lead to relevant results.

I.4.2 Limitations and unanswered questions brought to light by the exploratory phase

Analysis of the operational literature identified some points which must be given special attention in the survey of international literature, including at the **scale of an individual reservoir**:

- With regard to hydrology and hydrogeology, quantification of evaporation and infiltration from reservoirs has emerged as a potential source of uncertainty. Furthermore, it is important to cover the effect of reservoirs on groundwater-river exchanges and functioning of the hyporheic zone, with possible consequences on the ecological functioning of the river.
- With regard to physical and chemical characteristics, it was seen that there is a need to better characterise influencing factors, and to better quantify processes. In particular, to cover cumulative effects, it seems necessary to consider a flow/stock variation approach, while the available data and knowledge is most often based on

measurements of concentration under non-spate hydrological conditions, which is not adequate from this standpoint. Eutrophication, which seems common in reservoirs, also deserves special attention, along with greenhouse gas production, which, while seemingly insignificant for an individual reservoir, could become significant for a large number of such structures and on a global scale.

- It appears that the securing of access to water provided by reservoirs on a catchment area may affect its hydrological and physico-chemical functioning, both via changing possible cropping and cultural practices and by changing the soil-plant-atmosphere system it produces. This point deserves investigation.
- From the sediment transport perspective, if cited at all, it is most commonly in an overall manner: fine and coarse fractions are not distinguished, while their behaviour in the presence of a reservoir is very different. Here again, data for spate flow is rare or non-existent. These aspects should therefore be investigated, both for production during filling, deposition and resuspension (of particles and the associated elements) in the reservoir, and for influence on the downstream river.
- With regard to ecology, there is rather limited knowledge on the effects of hillslope reservoirs on the ecology of the area around and downstream of the reservoir. The international literature should therefore be explored on this aspect, and the search possibly widened to similar systems in terms of function: ponds, marshes, headwaters, and intermittent rivers, to unravel the determinants of their functioning and possible malfunctioning, and identify relevant functional descriptors.

This phase has also brought to light the **need for a conceptual framework for organising the knowledge and aspects of methods** to cover the question of the cumulative effects of reservoirs. The assessment therefore aims to find, in the existing literature, conceptual frameworks that have already been produced to study the cumulative effect of reservoirs on environments, but also more widely in studies pertaining to other types of bodies of water distributed over catchment areas, or even in the context of assessments of cumulative effects on other themes.

The issue of the **spatial organisation of reservoirs in the landscape** is felt to be important, and the effect of this organisation on flows of water or matter should be understood, and the ability to characterise this distribution investigated, both in terms of the position of reservoirs in the catchment area and with respect to the river, and in terms of the characteristics of these objects (surface area, volume, uses of water, and abstraction and, where relevant, return dynamics). The inter-agency study proposed indicators to assess the cumulative impacts of reservoirs: it will be checked if other indicators have been suggested in the scientific literature and tested in different contexts.

I.4.3 Approach adopted

Besides the specific questions mentioned above, the literature survey in Phase 2 of the assessment initially covered **the effect of an individual reservoir** for each theme. For this, the experts tried to identify, where available, aspects of context and the specific characteristics of the reservoir, both to **identify influencing factors** and to assess the possibility of transferring the results or knowledge to other contexts. The function of the reservoir was determined, along with its influence on both the quality of the water body created and on the downstream river (and even on the upstream river and surrounding area in the case of biology). Research methods were also analysed, in particular depending on their context of application and the data available. Next, the same approach was adopted for the **cumulative influence of a set of reservoirs**. Finally, for each theme, a concluding part summarises the main knowledge, tools and methods analysed, and considers possible links with other compartments, attempting to go beyond the single-theme approach of the cumulative effects of reservoirs on the environment. This involves describing how “immediate” changes on certain components (first order impacts on the diagram) affect others in cascade (second and third order impacts). Figure 3 proposes such a framework that can be applied to an individual reservoir. To **cover the cumulative effect of reservoirs on a catchment area**, the **spatial and temporal dimensions of the processes, in particular possible interactions between reservoirs**, need to be understood. It is essential that long-term effects are taken into account (creation of stocks, and interactions with climate change).

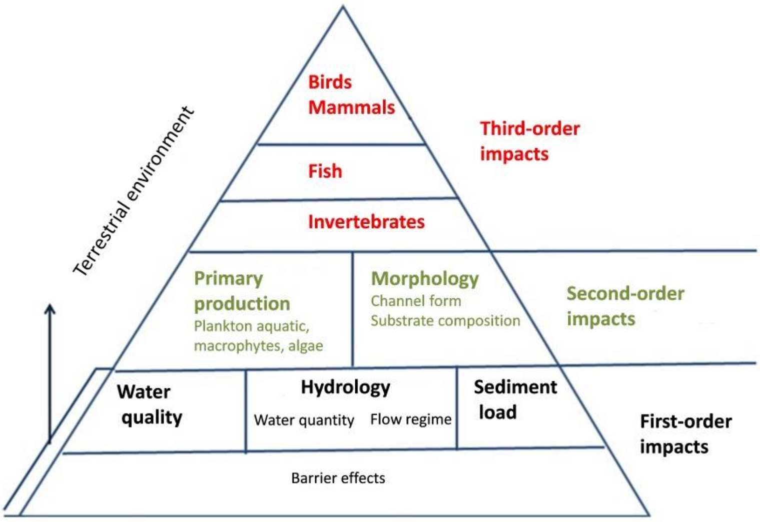

Figure 3: Example of a framework for assessing the impact of a reservoir on river ecosystems (Bergkamp *and al.,* taken from Petts, 1984).

Bibliographic queries were formulated to cover the questions mentioned above, for each set of functional characteristics (hydrology-hydrogeology; sediment transport-hydromorphology; physico-chemical water quality; biology). To arrive at a useable but extensive body of literature, these queries had to be modified either to restrict the geographical area covered (excluding tropical areas with regard to nutrients for example), the period considered (references later than 2000 for the literature survey regarding a single reservoir for physical and chemical characteristics), or to widen the search to larger reservoirs (such as for sediment transport) or to natural bodies of water (lakes), or by accepting that the nature of the objects considered is not always known (such as for ecology, where the type of water body is not always specified: pond, reservoir). It will be seen that this approach, which seemed to be the only pragmatic one, led to thematic analyses that ultimately considered relatively diverse sets of objects. Furthermore, it should be noted that despite the stress put in the queries on the cumulative effects of reservoirs, over a body of approximately one thousand references, only a small proportion of around 10 to 25% (a little higher for hydrology) actually covers cumulative effects, even though objects other than the reservoirs covered by the assessment were included (large dams, lakes, wetlands).

Here follow some examples of the questions, for a given basin, for which the assessment (in its 3 phases) ultimately seeks to find either direct aspects of answers, or aspects of methods to cover them:

- **Are there proven effects of a set of reservoirs on the hydrosystem and its environment? What are they? How are they measured? Do relevant indicators exist for taking them into account?**
- **At equivalent volume, what are the effects of many small reservoirs compared with a few large ones? What are the effects of their locations in the landscape – including with respect to the hydrographic network?**
- **Can the effects of future developments be predicted?**
- **Are there threshold effects that could lead to a change in the functioning of certain components of the catchment area? What are the resulting risks for deterioration of the quality of the environment?**
- **Are strong hypotheses that are not yet fully accepted used regarding the effects of a set of reservoirs? What are the research needs to test these hypotheses?**
- **What skills, tools, methods and data are needed to cover these questions?**

I.4.3.a Structure of the report

Before specifically presenting the effect of reservoirs on the various components of aquatic environments, this report first presents more general aspects of assessment methods for the cumulative effects associated with specific projects, or more generally with human activities. This Chapter highlights the methodology and governance questions involved in an assessment of cumulative effects approach. It also specifies the concepts used, which the rest of the report may call upon, sometimes implicitly. The report then covers the various sets of functional characteristics mentioned above, in an order based on Figure 3 : the effect of reservoirs on the hydrological and hydrogeological functioning of a catchment area (Chapter IV), on river sediment transport and hydromorphology (Chapter V), on the physico-chemical quality of water (Chapter VI), and finally on the biology of aquatic environments and their surroundings (Chapter VII). Each chapter covers the effect of a single reservoir then the cumulative effect of reservoirs, in each case highlighting the methods used, the tools available and the objects studied. As far as possible, the river, the reservoir as a new environment and the environment its replaces are covered together.

As has already been stressed, it was not always possible to restrict the analysis to the modestly-sized reservoirs that this assessment covers. In this case, there is an attempt to specify which results appear to be directly transferable to small reservoirs and which can only be transferred from a methodological standpoint. Given the importance of characterising the reservoirs on a catchment area, which recurs for each theme, a chapter is dedicated to the state of the art on this point (Chapter III), to better understand what current methods can achieve, in particular in the area of remote detection, both theoretically and from an operational perspective.

The overall conclusion aims to extract useful lessons for relevantly assessing the cumulative effect of reservoirs; it also highlights the gaps in knowledge and the needs that the assessment has identified.

Chapter II CUMULATIVE EFFECTS ASSESSMENT METHODS

It seemed useful, before more specifically covering the cumulative effect of reservoirs on the aquatic environment, to query the international literature on assessment methods for cumulative effects in a wider context, in order to identify more generally the concepts involved and aspects that should be taken into account in such an approach, and to determine if this could provide aspects of "specifications" for producing a method suitable for the case of the cumulative effects of reservoirs. The literature dealing with assessment of the cumulative effects of human activities on the environment is mainly North American, particularly Canadian, and originated in the 1980s. Articles from European countries are more recent, probably associated with member states implementing the EU Directive on environmental impact assessment (85/337/EEC).

It is observed that, in contrast to "simple" environmental impact assessment methods, **Cumulative Effects Assessments (CEAs)** are mainly found in unpublished sources, and rarely found in the academic literature, as they have most often been performed by those in the operational rather than scientific sector. Furthermore, the available literature most often covers cumulative effects assessment theoretically, or in the context of general planning studies, often covering large regions; it hardly ever covers CEAs performed in the context of environmental impact assessments for a given project. This limitation in the scope covered by the academic literature may lead to bias in the analysis based on it, which needs to be borne in mind. One solution proposed to reverse this trend consists of using forums to make these studies known and promote the practice of CEA.

Cumulative effects assessment in a given context uses definitions and concepts that must be shared by the various stakeholders to ensure that the results of the assessment are accepted.

II.1 DEFINITIONS AND CONCEPTS USED FOR CUMULATIVE EFFECTS ASSESSMENT

II.1.1 Various types of cumulative effects

The term generally used in the literature is most often **cumulative effects** rather than **cumulative impacts**, without the nuance between the two terms being made explicit. Here these two terms are used without distinction to express the consequences of implementation of developments or projects. Firstly, cumulative effects may be **homotypic** or **heterotypic**, depending on whether they result from multiple developments of the same type or are caused by the combination of two or more different projects or developments. They can also be distinguished by whether they develop via an **additive or incremental process**, a **supra-additive** process (where the cumulative effect is greater than the sum of the individual effects) or an **infra-additive** process (where the cumulative effect is less than the sum of the individual effects). The total impact is therefore equal to the sum of the impacts of the developments and to interaction effects (which may be positive or negative depending on whether the effects are supra- or infra-additive). Finally, cumulative effects may be classified as **direct, indirect or multivariate**: direct effects correspond to the case of a simple response (i.e. first order on Figure 3 for the environment in response to modifications caused by implementation of projects (stimuli)); indirect effects correspond to the case where responses are second order or higher; multivariate effects correspond to responses to multiple stimuli with inter-relationships. Indirect and multivariate responses are more complex, less well understood and harder to quantify. A cumulative impact assessment must cover these three types of response (direct, indirect and multivariate).

These definitions reflect the diversity of the types of cumulative effects to which a system may be subject, and the difficulty of defining the scope that a cumulative impact assessment must actually cover. It is thereby seen that the definition of "cumulative effects" or "cumulative impacts" vary in different legislative texts and articles that cover the issue, with some writers proposing their own definition, consistent with their perception of what a CEA should be. In particular, the nuances between the various definitions may involve which projects should be considered in the assessment: some lead to a notion of cumulative impacts associated with the accumulation of effects from various developments and works, while others focus on the notion of the cumulative effects over time from a given development. Another common definition, which is used in the United States, considers the cumulative impact as "*the impact on the environment which results from the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions regardless of what agency (Federal or non-Federal) or person undertakes such other actions.*" (Council on Environmental Quality (CEQ) Regulations, Section 1508.7). The definition of what can be considered as "reasonable foreseeable future actions" is itself quite sensitive and depends on the range of future scenarios considered. It therefore seems necessary that stakeholders agree on what is understood by "cumulative impacts" and, in particular, decide with regard to a given concrete action: (i) if the cumulative impacts concern the impacts of the proposed action integrated over time on the relevant environmental resource; (ii) if the cumulative impacts refer to the impacts of the proposed action on all relevant environmental resources at a given point; (iii) if the cumulative impacts include all existing developments or factors that may cause impacts around the proposed action, including past developments, even those which are no longer current but whose effects are still perceptible; (iv) if the synergistic or antagonistic relationships associated with environmental effects must be taken into account. The answer to these questions affects the scale in time and space to be considered for the CEA, and the number and type of projects or developments to be included in the analysis. The current assessment tends to fall in the third definition; but by considering together multiple environmental effects, which may be synergistic or antagonistic, it may also cover the last case.

II.1.2 Initial state, baseline state, metrics and thresholds

Assessment of cumulative impacts consists of estimating the impact of a planned action on a receptor, in combination with other actions. An environmental receptor is defined as any ecological characteristic which is sensitive to an action: **identification of at-risk receptors** for a proposed action is therefore essential, as is specification of suitable metrics for quantifying their change. These at-risk receptors are often associated with the idea of **Valued Environmental Component (VEC)**. For example, in the case where the effect of an action on biology is being considered, this assumes identifying the species and stages of development to be considered. Metrics are needed to characterise the state of the system (via the VECs considered) and its potential changes. The metrics used are often composite **indicators or indices**, built by aggregating variables that provide information on the state of the system, such that the resulting information is useful to decision-makers and stakeholders. To be relevant, these metrics must be compared with ranges or thresholds which characterise the state of the system and its deviation with respect to its baseline state, and identify the environmental components most likely to be impacted, or note that certain components have already been affected. Again, it seems important that common metrics be used by various CEAs, which implies **developing or modifying common standards, relevant over an area or in a given context**. **Thresholds must also be specified so that it can be decided whether the effects are acceptable or excessive for the ecosystem.**

Characterisation of the **initial state** of the environment at the time of the CEA is performed via comparison with a **baseline state**. This latter is defined as the state of a site where the conditions are such that the biota there is the product of natural and biogeographical evolutionary processes, with relatively little impact from modern human activity. It could be that there is no baseline for a receptor, and that its state at the time of individual assessments be taken as a baseline. Non-inclusion of historical data is known as **shifting baseline syndrome** and can lead to deterioration of the receptor over time. Comparison between baseline and initial states is an essential step of the CEA, and in some cases (see methods below) the main part of the assessment. It identifies trends from the past, and past and current human activities and their consequences, to better define the issues for the various VECs, and where necessary specify realistic objectives. Finally, good understanding of past actions and their cumulative effects, which implies a relevant definition of the initial state, could be harnessed to mitigate cumulative effects: where possible, mitigating the effects of current and past developments could improve the state of the environment and thereby allow consideration of new projects otherwise unacceptable given their expected cumulative effects with past developments.

II.2 EXISTING METHODS

There are various classifications for CEA methods with different objectives, tools and data used. Any method used must be able to report on the three following causal components:

- cumulative environmental changes (CEC) from single or multiple activities, which may be similar in nature or otherwise;
- accumulation pathways or processes, whereby CECs accumulate over time and space in a cumulative or interactive manner;
- different types of cumulative effects.

Two classifications are used primarily, and these are not entirely independent, as will be seen.

II.2.1 Stressor-based approaches vs. effect-based approaches

Stressor-based methods can be distinguished from effect-based methods.

Stressor-based approaches involve describing the project in question, identifying potential stressors at different project phases, identifying environmental receptors or valued ecosystem components (VECs) and then identifying the effects induced by interaction between the stressors and VECs. This final step requires the compilation of available data. Any residual effects are determined once any compensatory measures have been taken into account and once the significance of them has been compared to thresholds that are often defined on the basis of land-use planning objectives. This approach is deemed to be effective in identifying the potential local impacts of specific projects on environmental components. It is nonetheless limited in that its application assumes that all stressors associated with a specific project are known and that the interactions between stressors and ecosystem components have been characterised for the context in question, which is not always the case.

Effect-based approaches have been developed more recently in Canada, targeting a much broader scale than previous approaches (several hundreds of thousands of km² in the examples given). They consider the current state of the environment as the result of previous disturbances (ongoing or past) and try to identify as-yet-unknown stressors and their interactions on a wider scale. One of the major limitations of this approach is that it doesn’t allow a predictive approach. A stressor can only be identified after an effect has been measured. It also requires a wide-ranging dataset, covering a long period of time. The main advantage of this approach is that it identifies thresholds that have already breached, to assess the capacity of the receiving environment to withstand further anthropogenic stresses and to identify stressors requiring attention.

Authors that adopt this classification conclude that the two approaches are complementary and that the effect-based approach must precede the stressor-based approach. If a project is actually implemented, the stressor-based approach should be followed up with a monitoring campaign to assess whether the observed effects comply with predictions, in order to improve knowledge and adapt management measures, where applicable (Figure 4).

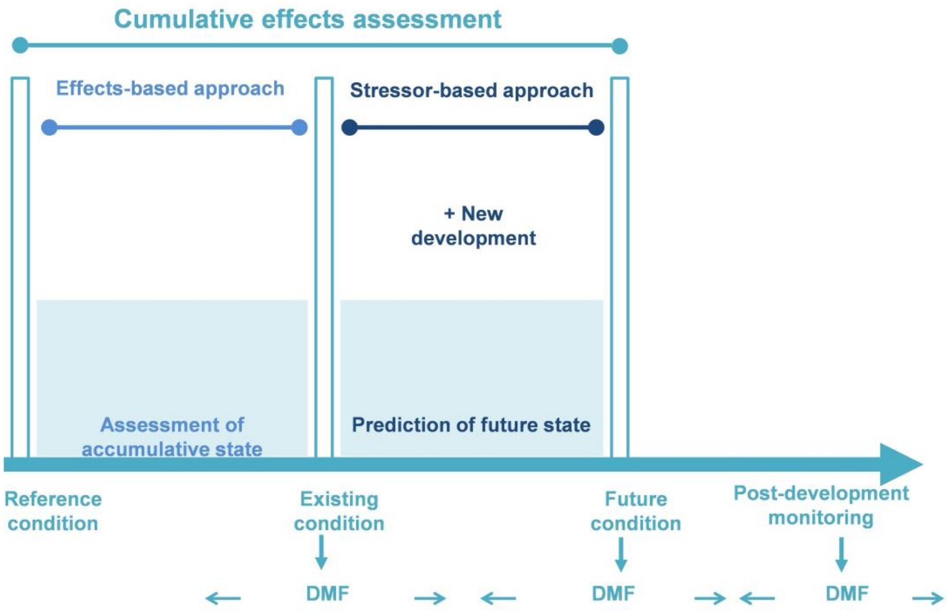

Figure 4: Proposal for assessing cumulative effects including effect-based and stressor-based assessments, decision-making frameworks (DMF) and post-development monitoring (Dube and Munkittrick, 2001). "Reference condition" here refers to the reference condition addressed in the paragraph that defines the initial and reference conditions and "Existing condition" refers to the initial or current condition. "Future condition" is the predicted condition as a result of the project, according to the effect-based approach, and observed in post-project monitoring.

II.2.2 Analytical approaches vs. planning-based approaches

Another classification could be proposed, distinguishing **analytical approaches and planning-based approaches**. Under analytical approaches, assessment of cumulative effects is an activity that primarily generates information, based on analysis and scientific approaches, in order to generate a flow of information to decision-makers, to enable them to make evidence-based decisions. Planning-based approaches use planning principles to prioritise resource-allocation choices. In this case, the final decision is based on explicit social norms, which form the basis of decision-making rules that help compare and prioritise alternative solutions and reach an appropriate trade-off between environmental, economic and social objectives. Cumulative impact assessment is seen as a corollary of a broader planning process, going beyond analytical functions such as information gathering, analysis and interpretation to include quantitative assessment of criteria, a multi-objective steering process and participatory decision-making. In order to properly take into account the three points mentioned above (multiple sources of change; cumulative or interactive accumulation processes; cumulative effects that vary in nature), a method should ideally be able to represent:

1. **Accumulation of effects over time**, when the interval between one disturbance and the next is too short for the system, its components or a process at work can recover from the first disturbance. Compliance with this criterion requires the assessment method to consider both the duration and frequency of disturbances, and to incorporate a long timeframe in order to detect long-term changes or delayed effects.
2. **Accumulation of effects in space**, which occurs when the spatial distance between disturbances is smaller than the distance required to remove or disperse the disturbances. Any assessment method needs to be able to consider the geographical scale of disturbances, define the spatial boundaries of the study accordingly and represent the way in which the disturbances and their effects are differentiated in space. It must also take into account all the cross-boundary flows/movements on the same scale (e.g. intraregional) and between different scales (local to regional and global). The ability to consider spatial distribution, in particular on the surface, is particularly important, because cumulative effects assessment is often conducted on a regional scale.
3. Different **types of disturbance**, which may have multiple sources, or disturbances from a single source that are repeated over time or space.
4. **Accumulation processes**, resulting from cause-and-effect relationships. Any method used must be able to reflect the way the system evolves over time.

5. **Functional effects**, i.e. alteration of processes (energy flows, nutrient cycle, succession) or changes to functional properties (e.g. assimilation or transport capabilities, breach of a threshold that changes the way the system works). This requires gradual changes, accumulation over time, delayed effects or threshold-related effects to be taken into account.
6. **Structural effects**, including changes in populations, habitats and alterations of geophysical resources (e.g. air, water, soil). Just as for the functional effects, any method used must be able to identify, analyse and assess the structural changes in the environmental system, or in one of its components or processes. This type of change is primarily spatial and it requires spatial accumulation, fragmentation effects or cross-boundary flows to be taken into account.

These criteria can be used chiefly to assess the analytical component of these methods, rather than the planning-related components. Most methods take the spatial dimension into account better than the temporal dimension. This is partly linked to the limited availability of historical data, but also reflects the **inherent challenge of considering processes that vary over time**. The variable and random nature of processes also makes them difficult to include in many methods. This suggests that **future developments should focus on methods to analyse and assess accumulation pathways**. **Modelling-based methods**, using numerical simulation and based on **geographical information systems currently appear to be the best approach to the multi-faceted issue of assessing cumulative effects**. Other methods that seem less complex, such as interactive matrices or network analysis methods may also provide interesting answers. However, it seems that geographical information systems are a necessary tool. Other types of methods could be combined for specific situations, depending on the nature of the issue in question, the purpose of the assessment, access to data and quality, resources available. It does seem that a combination of multiple methods should be used for a comprehensive impact assessment, in order to analyse and evaluate causes, pathways and effects.

Aquatic environments: a special case

The structure of catchment areas and the transfer role played by water means that environmental effects on river systems are, by very nature, cumulative over time and space. Almost all activities that take place within a catchment area have a direct impact on environmental factors - the soil, topography or plant life. In return, this changes the transfer of water, sediment, organic matter and pollutants into the river, whose condition depends heavily on the types of interactions and processes occurring in the entire river basin area. However, despite highlighting specific differences, articles about CEA in river basins (maybe because they cover large catchment areas of several hundred thousand km²) do not explicitly take account of the connectivity between transfer processes in the river basins; these processes are considered as surface juxtapositions, except as regards the hydrographic network in the strictest sense of the term (i.e. flows from upstream are included).

II.2.3 Scale and governance: closely-related concepts

The spatial and temporal scale on which CEA is performed must cover all induced effects. However, fairly often cumulative effects assessment is carried out on the scale of an individual project, similarly to project-based environmental impact assessments. This scale is often not the most relevant for cumulative effects assessments, in that the individual projects may have little impact in the context of the cumulative effects on the resources in question, caused by the interaction between multiple disturbances. Another difficulty is the fact that any increase in scale can tend to fade out local problems (i.e. specific projects) and others may become more significant (disturbances affecting the entire landscape). In rivers, specifically, the full range of different processes at work in a catchment area cannot be expressed on the same spatial scale.

One solution might be to adopt a **multi-scale approach**, focusing more closely on the most affected areas and paying a bit less attention to unaffected environmental components. A method that combined different spatial resolutions / degrees of precision, would enable extensive analysis of the cumulative impacts of all projects, developments or practices, but also more intensive analysis of a site or specific project. A study on this scale would also allow for a wider variety of types of management measures to be implemented around the project(s). A decision to use such an approach would however have to be taken by a strategic management body rather than the applicant for a specific project. **The choice of scale is closely related to the governance choices.** For cumulative effects assessments that are on a larger scale than an individual project and that cover other projects, it is more logical for an organisation with jurisdiction over a similar scale to conduct the assessment, rather than the applicant.

One point that comes out of the analysis is the need that almost all the authors express[16], for **cumulative effects assessments to be coordinated by a dedicated agency or organisation on a regional level** or a scale covering the area of several projects that might potentially require an assessment of cumulative effects. The arguments behind this position relate to the availability and accessibility of data, the transparent and shared definition of metrics and value scales, and the objectivity of assessment, which is essential for it to be accepted by civil society.

From a planning perspective, working on a larger scale can help to choose which projects to develop and optimise the most effective ways to reduce or compensate for the effects, as well as to monitor effects. In return, monitoring will enable post-project phases to be better managed, where applicable, and will also **generate additional knowledge on cause-and-effect relationships, which are always required for any relevant assessment**. This type of organisation is the only body that could have the resources (finance, skills and time) and sufficient long-term motivation to implement **such a strategy, as a long-term, recursive approach**. Applicants for projects “covered” by this approach could then participate in the data acquisition process, using common data collection specifications in order to best capitalise and leverage the data and to develop further knowledge on cause-and-effect relationships. Applicants could also make a financial contribution to the overall assessment process.

In the literature, cumulative effects assessment is generally seen as planning-related, but as was emphasized at the start of this section, scientific articles on CEAs rarely focus on project-specific studies and often chiefly address methodology, which may lead to some bias in the analysis. However, the fact that project-specific assessments are often evaluated in the most severe terms also highlights the difficulty of satisfactorily performing project-specific CEAs.

II.2.4 Conclusions

Although cumulative effects assessments must be based on a scientific approach and scientific knowledge, many aspects are not strictly related to science, and these must be explicitly addressed in order to ensure that the assessment is relevant:

- Firstly, it is essential that **the terms cumulative effect or impact are defined, both for the projects/processes analysed and the spatial and temporal scales considered**. The definition is not necessarily self-evident and can vary according to the context. It must be **explicitly stated by stakeholders** before the actual cumulative effects assessment begins in any given context.
- Secondly, **the Valued Environmental Components** (VECs) considered to assess the significance of effects must be identified and **value scales and/or thresholds must be defined** to enable a **shared appraisal** of whether the cumulative effects are too substantial (or not). **Assessment metrics** must also be defined. Here again, the decisions are not only up to scientists. They must be made early enough in the assessment process, once the reference and initial conditions in the system have been characterised. **Characterisation of the reference condition and initial condition** is important. If this is done properly, it gives initial knowledge on the way the system in question functions, including the most sensitive environmental components, and sometimes helps identify the most significant stressors.
- **Monitoring over time** is essential once the project(s) have been completed. It helps check the validity of ex-ante assessment, increases **knowledge on cause-and-effect relationships**, and where applicable, can be used to adapt project-related management measures.

Science can provide insight to address these various points, but cannot, on its own, answer all these questions, which require decision-making and long-term resource allocation. Discussions between scientists, managers and cumulative effects assessment “practitioners” will therefore be required. Public engagement is also desirable, in order to legitimise any decisions. Whatever method(s) are used, **data availability, identification of system determinants and an understanding of cause-and-effect relationships are essential.** Alongside improving CEA methods and practice, further

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[16] This has never been disputed. Whenever the question of governance is addressed, the need for a regional organisation is always mentioned.

study and research is required into the cause-and-effect relationships for the many human impacts on natural systems and VECs, which requires both field research and rigorous monitoring programmes.

This section has presented the general concepts and main types of methods used in assessing the cumulative effects of human actions, without focusing solely on reservoirs. It has also attempted to highlight the elements required for successful CEA, regardless of the type of project considered. The rest of the report will focus on reservoirs. The concepts in the following sections follow on from those discussed above, but are more limited to a single theme (hydrology, sediment transport, physical chemistry, ecology of aquatic environments), with specific vocabulary. Further discussion on interactions between different types of effects can be found in the conclusion.

Chapter III SURVEY OF RESERVOIRS AND THEIR CHARACTERISTICS

One essential step in a successful cumulative effects assessment is to survey the reservoirs and their properties. This is a key aspect of any modelling that is done. The data that is required will depend on the type of modelling adopted. However, it may be necessary to have spatialized data on the number of reservoirs and their position within the catchment area and in relation to rivers, as well as data on their volume and water surface area (current and maximum), their supply area and management-related data (water supply and return method; abstraction volume and dynamics). Depending on the case, this data may need to be large-scale in mesh form or on a (sub)-catchment area scale. Research in the literature did not find any studies focusing specifically on analysing the distribution (or density) of reservoirs in a catchment area according to properties (e.g. land use, use of water, physiographic characteristics).

This data may be acquired through surveys, inventories performed by the management bodies, or may be based on **pre-existing data**, such as Bd Topo® in France. This database however is not reservoir-specific and it may be difficult to use it to identify the way a body of water is used. However, in other countries, there is often no legal obligation to declare small reservoirs and inventories are therefore often incomplete. Many surveys therefore use **aerial and satellite images** to count or locate reservoirs. Small reservoirs are nonetheless difficult to identify and most reservoir impact modelling studies have combined a range of methods to ensure as comprehensive a survey as possible of their study area.

Box 4: Benefits of remote detection techniques

With the exception of studies focusing chiefly on modelling, studies that discuss the use of remote detection in identifying and characterising bodies of water generally focus on larger bodies, which are sometimes isolated, in a wide range of bioclimatic contexts. Most studies on bodies of water are based on aerial or satellite images. The main differences between data sources are the **spectral resolution** of the images (how detailed the available information is), the **spatial resolution** of the images (the size of object that can be identified), the **footprint of each image** (the land area shown) and the **frequency of image acquisition**. Other studies use active remote detection (lidar or radar). In this case, data is artificially generated by the remote detection system itself, which reduces constraints in terms of acquisition conditions, because measurements can be taken in cloudy weather or at night-time (Figure 5). It is important for the image resolution to correlate with the nature of the objects studies. A higher resolution, for example, will help in identifying and demarcating small bodies of water.

The methods used for image processing can also vary. Some authors have sought to develop extremely reproducible methods, by using free source data and open-source software along with automated image processing routines. Indicators have also been developed to better identify bodies of water, based on the spectral properties of water.

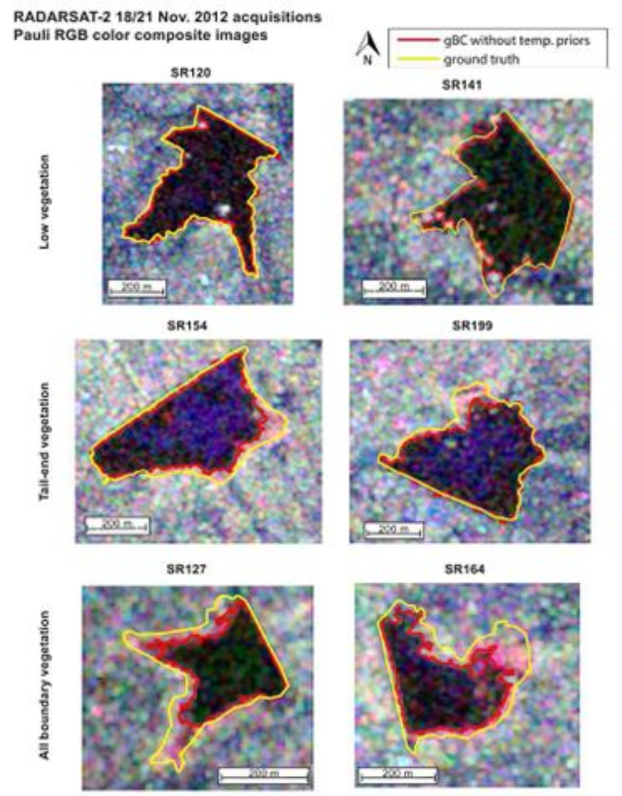

Figure 5: how to identify and demarcate bodies of water from a radar image (example) (Eilander *and al.,* 2014). Field reality (yellow line) and automatic demarcation from radar database information (red line).

As well as uses in determining the geometric characteristics of reservoirs, which is discussed later, remote detection can provide a range of information about various attributes of water bodies, such as turbidity and suspended load; nitrogen, phosphorous, inorganic or dissolved organic carbon concentrations; surface temperature; chlorophyll-a content; aquatic plant communities on the banks or in the body of water; presence of an algae or cyanobacteria bloom; methane emissions. The data used in such cases is mostly multispectral or even hyperspectral. The method involves determining empirical relationships between the imaging data and the *in situ* value of a given parameter. One major limitation of this method is that such relationships are often very difficult to transfer to dates or bodies of waters other than those where they were acquired. Semi-analytical methods are currently being developed, based on bio-optic models built on the inherent optical properties (light absorption and backscattering) and apparent optical properties (water luminance and reflectance). These methods often require more calibration data, but give robust results and subsequently reduce the need for field sampling to monitor the environmental quality of water bodies.

Sensor and data processing technology is moving forward rapidly (e.g. improved spatial and spectral resolution), creating greater potential for enhancing the assessment of reservoirs: detection, monitoring water area, estimating volumes, characterising water quality, monitoring habitats, etc. One point that requires care, however, is that the data of interest is not always available at the required resolution. It is also important to bear in mind that **it is complicated to choose which data and methods to use and then to implement them – this requires specific competencies**, which are often still mainly found in the academic world. Operational implementation of such techniques thus currently depends on the ability to develop partnerships with academia or to find service providers that are capable of using such methods. The development of platforms such as GEOSUD[17] and the fact that France has a renowned scientific community in the field of remote detection should help overcome most of these problems. The cost of data acquisition and processing can quickly become quite high and thought must be given to defining the study area, determining the exact needs and identifying which organisation should lead the study.

The **remote detection threshold for water bodies** is related to resolution. Surface areas as small as around one hundred m² may be detected. The use of images captured over a several-year period provides an understanding of the way water

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[17] http:// http://ids.equipex-geosud.fr/

bodies are formed. In arid or semi-arid areas, data should, wherever possible, be acquired at the end of the rainy season. Very few studies have sought to characterise the **position of reservoirs with respect to the river** (behind a dam on the river, on a stream diversion, on a slope).

Surface area is an important reservoir characteristic, in particular for calculating the evaporative flux, and is generally assumed to match the maximum reservoir area. However, changes in the water surface area over time can be taken into account, depending how frequently data is acquired. The greater the variation in water level, the more important this is.

Storage capacity, which is another important characteristic in simulating the impact of reservoirs, is a difficult parameter to estimate. Remote detection data can be used to determine this value by direct or indirect measurement. Direct measurement methods use photogrammetry based on aerial photographs, or are derived from a digital terrain model (DTM). The aim is to characterise the reservoir floor. Such methods are rarely used however, since the first requires a very onerous process and the second depends highly on the resolution of the DTMs. This leads to high levels of uncertainty, which can however be reduced if the volume is addressed on the scale of the catchment area as a whole. The development of lidar data means that relevant estimates can be made these days, and the resolution of available data is improving. These measurements are nonetheless distorted by the fact that the reservoirs have generally already been filled when data is acquired and what is actually measured is thus the water level in the reservoir. The date of data acquisition hence plays a crucial role for the quality of the estimate. Indirect measurement is more often used. This involves determining an empirical relationship (generally a power law) between the water body surface area (A) and its volume (V), based on a limited number of reservoirs. This relationship is then interpolated or extrapolated to other reservoirs. Table 3 illustrates the relationships used in a dozen studies. The parameters are variable from one region to another, particularly depending on the geomorphological context, but they remain generally constant within a given region. This highlights **the benefits of a specific data acquisition strategy for each area modelled**.

Table 3: Example of relationships between reservoir volume and surface area from various studies (Thompson, 2012). V = volume (m^3); A = area (m^2).

Relationship between Area (A) and Volume (V)	Calculation method	Study area
$V=0.0016.A^{1.56}$ $V=0.077.A^{1.3}$	Differences in the relationships are attributed to differences in relief	Two catchment areas in South Africa.
$V=0.187.A^{1.25}$	18 reservoirs of a volume up to 100 ML	Australia.
$V=0.0738.A^{1.25}$	Botswana. 15 small reservoirs measured out of 305	Botswana.
$V=0.2.A^{1.2004}$	Method not indicated	Australia.
$V=0.44.A^{1.4}$	Australia. 26 reservoirs of a volume between 2 and 39 ML	Australia.
$V=1.6\ A-108.6$ $V = 3.5\ A – 5742.5$	$A < 3{,}000m^2$, high irrigation demand $A > 3{,}000m^2$, high irrigation demand 100 reservoirs, mostly < 50 ML	Australia.
$V=0.17557.A^{1.2732}$	42 reservoirs measured	Australia.
$V = 16\ A$ $V = 20\ A$	Plain relief. $A < 50{,}000m^2$ Hilly relief. $A > 50{,}000m^2$	South Africa.
$V=2.A^{1.25}$ $V= 2.2\ A$ $V=0.215.A^{1.16}$ $V=2.8.A$	Low demand. $A < 15{,}000m^2$ Low demand. $A > 15{,}000m^2$ High demand. $A < 20{,}000m^2$ High demand. $A > 20{,}000m^2$	Australia.
$V = 0.145.A^{1.314}$	152 reservoirs of 0.4 to 420 ML	Australia.
$V = 0.002.A^{1.0713}$ $V = 2.10^{-7}.A^{1.92}$	Reservoirs in channels > 10 ML Reservoirs in flat areas > 10 ML Inventory database	New Zealand.

The catchment area that supplies a reservoir is an important characteristic in determining the inflows. This can be determined by using an inventory or through geomatics if there is a digital terrain model, but it does require reservoirs that are connected directly to the river to be distinguished from those that are not. The information obtained in this way is often limited to a small number of reservoirs, and this information needs to be extended to all reservoirs in the river basin. Some studies have developed linear or non-linear relationships between the reservoir surface area and the supply basin area. However, these relationships are again often specific to the catchment areas studied and cannot be applied to very different contexts.

The **reservoir management method** is also an important piece of input data for modelling. This means the way in which inflows and abstraction flows are managed and the regulation and return methods. Abstraction methods are addressed in Section IV.1.5 of the Hydrology Chapter. Filling and regulation methods are more rarely incorporated, partly because most studies represent hillslope reservoirs that are not on a river and are filled via a supply basin. These reservoirs cannot be disconnected from their supply basin and cannot return water to the river other than by overflowing. They cannot have a limited filling period or compensation water. Some studies take into account **water supply management, return to the river, or maintenance of a minimum flow rate. This type of data can only be obtained by a field survey**, or by working out the management methods based on current regulations. Early season reservoir water level is also an interesting variable, which can be determined by remote detection or, again, worked out based on usual practice within the river basin in question.

Chapter IV CUMULATIVE EFFECTS OF RESERVOIRS ON HYDROLOGY

This Chapter addresses the influence of reservoirs on hydrology and hydrogeology. The reservoirs discussed here have a volume of less than one million m^3. Large dam reservoirs have been extensively documented in scientific literature, and are different from those reservoirs covered by this study. Their positions and volume are well known, they are often multi-usage and their method of operation is relatively well characterised, which is often not the case for the many smaller reservoirs present in catchment areas. They are therefore not of significant interest for this chapter. The reservoirs studied in scientific literature represent fairly contrasting climatic and geological contexts and operating/management methods, that are quite different from the conditions in France. Arid, semi-arid or Mediterranean climate conditions feature heavily (Australia, North Africa, Southern Africa, Spain, USA, Brazil), along with dry tropical climates (India, Brazil) or oceanic climates (New Zealand). The geology varies, with permeable zones and very large groundwater reserves in India, where reservoirs are used to improve groundwater recharge and more impermeable zones. In the impermeable zones, reservoir water is mainly used for irrigation or livestock watering; a minority of them are used for flood prevention and sediment retention.

The exploratory phase of the assessment study showed that knowledge of hydrology on an individual reservoir scale was limited, leading to significant uncertainty in estimating the cumulative impact of reservoirs. This chapter first focuses on how to understand and estimate the terms of the water balance of reservoirs, then presents methods (observation and modelling) that can be used to analyse and quantify the cumulative effect of reservoirs, before detailing the main results from the use of these methods.

IV.1 LOCAL INFLUENCE OF A RESERVOIR: MAIN PROCESSES

The hydrological functioning of a reservoir can be influenced by a range of processes. These processes are often described through quantitative analysis using the water balance of the reservoir that estimates the flows involved in each process. The processes giving rise to inflows into the reservoir are distinguished from the processes giving rise to outflows (Figure 6). Inflows comprise the following: (i) runoff and streamflow into the reservoir; (ii) rainfall and other direct precipitation on the reservoir surface; (iii) any inflow from groundwater, if there is an upward flow; (iv) condensation inflow (i.e. negative evaporation). Outflows comprise the following: (i) infiltration losses if there is downward flow into the groundwater; (ii) evaporation losses; (iii) abstraction from the reservoir; (iv) outgoing streamflow from the reservoir.

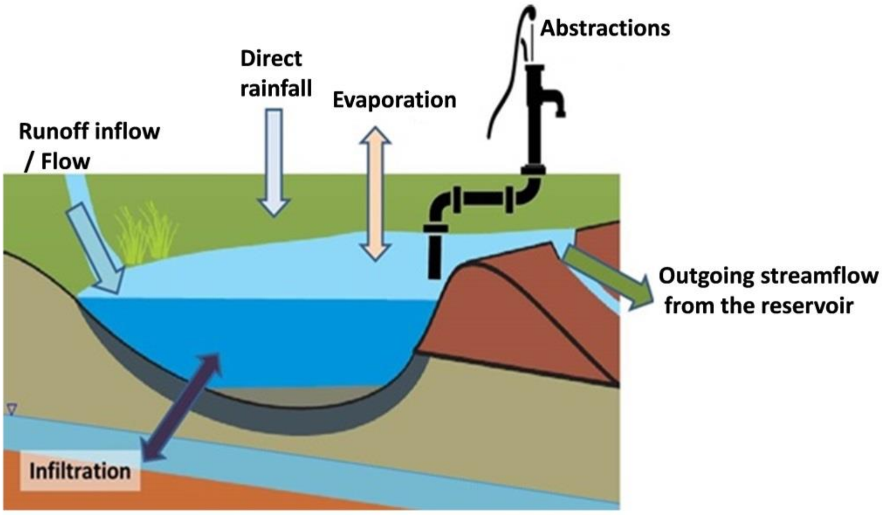

Figure 6: Reservoir water balance (schematic): inflow comes mainly from runoff and streamflow, direct rainfall, possibly some inflow from groundwater and condensation. Outflow is generally related to evaporation and infiltration losses, abstraction from the reservoir and outgoing streamflow.

Variation in reservoir volume is thus equal to the difference between inflow and outflow. The exploratory phase highlighted limited knowledge of these different terms, and a need for further explanation. If the reservoir is on a river, inflows are mainly from the incoming flow from the river upstream of the reservoir. Remaining inflows come from the reservoir's catchment area.

IV.1.1 Infiltration

It is difficult to quantify exchanges between the water body and the aquifer. A strict calculation would require precise knowledge of the hydraulic and topographical properties of the reservoir terrain and the water levels in the reservoir and underlying aquifer. Various methodologies, similar to those used in studying exchanges between a groundwater source and a river, can be used to generate approximations. Infiltration is usually studied and quantified for groundwater recharge reservoirs (these reservoirs are used principally for irrigation), and in this case, infiltration is facilitated as much as possible, unlike with most reservoirs in France. In such reservoirs, infiltration may be as high as 75% to 80% of water intercepted by the reservoir. For water storage reservoirs, the **median infiltration flow value is around 1-2 mm per day**. Reservoirs that log losses of 4-5 mm per day should be considered problematic, requiring solutions to be found.

IV.1.2 Evaporation

Evaporation losses often account for an important proportion of the water balance. Values of around 40% of inflow are often cited, which is a significant volume, in relation to the number of reservoirs in any given area. Measuring evaporative flux is difficult and uncertain, despite the use of complex techniques (scintillometry, eddy covariance*). Digital estimates can also be used, based on atmospheric variables, but this field remains a research subject. Moreover, evaporative flux depends both on climate-related features, environmental characteristics and reservoir characteristics (surface area, depth, configuration, outflow or otherwise). Relationships between pan evaporation (i.e. evaporation from Class A evaporation pans) and evaporation from reservoirs have been development in some catchment areas, based on reservoir characteristics and time of year. Nonetheless, they are specific to the catchment area for which they were developed. Studies agree that evaporation from a smaller reservoir is generally lower than pan evaporation measurements or evaporation from another type of environment, since the air above the reservoir tends to get saturated with humidity. This process is, however, less efficient than for larger lakes. The highest measured or estimated values are often **3 to 5 or 6 mm per day** or even up to 9 mm per day for periods that can be longer than 100 days. The overall evaporation loss can be 1300 to 1400 mm per year.

In some countries, techniques have been developed to reduce the evaporative flux: 1/ adding a film-generating product to the surface, 2/ adding pigment to alter the reservoir albedo, 3/ fully or partially covering over the reservoir, 4/ landscaping the banks to limit wind, 5/ optimising a network of reservoirs (by using reservoirs with the highest temperature first).

IV.1.3 Direct rainfall

This refers to the inflow of water from rain falling directly on the free surface of the reservoir. The direct rainfall flow is generally fairly low compared to the other terms in the water balance, except in areas where streamflow is low. Direct rainfall can be estimated based on the reservoir water surface area and the precipitation, as measured using conventional instruments such as a rain gauge or pluviometer.

IV.1.4 Incoming and outgoing streamflow

Incoming streamflow into a reservoir depends on its position in the catchment area and its connection with the river and also on river basin characteristics (pedology, geology, climate, land use). It is therefore difficult to make estimates without knowing the context. If the reservoir is connected to a river, inflow can easily be directly measured. Estimating the incoming streamflow into a hillslope reservoir is more difficult. Inflow can be modelled. Several methods and models can be used to estimate this inflow. The simplest is the model developed by the Soil Conservation Service in the USA, which considers that streamflow is proportional to the rainfall in the reservoir supply basin; the curve number depends on the shape, gradient, soil type and humidity of the basin.

Outgoing streamflow is generally easy to measure. Nevertheless, information on outflows from all reservoirs in a catchment area is rarely available. Inflow and outflow vary significantly with local climate and physiographical conditions, but also depend on the reservoir management method. If the outflow cannot be measured, it is simulated. In this case, the reservoir management method considered for estimating outflow is important. It should be highlighted that almost all the reservoirs studied are managed with “fill-and-spill” methods, meaning the only water return method is overspill, when the reservoir is full. The outgoing streamflow therefore results from the volume of water in the reservoir, the incoming streamflow, the infiltration and evaporative flux and any abstraction from the reservoir. With this management method, the instantaneous effect of the reservoir is binary: either i) the reservoir is partly empty and it reduces runoff and incoming streamflow by 100%, or ii) it is full to maximum capacity and the effect on runoff and streamflow is zero, since the reservoir releases all incoming volumes downstream. Other types of reservoirs with a minimum flow system, or “actively” managed are very little discussed in the literature.

Irrigation can have an effect on flows within the water cycle and reservoir inflow, for instance by increasing runoff from irrigated land areas into reservoirs. This aspect has rarely been addressed. Although irrigation does increase water concentration in the soil, one study of a catchment area in Alberta (Canada) showed no significant effect on runoff. On the other hand, in flood-irrigated rice-growing areas, these flows should be taken into account.

IV.1.5 Abstraction from the reservoir

In most studies, water is abstracted from reservoirs in order to irrigate crops or water animals. There is often significant uncertainty around these flows, concerning both their cumulative values and the temporal dynamics. Two broad types of method are used to quantify them.

One approach, which is used mainly in Australia, considers that annual abstraction accounts for a certain percentage of total reservoir capacity. The percentage value is obtained through surveys of reservoir owners or sometimes by remote detection and is very variable depending on usage (irrigation v. livestock watering) and region: from 35% in Western Australia to 83% in Victoria for irrigation and an average of 83% across Australia, with variations from 10% to 400%. Percentages appear more stable for livestock watering at around 50%. This abstraction is either assumed to be constant throughout the year, or is considered using a seasonal distribution, according to known uses.

The second approach involves characterising demand. Livestock watering needs are considered to be constant throughout the year (e.g. 35 litres per unit of tropical livestock per day in a study in Burkina Faso). At best, irrigation-related needs are based on the needs of the irrigated crops, but with no consideration of the potential difference between crop needs, farmers’ water demand (which includes both a yield objective and time- and equipment-related constraints) and the actual water use (which includes the effect of any official restrictions or equipment breakdowns).

Given the general lack of information availability (in the best-case scenario, information covers annual abstraction volume and/or irrigated area and crop type) and the lack of data on abstraction management rules, irrigation abstraction is taken as the crop needs, calculated on the basis of the crop coefficient Kc, which varies over time, and potential evapotranspiration (PET). This estimate does take account of climate conditions for the current year, including intra-annual variations.

It can thus be seen that this important term in the reservoir water balance, which may account for a significant percentage of outflow, particularly for fill-and-spill reservoirs, is poorly known - both in terms of cumulative amounts and temporal dynamics.

Abstraction strategies in situations where several reservoirs are available (hillslope reservoir v. communal reservoir), or where a reservoir is just one resource of many (ground water, river) are very rarely addressed in scientific literature.

IV.2 CUMULATIVE EFFECTS: DIFFERENT ASSESSMENT METHODS, CONVERGENT RESULTS

The cumulative effects of reservoirs on hydrology can chiefly be derived from observations or modelling. Although there are different methods for assessing the cumulative effects of reservoirs on hydrology in a catchment area, the primary difficulty in comparing results and highlighting the determining factors is the variety of indicators used to describe these effects and the range of different situations.

The effects of reservoirs on a hydrological regime can theoretically be assessed by analysing a range of characteristic flow rates. The effect on **annual flow rate** is most often reported. The reduction in annual flow rate is often as high as 20% to 30% (Figure 7). However, the impact of reservoirs on annual flow rates varies from one study to the next. It is impossible to establish cause-and-effect relationships between the reduced annual flow rate and simple factors such as reservoir density (number or volume), annual precipitation or annual flow rate. Significant reductions in flow have been quantified for a wide range of values for these factors.

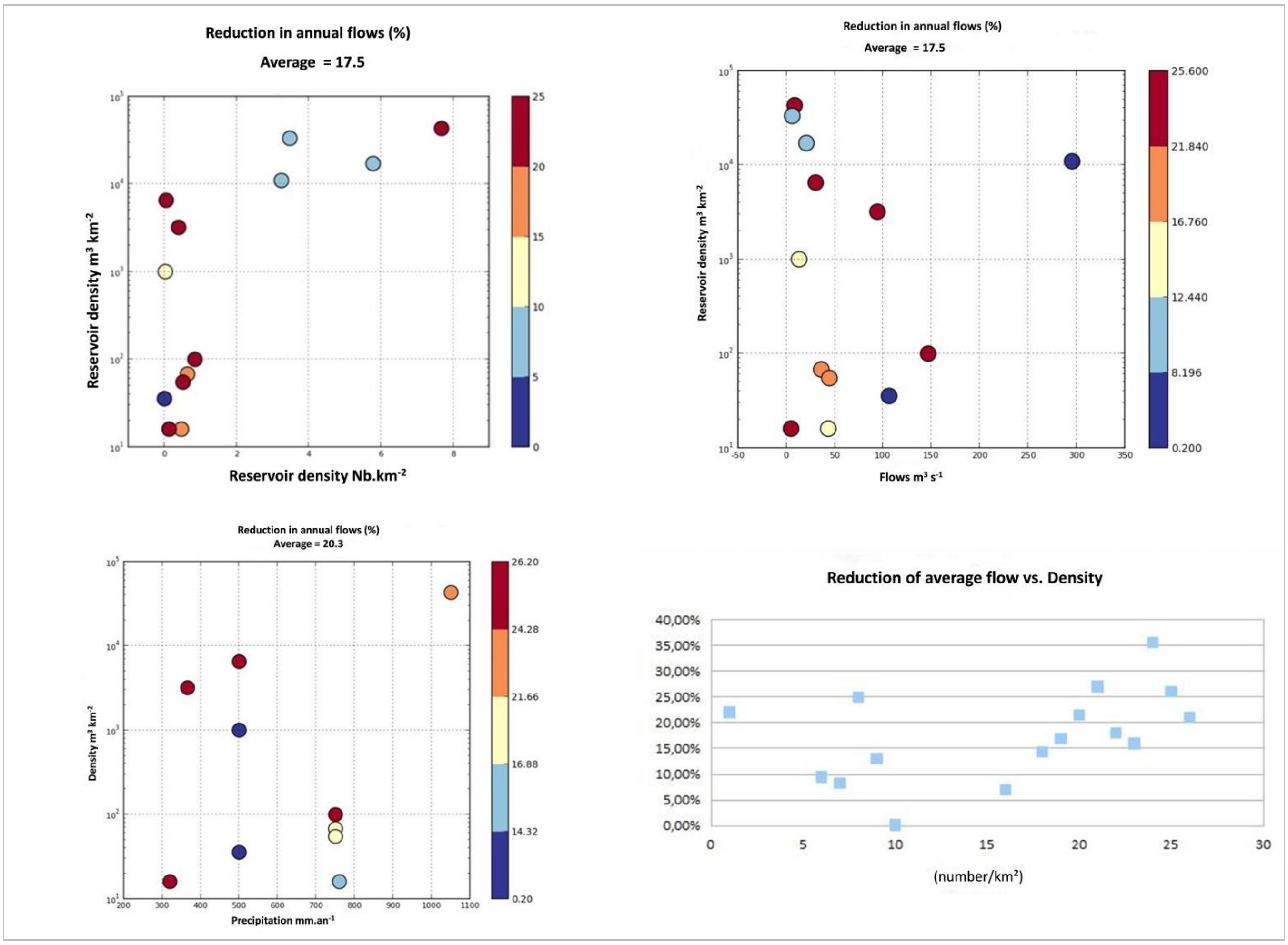

Figure 7 : Reduction in annual flow rate (symbol colour, percentage reduction) from the literature, according to a) density (number of reservoirs per km²) on the x-axis and area density (area in m³ per km²) (top left); b) flow rate in m³ per sec, reservoir density

(area in m^3 per km^2) (top right); c) precipitation (mm per year) and reservoir density (area in m^3 per km^2) (bottom left); and d) number of reservoirs (bottom right). The number of articles available varies according to the indicator studied.

This can be explained by other factors, such as equipment capacity and annual rainfall and flow rate values, that partially control the effect on annual flow rate. It is thus supposed that water abstraction (volume and distribution over time), annual hydrological variability and the spatial distribution of reservoirs are important factors. Moreover, the descriptors used (spatial density - volume or number of reservoirs) are spatial means across the whole catchment area. It could be assumed that, for the same density, the impact may be different, depending on whether the reservoirs are distributed homogeneously throughout the river basin or mainly upstream (or downstream), which influences their filling capacity. Finally, the effect on annual flow rate depends on relationships between abstraction distribution, emptying the reservoirs, and inflow distributions, feeding into the reservoirs. Reservoirs may be filled once in a hydrological year, or several times, and annual rainfall may not be a sufficient descriptor. However, one constant is that for any given reservoir network, the effects are higher in dryer years (i.e. years with low precipitation and/or flow rates lower than the inter-year averages), as shown in Figure 8a.

The effect of reservoirs is sometimes analysed through a volume-related indicator of the **ratio between annual river flow volume and total capacity (volume) of reservoirs.** This indicator shows that the effect of reservoirs is often greater than their storage capacity. Values of 2 to 3 m^3 per m^3 (Figure 8b), or even 3 to 4 m^3 have been estimated in Australia, the USA and Spain. This shows that the reservoirs are filled and undergo abstraction (voluntary for human uses or involuntary through infiltration and evaporation several times over the course of the year, meaning that the volume of water used may be greater than the storage capacity.

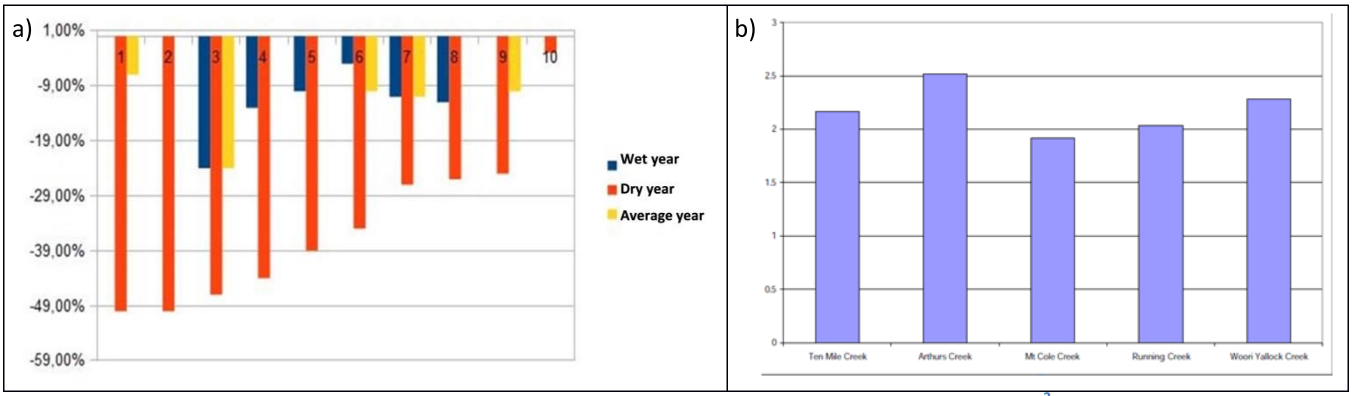

Figure 8: a) Effects of reservoirs on mean annual rates for dry, wet or average years. b) Effect of one m^3 of agricultural reservoirs on flow rates: values greater than 1 indicate that a reservoir capacity of 1m^3 leads to a flow rate reduction of more than 1m^3. Based on Neal. *and al.,* 2000.

The handful of studies on **high-water or low-water flow rates** show that there is a significant effect on these flows, with maximum reductions of 45% reported for high-water flow rates and 60% for low-water flow rates. The **filling capacity of reservoirs** is rarely addressed, even though it can be a problematic issue, particularly for headwaters reservoirs. **Inter-year variability in flow rate** is also affected by reservoirs, and changes in this variable can have environmental consequences. In general, reservoirs have a greater effect in reservoir filling phase because fill-and-spill reservoirs do not allow water to flow downstream. This period of transition between low water and high water is in general a period of moderate flow rate and the reservoir inflows are high compared to the streamflow volumes flowing into the rivers. Like the annual flow rate, it is difficult to generate generic information on the variation of typical flow rates caused by a reservoir network on a hydrological regime, or on cause-and-effect relationships between this variation and simple descriptors of the reservoir network, the climate and hydrology. Firstly, the corpus of studies and associated data is often too limited to develop any statistical analysis. Secondly, other factors, related in particular to reservoir water usage and management, could play a causal role.

This summary of the primary cumulative effects of reservoirs on hydrology is based on two main types of studies - **observation-based studies** (half a dozen studies) and **modelling studies** (around twenty). These two methods are presented below. The unequal use of the two methods is partly because it is difficult to obtain observations relating to a “reservoir-free” reference condition. Some studies take the reference condition from a similar but uninfluenced river basin; others deduce it from analysis of variation in basin characteristics and hydrology over time. Another method involves estimating the cumulative effect as the sum of the effects of each reservoir, which is found by comparing the observed flow rates upstream and downstream of the reservoirs at several locations in the basin over several years. This requires significant efforts in terms of observation equipment and resources over a long period of time.

IV.2.1 Observation-based methods

There are very few observation-based studies, which often date back to earlier than the 1980s. Documented research has mainly taken the form of theses or reports, some of which may have slipped through the net of bibliographic research. Various observation-based approaches are used to quantify the effects of reservoirs: 1) monitoring of flow rates upstream/downstream of reservoirs or a set of representative reservoirs in a river basin and their variation in volume, 2) monitoring of similar river basins but with different reservoir patterns, 3) multi-factor analysis of long flow rate histories, meteorological data and information on reservoir development.

The studies found address basins in North-western USA, North-eastern Brazil, China, New Zealand and South Africa - **a variety of climate and density scenarios.** The diverse range of situations and characteristic flow rates analysed in these studies again makes it difficult to compare results and deduce quantitative rules. Nevertheless, all the studies found a reduction in flow rate caused by reservoirs, sometimes more through evaporation or infiltration losses (Figure 9) than through water usages. These losses, in some cases, can lead to a 3 to 4 m^3 loss of flow volume per m^3 of reservoir capacity. In some catchment areas, infiltration losses from the reservoir can contribute to maintaining the flow in a downstream river that had previously been intermittent. Reduced flow rate varies over time, both within a single year and from year to year, but may often be particularly substantial for high-water and low-water flows. As previously mentioned, the reduction observed is more significant in dryer years. With the variety of situations and impact descriptors used in the different studies, it is difficult to make more general conclusions that can be applied to the French context.

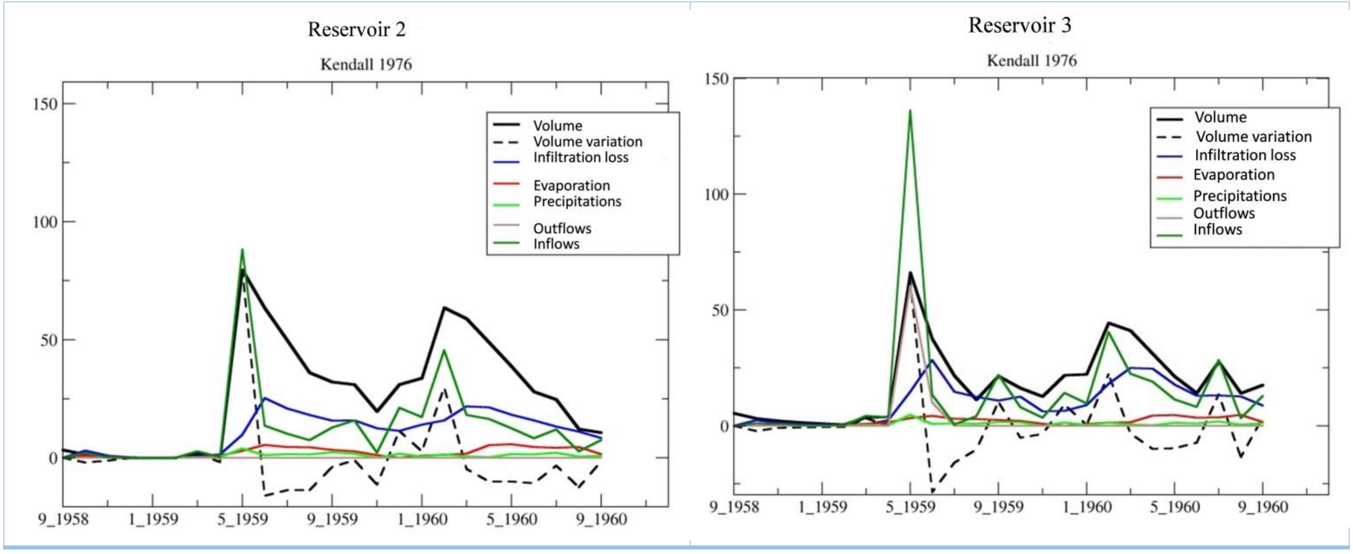

Figure 9: Monthly water balance of two reservoirs in Oklahoma that were monitored between September 1958 and September 1960. Black: reservoir volume, black dashes: variation in reservoir volume, dark green: inflow from supply basin, light green: precipitation on the reservoir, blue: infiltration loss, red: evaporation loss, grey: outflow. All volumes expressed in thousands of m^3 (Kennon, 1966).

IV.2.2 Modelling-based methods

Most research into the cumulative effects of reservoirs on hydro(geo)logy uses modelling to simulate streamflow at one or more points in the catchment area that contains reservoirs and the water balance of the catchments. The cumulative effect of the reservoir network is then estimated on the basis of hydrological indicators calculated from simulations run with and without the reservoirs in the model. Figure 10 illustrates this for a set of catchment areas in Australia.

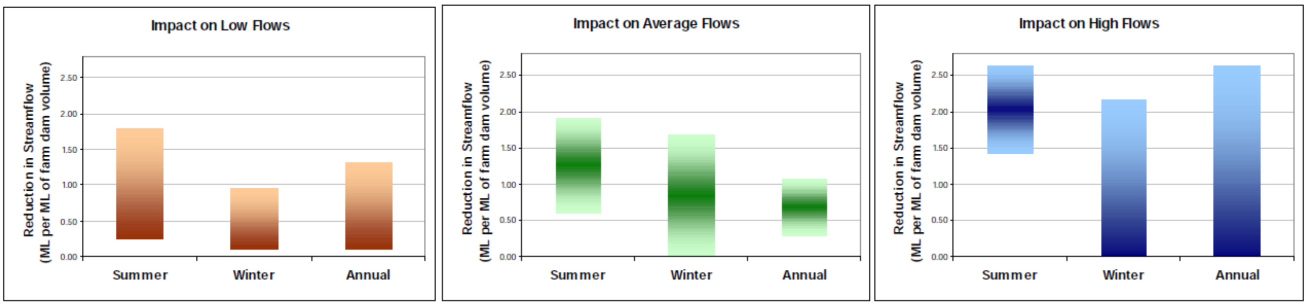

Figure 10: Impact of reservoir networks on summer, winter and annual average streamflow. The difference in streamflow is expressed as a ratio of the cumulative reservoir capacity. Impact on low flows (left). Impact on average flows (middle). Impact on high flows (right). The values come from a compilation of modelling-based estimates over a set of catchment areas in Victoria State, Australia (Nathan and Lowe, 2012).

Various approaches are used for modelling and they vary in terms of objectives, available data, but also because of the modelling practices of the people or organisations carrying out simulation. They can be categorised by **the way they describe the spatial distribution of the reservoirs and their characteristics** and the **way they conceptualise and calculate flows within the catchment area.**

IV.2.2.a Representations of reservoir networks that vary significantly from model to model...

The way in which the reservoir network in a catchment area is represented is one of the main differentiating factors between models found in scientific literature. Representations can be grouped into three broad categories: (i) spatially explicit representation, whereby each reservoir is taken into account individually, (ii) global representation, whereby the reservoir network is represented in the form of a single equivalent reservoir, (iii) statistical representation, which represents reservoirs in categories by capacity. There is a connection between the way the reservoirs are represented and the hydrological models. Some models use global representation because of a lack of sufficiently detailed information on their reservoirs, even though their structure would allow them to show the spatial distribution of the reservoirs. Other models are forced “by nature” to use global or statistical representation, as explained below.

The benefit of **spatially explicit representation of reservoirs** is that the cumulative effect of reservoirs is simulated at different tiers, in particular upstream and downstream of the hydrographic network. This enables the local impacts to be quantified. These could be expressed on a larger scale, when the only calculation is of the global impact at the catchment area outlet. This representation method is rarely used, because of a lack of sufficiently comprehensive data on reservoir network characteristics (number, location, geometric characteristics, abstraction, see Chapter III). In addition, it requires the hydrological model to be able to simulate incoming streamflow and/or runoff into each reservoir.

Global representation based on an equivalent reservoir is the most widely used method. A network of hillslope reservoirs in a given area is represented as a single equivalent reservoir, which is assigned the combined characteristics of all reservoirs in that area. Depending on the model and the available data, one equivalent reservoir may be used for the whole catchment area or one for each sub-basin or even for each mesh of the model. Some models use the streamflow into the equivalent reservoir that corresponds to the simulated value for the whole basin or sub-basin; others use a fraction of this flow. In the latter case, the fraction is assumed to match the fraction of the basin (or sub-basin) area drained by the reservoirs as a proportion of the total basin surface area. The main advantages of this representation is that it requires less data and the model is easier to use. The only effect that can be simulated, however, is the influence of the reservoir network on the outlet of the catchment area or sub-basin represented with the equivalent reservoir. Spatialized simulation of flow rates along different reaches of the hydrographic network is not therefore possible. This limitation, which can be resolved if there is a high-resolution division into sub-basins, is problematic if the aim, for example, is to estimate the influence of reservoirs on the quality of ecological habitat along different reaches. This representation also makes two major assumptions, whose validity is rarely observed: i) the influence of a reservoir is not related to its position in the (sub-)basin or its position with respect to the river, apart from its influence on various flow and water balance components, ii) water flows controlling reservoir drainage and filling are consistent throughout the (sub-)basin. Moreover, none of the connections between reservoirs in the (sub-)basin can be taken into account. Local climate, soil, lithology and land-use effects may be important factors in these flows.

Statistical representation considers a set of equivalent reservoirs, where each equivalent reservoir has the average characteristics of reservoirs in a given capacity category. Each reservoir's condition and hydrological functioning are simulated by the model, based on the reservoir inflows and outflows. This representation can be viewed as a variation of the equivalent global reservoir approach. The way each reservoir category functions depends on the model. The inflow may, for instance, depend only on the estimated drained area for this reservoir category, or it may also include some or all of the outflow from another smaller reservoir category that is considered to be located upstream and connected to the downstream category, as the case may be. This representation method therefore requires rules for the connections between reservoir categories and between the different categories and the outlet; the distribution of flows between reservoirs and the outlet also needs to be defined. In the applications, these rules appear to most often be based on **empirical expertise rather than topological analysis of the reservoirs,** the hydrographic network and streamflows within the basin studied. Figure 11 conceptualises the connections and distribution of flows in the Brazilian WASA model.

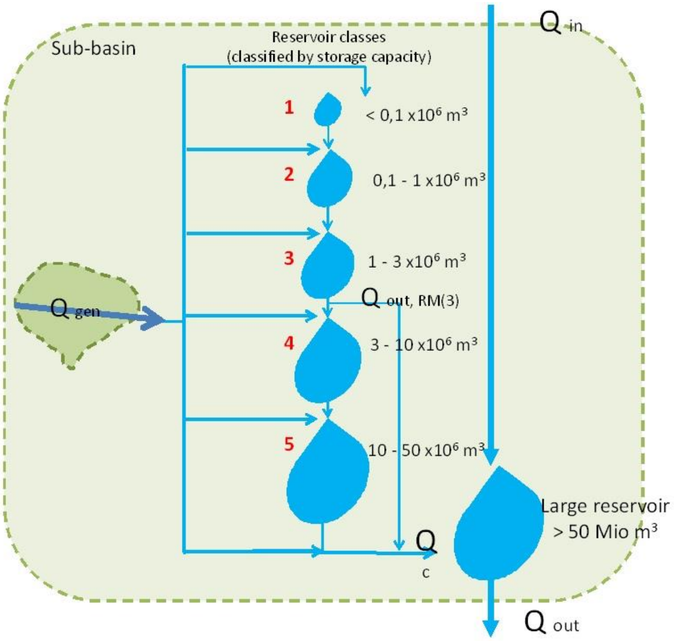

Figure 11: cascading diagram of reservoirs from WASA model. Each equivalent reservoir represents a reservoir capacity category. In this example, 5 categories are represented, from the lowest-capacity (<100,000m^3) to the highest-capacity category (10-50 million m^3). The sub-basin in question has a large reservoir (LR) at its outlet, whose hydrological functioning is explicitly simulated. Based on (Güntner *and al*,, 2004).

IV.2.2.b ...based on different conceptualisations of how the catchment area functions...

Modelling the cumulative effect of reservoirs on the way a catchment area functions **requires the hydrological balance of the reservoirs to be simulated** and **other water flows within the catchment to be estimated**, as shown in Figure 12.

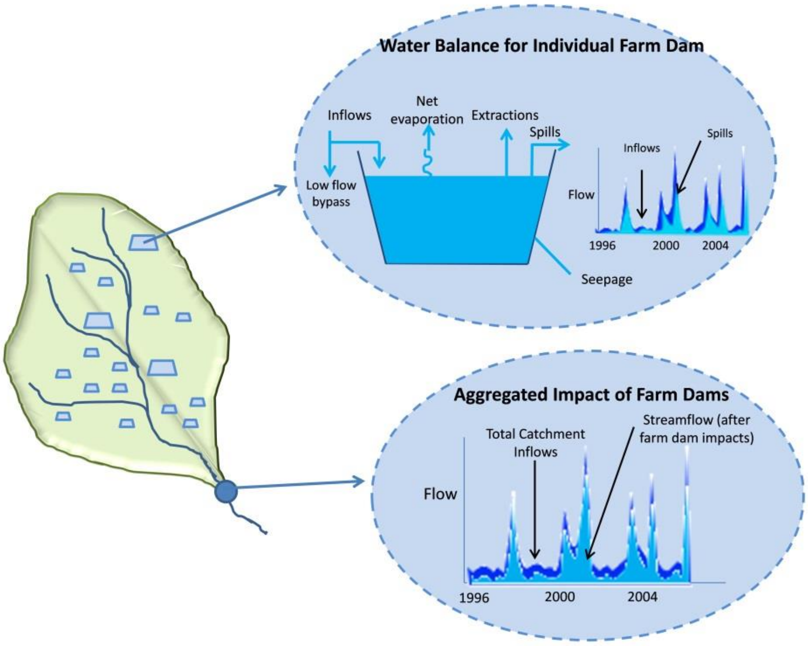

Figure 12: Conceptual representation of a hydrological model simulating the cumulative effect of reservoirs on flow rate at outlet (TEDI model, (Nathan and Lowe, 2012)).

With one exception, where the functioning of the reservoir (or equivalent reservoir, or reservoir category - depending on the representation strategy used) is determined in the model because information was available on reservoir management (abstraction and return flows), the **representation of how the reservoir functions** is based on its calculated water balance at a time interval that may range from one day to one month, depending on the model (Table 4). In the vast majority of cases, the models only represent fill-and-spill reservoirs, where water is returned downstream only in the event of overspill, which reconnects the catchment area they drain with the rest of the river basin. There are very few models that take into account any compensation water or "active" management of water returned to the river. The reservoirs(s) are most often assumed to be empty in the early season. Table 4 summaries the different types of spatial representation used for the reservoirs and hydrological processes simulated by the different models studied. Abstraction from the reservoir(s) is estimated in an often simplified or simplistic manner, usually for lack of information, as mentioned in Section 28.

Table 4: spatial representation method used for reservoirs and processes in the models studied

Model	Reservoir representation	Time interval, Dt	Process						
			Inflow	Downstream flow	Evaporation	Direct rainfall	Infiltration	Groundwater	Abstraction
TEDI	Statistical	Month/day	Observed flow	Fill-and-spill	x	x	x		x
CHEAT	Spatially explicit	Month	Observed flow	Fill-and-spill + compensation water					
WaterCAST	Statistical	Day	Hydrological model	Fill-and-spill	x	x			x
WASA	Statistical	Day	Semi-distributed hydrological model	Fill-and-spill	x		x		x
Deitch et al.	Spatially explicit	Day	Observed flow	Fill-and-spill					
PITMAN	Catchment area	Month	Global hydrological	Fill-and-spill	x				x

	equivalent		model						
SWAT	Sub-basin equivalent	Day	Semi-distributed hydrological model	Fill-and-spill	**x**	**x**		**x**	**x**
ISBA-Rapid	One equivalent per grid square (64 km²)	Hour	Distributed hydrological model	Fill-and-spill	**x**				**x**
ACRU	Catchment area equivalent	Day	Hydrological model	Compensation water / fill-and-spill +	**x**	**x**	**x**		**x**
POTYLDR	Catchment area equivalent	Day	Hydrological model	Regulation of return flows / fill-and-spill	**x**	?	**x**	**?**	**x**
GR4J*	Catchment area equivalent	Day	Global hydrological model	Return flow: inflow - variation in reservoir volume (predetermined value)					
HYDROMED	Catchment area equivalent	Day	Global hydrological model	Fill-and-spill	**x**	**x**			**x**

* The GR4J does not establish a water balance for the reservoirs. The observed variations in reservoir volume are input variables for the model.

There are two broad categories of methods for estimating water flows in the catchment area or at its outlet. **The first is based on measured flow rates at the catchment area outlet.** In this case, the model is used to estimate flow rates at key points in the hydrographic network, especially for instance at reservoir inlets. The flow rate is spatialized along the hydrographic network on the basis of rules that are often geometric and based on the upstream areas drained. This also assumes a specific constant flow rate along the hydrographic network. In comparison with flow simulation, the advantage of this approach is to avoid the need to collect certain data (e.g. soil, vegetation) that would be necessary for flow modelling and model calibration. Modelling can focus on studying the way the reservoirs function and their influence on basin hydrology. However, since this approach uses observed flow rates that have already been “disturbed”, the only way to determine the impact of reservoirs is to assume that the hydrological response is linear. This means that the observed-flows model, which includes a representation of the reservoirs in the basin, *de facto* simulates the impact from twice the reservoir volume, since the reservoir-related flow reduction is subtracted from the observed flow, which already includes the reservoirs. The difference between flow observations and simulated flows should therefore be halved and added to the observed flow to estimate the uninfluenced flow. Although this is a significant assumption, the benefit of this method is that it is fairly easy to use.

The second method is more conventional. It involves simulating **water flows and incorporating the reservoirs.** Hydrological modelling can be used to simulate water flows within the catchment area (runoff, streamflow, groundwater flow, evaporation, transpiration, etc.), in particular the flows that determine the hydrological functioning of reservoirs or that are reservoir-dependent. The primary benefit of hydrological modelling is to simulate the runoff and streamflow that supply reservoirs or that are altered by the presence of reservoirs. The same variety of spatial resolution exists here as for “conventional” catchment area modelling (Table 4) :

- **global models**, which consider the catchment area to be a single entity; most of these models have been developed to calculate flow at catchment area outlet. With one exception (GR4J), the approach taken with a global hydrological model is to first simulate streamflow and runoff in the catchment area, which then become input variables for the equivalent reservoir water balance model. The GR4J takes a different approach. Variations in observed volume in the reservoirs are known in the application, and are treated as input variables. The only way of representing the reservoirs in these models is as an equivalent reservoir. It should however be emphasized that any catchment area can be split into sub-basins and the global model can be applied to each sub-basin with an associated representation of transfers along the hydrographic network. In this case, the global model could almost be considered as a semi-distributed or distributed model, whereby the minimum basic grid size is the elementary sub-basin. (By essence, a global model only represents the outflow from a catchment area).
- **semi-distributed models**, which split the catchment area into large hydrological units that are assumed to be homogeneous in terms of hydrological functioning and properties. Depending on the model, the redistribution of water between these units may or may not be represented. In some studies, an equivalent reservoir was used and in others a statistical representation.
- **distributed models**, which represent catchment area properties and the connections between different elements in a spatially explicit manner. These models simulate hydrological flows at all points in the basin, or at least average

flow for each discrete element within the catchment. The overall area is most often split into discrete grid squares. For instance, ISBA-Rapid is a distributed model, where the area is split into 8 km by 8 km grid squares, and all reservoirs in a grid square are represented by an equivalent reservoir. These are the only models that allow for spatially explicit reservoir representation.

IV.2.2.c ... and difficult to assess

In general, use of a hydrological model to simulate flows in a catchment area requires an assessment phase, also known as validation. This consists of analysing the relevance of the model in simulating the way the studied catchment area works. It involves comparing one or more observed variables with the equivalent value as simulated by the model - most often outgoing flow. This phase can be used to understand the validity of the model's underlying assumptions, structure and the set of parameters used. For modelling catchment areas with reservoirs, depending on the model structure and available data, this validation phase may solely involve comparing observed flow and simulated flow at the basin or sub-basin outlet, or may look at water volume in the reservoirs, or internal variables, such as groundwater level at certain locations. In the special case of models that use the observed flow rate at the outlet as an input variable, the validation process is unclear. Whatever the case may be, assessment is fairly difficult. If simulated flow is compared with observed flow, the hydrological model is assessed along with the way the reservoirs are represented. Any bias in the estimated water balance may be exacerbated or diminished by the way the reservoirs are represented. Any relevant flow-related model assessment should be able to cover a fairly long period of time, ideally starting before the reservoirs were developed. However this type of assessment is hindered by a lack of data. Multicriteria assessment would theoretically be more reliable, for instance looking at flow rates at different points and the reservoir volume, but would again require data that is often difficult to access.

Model validation could be supplemented by sensitivity analysis, in order to identify which parameters or input variables have the greatest influence on simulation results. **The uncertainties around assumptions relating to reservoir position and functioning**, which stem from the choice of using an equivalent reservoir or statistical distribution to represent the reservoirs, **are only rarely analysed.** This is probably because the exercise is so difficult. It would require that different simulations from a single model could be compared, looking at different spatial distributions of the reservoirs - provided that there is realistic data on these distributions. This process is rarely used and the rare cases identified show that the sensitivity to parameters differs depending on the characteristic flow simulated (average flow, peak flow, low-water flow) and depending on the hydrological regime at work in the catchment area.

IV.3 CONCLUSION : CUMULATIVE EFFECTS OF RESERVOIRS ON HYDROLOGY

The impact of reservoir networks on hydrology has been demonstrated and quantified in all the observation- or modelling-based studies. Effects include a reduction in average flow, low-water and high-water flows and a decrease in the annual flow variability. Effects have also been reported on groundwater reserves and wetlands, with such impacts extending all the way to estuaries and the sea.

Nevertheless, the intensity of the effects is fairly variable, even within a single river basin. It depends on inter-year variation in climate conditions - flows are always reduced more in dry years than in wet years. There is also variation from one basin to another. Variability between basins, even in similar climatic and geological contexts, can be explained by differences in the number of reservoirs, their location and/or the way they are used.

As far as we are aware, no study has sought to analyse the relevance of simple indicators, in particular reservoir density, in order to assess the impact of reservoirs. Most studies focus on one specific catchment area, and do not aim to **correlate impacts with indicators.** There is no trace of an indicator that has been developed, such as a ratio of effective rainfall to reservoir volume. A broad analysis of the case studies examined suggests that reservoir density alone is not a sufficient criterion for quantifying the hydrological impact, but the question has not really been resolved given the small number of case studies available.

The methods used to identify and quantify the cumulative effect of reservoirs on hydrology are rarely observation-based (half a dozen studies) and more frequently modelling-based (around twenty). Modelling is theoretically a more affordable method, but faces two challenges: i) how to represent all reservoirs in the catchment area with their individual physical characteristics (location, area, volume), usage and management methods, ii) how to simulate the way each reservoir works (and potentially any interactions between them), in relation with the way the catchment area as a whole functions.

It is difficult to access comprehensive reservoir data (location, properties, uses) (see Chapter 3) and the most common strategy is thus to adapt the model to the available data. Most models thus represent all reservoirs by volume categories, with no individual details of spatial distribution. The uncertainty associated with this spatial simplification seems low compared with other sources of uncertainty, but this undoubtedly depends on local contexts. One of the main sources of uncertainty in modelling is the estimated reservoir water balance, because there is limited knowledge of the way the reservoir water is used (i.e. volume and time period of abstraction), the reservoir filling capacity (which depends on the way the associated sub-basin functions) and any evaporation losses from the reservoir (sometimes significant, depending on the region).

The literature review, focusing on observation- and modelling-based estimates of the various terms of the water balance, shows that it is difficult to estimate these flows. Nonetheless some methodological recommendations can be made.

In these different studies, we saw that reservoir management methods involving compensation water or specific filling periods were only rarely taken into account, despite these elements appearing to be important points in the exploratory phase of the assessment study. Likewise, relationships between crop systems, irrigation practices and reservoir functioning that could be used to enable fine-grained, robust and non-context-dependent modelling were not significantly analysed. However, because irrigation keeps soil damper, it may promote runoff that contributes to the flow rates in irrigated sub-basins. The relative position of different crop systems (with greater or lesser irrigation at different periods) can have an effect on flow intensity. In addition, indirect effects of reservoirs, for instance on land use and agricultural practices, are generally not taken into account in the studies. It is however certain that changes in land use influence catchment area hydrology. Irrigation generally leads to an intensification and/or diversification of crop-growing practices. Changes in land use therefore has an undoubted effect on reservoir filling and draining, which in turn will impact catchment area hydrology after the creation of reservoirs.

From a scientific perspective, the **key obstacles** to progress on assessing the cumulative impact of reservoirs on hydrology chiefly concern access to data on reservoirs and their uses. Some degree of regionalisation is possible, both for reservoir characteristics, reservoir distribution within basins, reservoir uses and their influence on the hydrological regime. However, these parameters are context-dependent and data collection would thus require observation and/or modelling across a range of catchment areas with reservoirs. This strategy could generate a reservoir classification, which could help determine which modelling type is appropriate for each case, particularly in terms of reservoir spatialization. **Modelling-based studies** have the classic limitations of hydrological modelling, made worse by a lack of knowledge on evaporation or infiltration water loss. **Observation-based studies** have to be run over long periods and must distinguish the effects of natural variability from human effects. The inclusion of indirect effects, especially changes in land use, will require a relatively long-term perspective, which again raises the issue of access to the appropriate data.

Because of the wide variety of storage capacities and their overall volume on a worldwide scale, the effect of small reservoirs is comparable to that of large dams and reservoirs. In addition, these reservoirs have a life cycle of several decades in general. It is therefore important to include the impact of these reservoirs on hydrology, again over a long period of time. In regions where climate-change predictions forecast increased drought, the impact of existing reservoirs on hydrology (even without any new reservoir developments) should be expected to increase.

Chapter V CUMULATIVE EFFECTS OF RESERVOIRS ON RIVER SEDIMENT TRANSPORT AND HYDROMORPHOLOGY

The scientific literature generally covers the effect of reservoirs on river sediment transport and hydromorphology for large, usually individual, structures on major rivers. There are very few references that deal with hillside structures, or the cumulative impact of structures. This chapter is therefore based on knowledge for larger reservoirs than those considered under this assessment, and seeks as far as possible to identify the knowledge, methods and tools that can be transferred to this study. While the processes involved are basically the same, orders of magnitude and the hierarchy of dominant processes vary.

This chapter first presents the influence of a single reservoir on sediment transport, the effects on the downstream river, and the tools and concepts available for analysing them. These need to be covered before moving on to a set of reservoirs, which have sustained less interest in the scientific literature.

V.1 EFFECT OF A RESERVOIR ON RIVER SEDIMENT AND MORPHOLOGY

The effect of a reservoir on river sediment and morphology is a result of the reservoir's influence on two variables that control these processes: **the hydrological characteristics of flows,** and **sediment concentrations and flows.** Once these effects have been considered, it is possible to examine their influence on **hydrographic network morphological alteration*** variables downstream of the reservoir. The influence of a reservoir on the hydrological regime was covered in the previous chapter. In general, it reduces flow volumes and flood peaks, in a way that varies depending on its own characteristics, those of the catchment area which supports it, and the uses of the water it stores.

V.1.1 A reservoir traps sediment…

One of the primary effects of a reservoir is sediment trapping, through a reduction in flow and transport capacity. This effect can be measured directly by time-dependent bathymetry, or analysis of sediment cores. However, this data is known to be difficult to analyse, and debatable, particularly due to the significant spatial and temporal heterogeneity of deposits within reservoirs. It can also be estimated via digital modelling, the use of sedimentation indices, or ratios based on the capacity of reservoirs and the catchment area or estimated inflow. These indices have been developed for large reservoirs, and are considered valid for the medium and long term. However, strong seasonal and annual variability in trapping efficiency can sometimes be observed, depending on the occurrence of extreme events, and the characteristics of ground cover (vegetation) or the reservoir.

The total volume of sediment deposited in a reservoir depends on gross erosion of the upstream catchment, the proportion of sediment delivered to the reservoir, the sedimentation characteristics of the sediment within the reservoir and the internal production of biogenous sediment in some reservoirs through the settling of particulate residues from primary production. In most cases, upper catchment areas provide over 75% of the bedload* of a river. Cattle accessing banks or wave action can, however, erode the banks and contribute significantly to sediment flows going into the reservoir. **The production of sediment** and transport from the source area to the deposit point depend on a number of variables, including precipitation, geological, topographical and land use characteristics. Most sediment transport in a catchment area occurs during the heaviest periods of rainfall. Agricultural basins generally produce more sediment than wooded basins, and for cultivated land, vegetation-free surfaces or land with low-cover crops can have an export rate (production of sediment per surface unit) that is 10 to 20 times higher than land with permanent cover. Bank erosion is likely to provide a significant source of sediment even in basins with high vegetation cover. Furthermore, small catchment areas generally have a higher export rate than larger basins, where the "internal" deposition rate is higher.

Trapping of sediment in the reservoir depends on its particle size, the size of the reservoir, and flow velocities within it. A distinction can be drawn between **the bedload**, or coarse sediment, for which the trapping rate is nearly 100%, and **the suspended load,** or fine sediment, for which the trapping rate is more variable. There is no absolute diameter threshold between these two fractions, since the difference between the two mechanisms also depends on the hydraulic energy (velocity, turbulence, etc.). To give a sense of scale, coarse sediment corresponds to particle size fractions from medium-sized sand (>500 µm) to blocks. The export or sedimentation rates in the literature cover all types of sediment, and virtually never differentiate between coarse or fine sediment, although, from an ecological perspective, coarse particle-size categories are essential for aquatic biocenoses and the maintenance of biological communities. Conversely, the fraction considered geochemically active is smaller than 60 or 50 µm, according to studies. It may therefore be considered that, if there is no equipment that makes them transparent for sediment transport (diversion, sediment ramp), large structures trap 50% to 100% of the inflowing sediment load, and therefore partially or completely disconnect the upstream and downstream parts of the catchment area as far as sediment transport is concerned. Some studies that focus on smaller structures give equivalent figures (60% to 100%). Others give lower efficiencies (35% to 60%) for reservoirs with a low dam (2 to 4 m). For some of these small structures, the deposition rate is so high, that they can fill up in just a few decades, and become transparent for sediment transport.

Depending on use of the reservoirs and the management method adopted, some of the sediment trapped can be deliberately released through draining, flushing or dredging.

V.1.2 …and modifies the morphology of the downstream river in a complex way.

By modifying both liquid and solid flows downstream, a reservoir can alter the morphological functions of downstream reaches. In order for this alteration to be significant: (1) the changes in flows must affect bankfull discharge[18] and particle movement flows, the only flow rates considered hereon in this chapter, (2) reservoirs must block the bedload (i.e. sediment of an equivalent size to that which makes up the downstream bed) and, (3) the downstream reaches must have an adjustment capacity.

Morphological changes to rivers can be analysed by time-dependent analyses of river form (width, fluvial style) using aerial photographs, combining *in situ* data (repeated topographical measurements) and sediment transport models, or through the use of conceptual models of potential alterations. Study of the morphological impact of dams has particularly focused on large structures, and primarily on the river channel. More recently, alluvial plains have been taken into account, although their development is also influenced by structures.

Generally speaking, for a reach of river, if the quantities of sediment - which make up the bedload - going in and out are identical, the reach is considered to be in a sediment equilibrium state. If the quantities of sediment going in to the reach are greater than the quantities going out, the sediment balance is positive, which leads to accumulation of material in the bed and aggradation. If quantities going in are lower than quantities going out, the sediment balance is negative (sediment is decreasing). The main consequence of a negative balance is incision* of the river bed. Figure 13 summarises one of the first conceptual models, which presents the various altered states of the channel resulting from various combinations of liquid and sediment flows:

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[18] The bankfull discharge is the flow rate high enough to cause morphological alterations in the river bed. To give a sense of scale, these flow rates generally occur every 1.5 to 2 years.

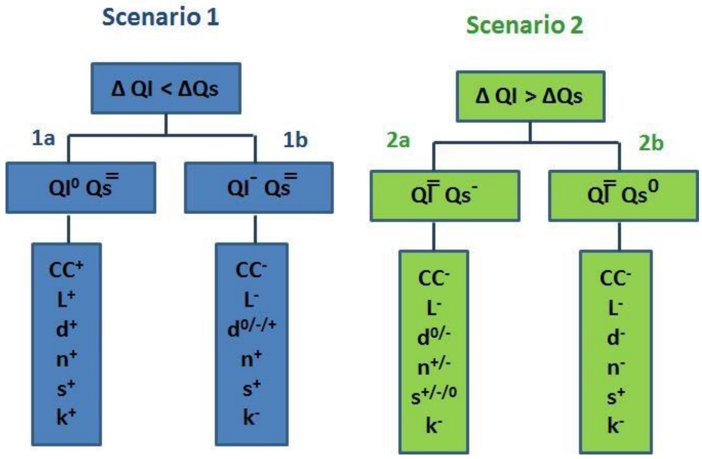

Figure 13: Type of channel alteration downstream of a dam in response to relative changes in discharge (Ql) and sediment inflow (Qs), where fluvial metamorphosis is dominated in scenario 1 by a reduction in sediment load, and in scenario 2, by a reduction in flow rates. Extreme conditions are represented in cases 1a and 2b, and the arrangement (1a, 1b, 2a, 2b) represents a hypothetical downstream sequence of channel changes below a dam. Note, however, that the absolute magnitude of channel changes will decline downstream, as the impact of the dam on flows and sediment loads decreases. The superscripts indicate the magnitude of change: 0 no significant change, + increase, - decrease and = major decrease. Morphological variables are: CC-channel capacity (i.e. the dimension of the wet section), L-width, d-depth, n-roughness, s-gradient and k-transport capacity (according to Petts and Gurnell, 2005, based on Schumm, 1969).

- **Scenario 1** characterises a river showing a strong decrease in sediment load and/or where the dam has little impact on flood flows. In this case, vegetation establishment is slow, and growth minimal. In extreme cases **(Scenario 1a),** and typically within sand-bed channels, clear-water released by dams leads to channel incision. However, in most cases, structures also impact flood magnitudes **(Scenario 1b).** Therefore, especially within meandering rivers with coarse sediment loads, the river experiences an increased gradient following bed incision, but lateral sedimentation contributes to the construction of a new floodplain at a lower elevation than the former one, thereby reducing the channel width.
- **Scenario 2** illustrates the impacts of dams on rivers with limited sediment load variation, but where flow regulation is extreme. In this case, channel alteration is characterised by a reduction of channel width and transport capacity.

Alterations affect both the vertical and lateral developments of river beds. Depending on the case, **vertical mobility** will lead to bed incision and gradual river bed armouring (increase of the median size of particles making up the river bed) or inversely to aggradation* when the modified flow rates stay below sediment flowing in from the river upstream, lateral erosion and tributaries. The incision process could occur when the ratio between the bankfull discharges before and after development/regulation exceeds 0.9, and the aggradation process when it is below 0.75. **Lateral mobility** modifies sinuosity rates (for meandering rivers) and reduces the variability of widths or horizontal movement (Figure 14). Reduction in channel width* often includes increase in vegetation, which contributes in return to stabilising the bed.

Figure 14: Changes to the Durance bed between 1958 and 1998, associated with sediment extraction and the construction of the Serre Ponçon dam. (Based on Chapuis and Collomb, 2012)[19].

The complex interactions between the various processes involved, together with the diversity of catchment areas, make it difficult to establish a single model for the morphological response of rivers to regulation. In addition to the relationship between sediment and liquid flows and their variations, a number of factors can influence the morphological changes to a river: the nature of alluvial sediment, the location of sediment source areas, whether or not there is vegetation, the geology of the catchment area, the fluvial style (straight-line, meandering, braided, anastomosed), the geometry of the channel, the functioning of tributaries. **The particle size of the bed** plays a crucial role in the nature of changes. Sandy reaches tend to respond quickly to disruptions by quickly changing the elevation of the channel bed, with width alteration coming later, while the latter is the most significant variable for reaches with a coarse sediment load. **Vegetation** plays an active role in modifying channels, a role controlled by vegetation characteristics (speed of growth, resistance to removal, dispersal capacity, etc.) and hydromorphological dynamics (flood regime, fluvial power, etc.) Depending on the case, rapid development of vegetation will influence sedimentation and erosion as the bed changes over the period of a decade, while slow development (over roughly a hundred years or more) will only have a moderate influence, such that changes to the channel will remain dominated by geomorphological processes. **Tributaries** can also influence the alteration of channels if they are in the area affected by it, depending on their own contribution in terms of liquid and sediment flows.

An important aspect of the morphological alteration of a channel is its complex and variable response in both time and space, and the fact that its magnitude depends on a number of factors. The system evolves through a relaxation phase of varying length, consisting of a series of transitional states corresponding to a progressive change in the morphology of the river in response to changes in flows and the sediment load.

From the perspective of the **temporal scale**, changes occur more rapidly if flows increase (a few years) rather than decrease (decades or centuries). This time scale is also influenced by a change in the frequency of bankfull discharges. Sandy rivers also demonstrate quicker alteration than other rivers. Finally, channel width generally decreases faster than it expands, and change in style or gradient is even slower, as summarised in Figure 15.

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[19] 2012 Chapuis M., Collomb D. – *La cicatrisation des rivières méditerranéennes françaises après les grandes perturbations de la deuxième moitié du XXe siècle*: *réponses des systèmes fluviaux et stratégies de gestion*. *Exemples de la Durance, du Var, de la Cèze* (Healing of French Mediterranean rivers after the great disturbances of the second half of the 20th century: fluvial systems responses and management strategies. A case study of the Durance River, the Var River and the Cèze River) *Revue Méditerranée* (AERES list of 13/02/2013), vol. 118, pp. 65–74,

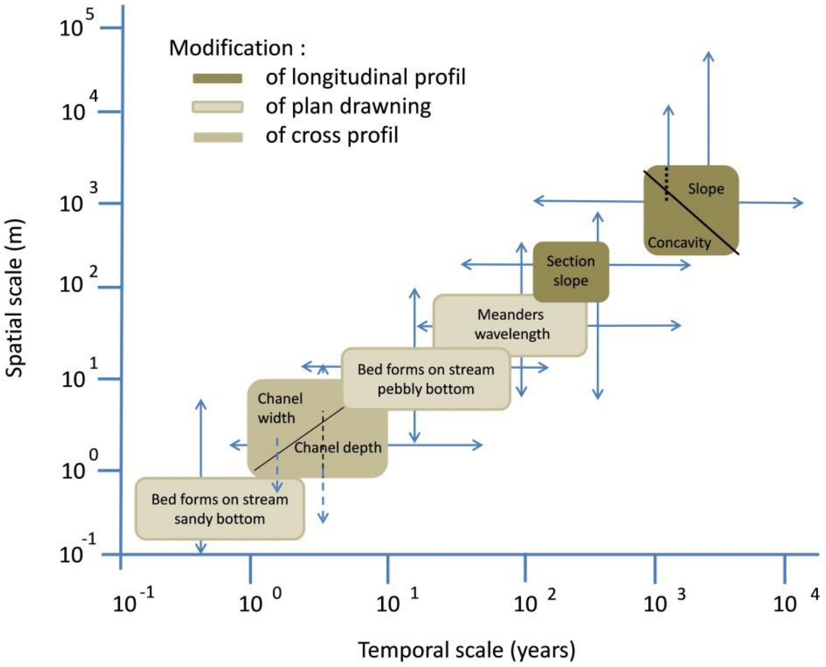

Figure 15: Spatial and temporal scales for the alteration of fluvial forms (based on Knighton, 1984).

With regard to **space scale**, the distance after which the influence of the dam reduces seems to be of the order of 50km to 120km for the large structures covered in the literature, with a general increase in alteration of the order of 0 to 2 km/year, reaching several tens of km/year in a few rare cases. The degree of alteration varies depending on a number of factors other than distance from the structure: bed particle sizes (armouring in place or not), whether or not there is cohesive material or vegetation in the channel, erosion of the banks (whether or not sufficient sediment is introduced to counteract the deficit), flow management.

The literature pays very little attention to small structures: the phenomena observed are similar to those cited above, but there is too little data to offer orders of magnitude according to situations.

V.2 CUMULATIVE EFFECTS OF RESERVOIRS ON RIVER SEDIMENT TRANSPORT AND HYDROMORPHOLOGY

There is very little literature that specifically covers these aspects (around ten references) and it basically covers large dams in series along large rivers, or networks of small hillslope reservoirs.

V.2.1 Cumulative effects on sediment trapping

With reference to the definition and concepts presented in II.1.1, it can be said that the cumulative effects on sediment trapping are mainly homotypic (virtually all sediment is trapped) and that depending on the relative position of other reservoirs, the process can be either additive (reservoirs on various tributaries) or infra-additive (reservoirs in series: the upstream reservoir traps some of the sediment that would have been trapped in the downstream reservoir). However, these effects are both direct and indirect (a reservoir can lead to increased erosion downstream, producing sediment that can then be trapped in another reservoir). Modification of large-scale sediment flows is evaluated based on estimations of the volumes trapped produced using time-dependent bathymetry measurements in some basins, or using distributed models of erosion. A common approach involves measuring or estimating (using simple conceptual models, as seen in V.1.1) trapping in some reservoirs, and transferring these results to other reservoirs. Some models include sediment trapping by dams located upstream, and the reduction of sediment trapping when reservoirs are being filled. The WATEM/SEDEM model, a raster distributed model, basically consists of three main components: (1) assessment of land loss, (2) assessment of sediment transport capacity, and (3) routing of sediment. It is the only one to have been used for assessing the cumulative effect of small hillslope reservoirs, and now seems one of the best fitted to this purpose. The other models covered have been applied to very large basins (such as the Three Gorges Dam or the Yellow River). However, this model needs to be supplemented by the representation of other processes, such as bank erosion and the sediment deposits in floodplains.

Observations and models produced show that overall, agricultural land use leads to a strong increase of hillside erosion (e.g. increase of 370% for an Australian basin between the pre-European period and the present day), which may be significantly counter-balanced by the presence of reservoirs (2.5 times for the previous example), especially for the coarse sediment fraction. These temporal dynamics therefore raises the question of the definition of the baseline state. Reservoirs tend to silt up significantly, sometimes quickly, in erosive contexts, which is not always anticipated when they are built. For example, in the United States, the number of reservoirs is estimated at between 2.6 and 8-9 million (depending on inventory methods), and it is estimated that 21% of the country's total area, representing 25% of all groundwater and runlet erosion, is drained by reservoirs which are fully sedimented. This assessment makes small reservoirs a significant sediment sink. Another study combining simulations and observations in Southern Spain shows that changes in land use can lead to significant changes in sediment inflow, and that reservoirs trap over 77% of sediment, and that most of them are silted up, with 81% showing signs of downstream erosion. Once again in Spain, total sediment transport in the lower Ebro valley (including 40% of bedload) now only represents 3% of its value at the start of the 20th century. 90% of the fine sediment and 100% of coarse sediment is trapped in two reservoirs, and the sediment that is currently being transported only comes from bed incision and bank erosion.

V.2.2 Cumulative effects on river morphological changes

Here again, analysis of changes is based on observing effects using similar methods to those cited in V.1.2 and applied on a larger scale, or on modelling. There are very few predictive modelling approaches for morphological changes downstream of a hydrographic network affected by multiple reservoirs. While there are many conceptual models for "predicting" the evolution of a river bed downstream of a reservoir depending on changes in control factors, it seems that, at the moment, there is no simple solution for assessing the specific effect of reservoirs as opposed to other control factors, or assessing the effect of reservoirs located outside the hydrographic network. Here we are dealing with indirect and varied effects, and implementation of models like this faces the following difficulties: (i) estimating sediment production from hillsides that then transit as bedload, (ii) taking into account any deviations in predicted trajectories, or integrating specific expert knowledge or local constraints, (iii) taking into account the fact that the system was not necessarily in morphological equilibrium before disruption, (iv) taking into account system response times.

The effects observed in the few studies available for analysis suggest a decrease in the width of the active channel and migration of river channels, which can include development of surrounding vegetation with a form and structure* that differs from that of the pre-existing vegetation, in some cases. Given the lack of data available, it may be worthwhile considering the analogy between these systems of catchment areas fitted with reservoirs and basins of natural mountain lakes: the spatial distributions of sediment sizes and the hydromorphological alteration of channels within a hydrographic network are well explained here by the location of sources (hillsides and tributaries) and sediment sources (lakes) upstream, which thereby become important local controls on hydrographic networks in mountains. The conceptual model of hydromorphological changes that occur downstream in a catchment area with and without a lake presented in Figure 16 could therefore be adapted to the context of manmade reservoirs, and used to assess their cumulative impact on hydromorphology.

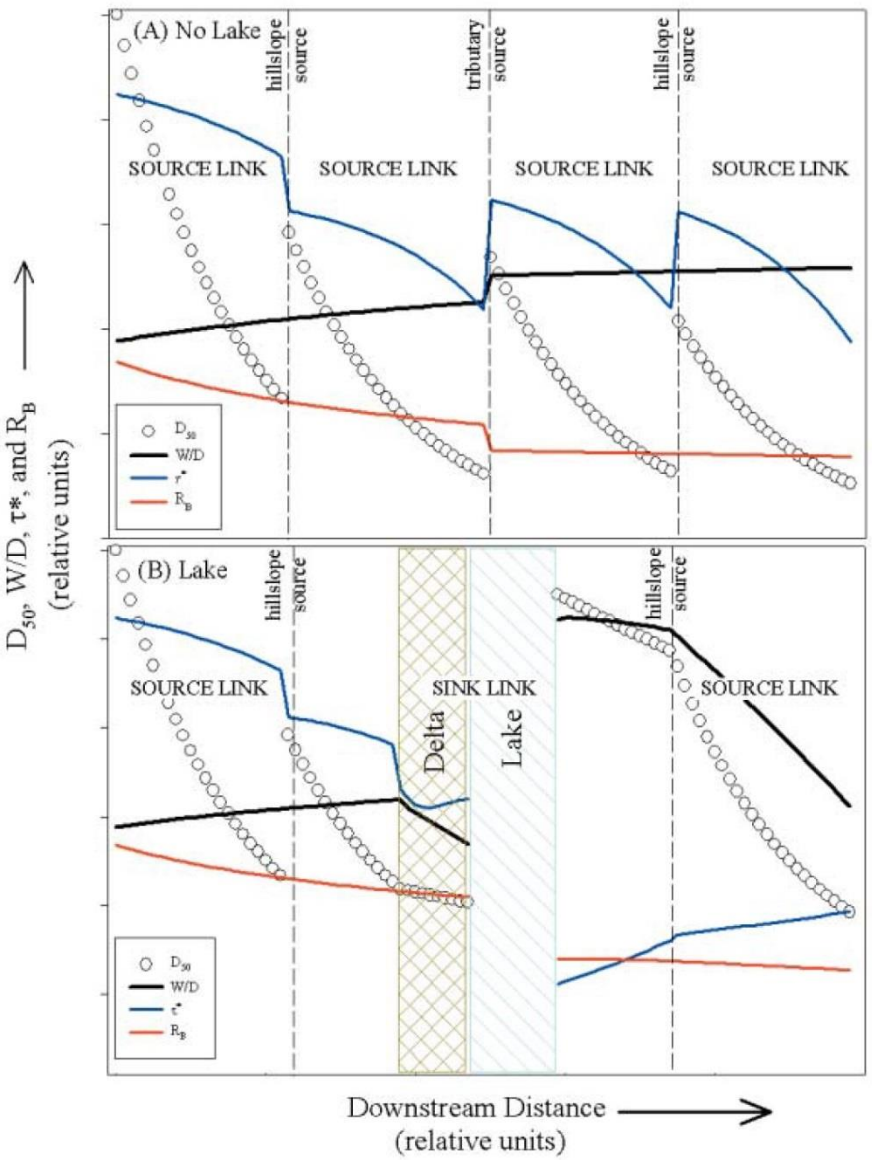

Figure 16: Hydromorphological changes along a river depending on whether it includes a lake (B) or not (A) (Arp *and al.,* 2007). D50 is the median river bed sediment size, W / D is the width-depth ratio for the channel, τ * is the shear stress (with no dimension) at the maximum flow rate for the D50, and RB is the maximum runoff.

V.3 CRITICAL ANALYSIS AND WAYS FORWARD FOR THE OPERATIONAL ASSESSMENT OF THE CUMULATIVE IMPACT

There is a significant lack of knowledge regarding the cumulative effect of reservoirs on sediment transport and morphological changes to rivers, partly due to the fact that most of the scientific literature on the subject covers large or very large structures on rivers, and also because the question of cumulative effects is virtually untouched. Furthermore, while **the effect of reservoirs on sediment flows is generally unequivocal (almost total storage of sediment** for coarse sediment, with more variable but significant levels of storage for fine sediment), **the effect on downstream morphological changes varies a great deal.** This variability is explained by the fact that the type and extent of the alteration depend partly on the **relative change in the control factors – i.e. the liquid flows (bankfull discharge) and the sediment flows**, and partly on the local conditions under which the effect occurs (reach gradient, river adjustment capacity, whether or not local structures are in place, whether or not there is vegetation, etc.) **The high number of potential combinations makes the development of effective predictive models difficult.**

From an operational perspective, analysis of the literature **highlights the importance of taking into account the sedimentary context of each catchment area in order to assess the cumulative effect of reservoirs.** Overall, at least two contexts should be distinguished: basins where sediment production and transfer is high from hillsides to the hydrographic network, and hydrographic networks with a sediment deficit.

- **In basins where the production and transfer of sediment from hillsides to the hydrographic network is high**, while the high sediment flow creates a management problem (silting of reservoirs, clogging of spawning grounds), the reservoirs could play a positive role in reducing these problems by storing sediment in reservoirs. **An initial analysis suggests that, in quantitative terms, this cumulative effect is relatively close to the sum of the individual effects,** but the spatial distribution of the stored sediment depends on the relative positions and characteristics of the reservoirs. While feedback processes between neighbouring reservoirs seem fairly limited, there is clear evidence of interaction: estimation of reservoir silting rates must take into account whether or not there are upstream reservoirs, as these "protect" downstream reservoirs from silting. On the other hand, from the perspective of ecological continuity and habitats, an additional reservoir introduces a risk of discontinuity.
- **For hydrographic networks with a sediment deficit** and associated challenges (embrittlement of structures, disconnect between wetlands, degradation of aquatic habitats, etc.), reservoirs have a generally negative effect. **In this case, the position of each reservoir within the basin is important, depending on whether or not it generates a fresh discontinuity between the reach in deficit and the production zones.** If so, its impact will be much higher if its water supply zone produces lots of sediment. Otherwise, its impact will probably be low or negligible.

The number of reservoirs also influences the cumulative effect, depending on whether the distance between reservoirs is greater than the length of influence or not. If not, the length of the river can become entirely artificial. However, this direct length of influence depends on a number of factors, which makes it difficult to propose reference values in the current state of knowledge. Studies still need to be performed on the lengths of disrupted reaches downstream of a reservoir depending on various configurations, and therefore on the impact of a new reservoir depending on its distance from an existing reservoir.

Three categories of tools and methods are available to this end. The first category can be used to **characterise the hydromorphological context,** and especially identify whether the basin in question is in sediment excess or deficit. Many management areas have already been covered by physical assessments. In France, approaches such as the *Système Relationnel d'Audit de l'Hydromorphologie* (SYRAH – Hydromorphology audit relational system) developed by Irstea can be used. This produces spatialized data on the risks of alteration of the hydrological and morphological functioning of water bodies. The second category of tools serves **to estimate trapping in reservoirs**. These are often based on sedimentation indices or ratios of reservoir capacity to inflows, or reservoir capacity to the catchment area, **developed primarily for large reservoirs** and long-term forecasts. A digital model has been developed for reservoirs of less than 1 ha in size, but has not yet been used much. The third category involves models for **anticipating morphological changes in rivers**: conceptual models are very well developed and complete, but predictive models are not very effective, due in particular to the complexity of combining upstream and local factors and effects.

In conclusion, the bibliographical analysis shows that there is undoubtedly a great deal more scientific work to be done on the issue of assessing the cumulative effects of reservoirs on the hydromorphological aspect of rivers (improvement of existing models, etc.). Furthermore, the fact that a high number of the studies analysed cover large structures suggests that specific studies of small reservoirs, and particularly the particle size selectivity of trapping depending on the size and position of reservoirs, or on biogenous elements, need to be performed. These aspects are not dealt with in the literature, and could provide a partial explanation for the fact that trapping rates are generally a bit lower for small reservoirs than for large ones.

Box 5: The specific case of draining

The assessment does not specifically cover the case of draining. However, given the significant influence that such events can have despite their short duration, it seems important to touch on them.

The influence of draining on sediment transport

Opening the bottom outlet gate creates a new hydraulic regime, which drags sediment located by the gate. The dead storage then passes through when the reservoir is almost empty and the river is again forming its bed in the reservoir sediment. This fairly short stage, which lasts several hours to several days, with the contribution of pore water coming from the mud drying, is the period of maximum risk, characterised by the hydraulic drag of sediment, the collapse of the as yet unconsolidated banks and the release of chemical compounds determining often exceptional concentration peaks, especially with regard to nutrients. The dried-out stage, with a highly variable duration, is characterised by a risk associated with the passage of floodwater in the empty reservoir, which can lead to significant hydraulic drag of sediment. Concentrations of suspended matter can then be higher than when the dead storage goes through, and can damage downstream fauna (immediate lethal effect and clogging of the river bed in the longer term). Sometimes the suspended matter peak increases as it moves, because the higher flow rate in a reach that is normally short-circuited causes bank cleaning and erosion.

Effects of draining operations on biotic communities

The potential ecological consequences of draining on the environment have, it seems, sustained very little interest in the scientific literature. The research available primarily focuses on hydroelectric reservoirs, with other types of reservoirs being taken into account more sporadically.

Draining, via the physico-chemical changes that it generates, has potential consequences on biotic communities in both the short and long term. Furthermore, the potential for toxic contamination generated by draining is sometimes raised in the scientific literature, to cover the impact of these management operations on biotic compartments. Aquatic organisms are highly affected by draining operations, which almost always cause deaths, the most visible of which are for fish and crustaceans (crayfish). It may be assumed that smaller organisms are also impacted by these draining operations, but their mortality is much less evident. The Water Framework Directive recommends a suspended matter threshold concentration of 25 mg/L in order to preserve fish life in freshwater, but during draining operations, suspended matter concentrations often exceed 10 g/L.

Draining operations also have particularly strong immediate impacts on communities of benthic macroinverterbrates. Several monitoring operations performed a few kilometres downstream of a reservoir show population reductions of 90% of more, and high impacts on taxonomic diversity*, with taxa that are particularly sensitive to draining operations, compared to the situation before draining. However, several studies also show the strong resilience of invertebrate communities after draining, with a return to their initial structure within a few weeks or months of the draining operation. However, draining has much more long-term impacts on fish populations and their habitats (deposits of fines, pore clogging of substrates and/or spawning grounds).

Chapter VI CUMULATIVE EFFECTS OF RESERVOIRS ON RIVER PHYSICO-CHEMICAL CHARACTERISTICS

The “physico-chemical quality” of water is a concept that is traditionally associated with the environmental management of aquatic environments and associated water resources (drinking water supply). It expresses the expected effects of its composition on the various uses of water and how aquatic ecosystems function. It comes particularly into play in assessments of the ecological status of a water body under the WFD. It is analysed via a set of physical and chemical parameters (temperature, turbidity, pH, concentrations of dissolved substances and particles, minerals and organic matter, macro and micro-pollutants, etc.), with varying degrees of interdependence, which are then compared to environmental standards backed up to differing extents by an understanding of the response of aquatic ecosystems. This chapter covers the effect of reservoirs on the following physico-chemical characteristics and chemical species - temperature, concentrations of dissolved oxygen, nitrogen, phosphorus, heavy metals, pesticides and greenhouse gases - all of which we consider key functional parameters for aquatic environments and water quality.

First, a literature survey was performed separately for each of these parameters. This choice is justified by the diversity of biophysico-chemical processes affecting each of them and therefore the diversity of their determining factors. Furthermore, scientific publications are often dedicated to a single water quality variable, or sometimes cover them in pairs (temperature and oxygen, nitrogen and phosphorus, etc.). Moreover, biogeochemical transformation processes vary a great deal and are specific for each variable, and the behaviour of different chemical species differs enormously depending on whether they are primarily in dissolved or particulate form (in particular via adsorption on solid particles), with the option of changing between dissolved and particulate phases in some cases under particular conditions.

However, these variables are subject to a whole range of interactions, either because they are involved together in some biophysico-chemical transformation processes, or because they jointly influence the biological quality of the aquatic environment. Moreover, a positive effect on one parameter can involve a negative effect on another. **When evaluating the cumulative effect of reservoirs on the physico-chemical** and biological **quality of water**, **it is therefore important to consider them together.** Indeed, although these variables are affected by various processes, the latter depend on a small number of processes (orders 1 and 2 on Figure 1), essentially associated with the development of lentic conditions created by a reservoir.

In order not to weigh down the summary report, the effect of an individual reservoir on each of these parameters is covered in Appendix III. Instead, this chapter focuses firstly **on the influence of a reservoir on overall river physico-chemical quality, by comparing the main effects on the various chemical species.** It then deals with **the cumulative effect of reservoirs on river physico-chemical characteristics,** generally from a theoretical perspective, as we will see. The studies analysed usually cover large river dams. Small reservoirs, and even more so hillslope reservoirs, are given very little attention in the literature. Our analysis also uses knowledge drawn from limnology, since the processes in play in natural lakes and artificial reservoirs are partly similar, even if some differences prevent us from transferring the effects observed as is: (i) construction of a reservoir involves the submersion and destruction of land ecosystems which can also have a role on the physico-chemical quality of water; (ii) artificial reservoirs present higher fluctuations in water levels (drawdown), associated with the seasons and their management; (iii) unlike lakes, reservoir outlets can be located further down in the water column, which can lead to release of water - with deep water characteristics - and sediment downstream.

VI.1 EFFECT OF A RESERVOIR ON THE PHYSICO-CHEMICAL QUALITY OF WATER

A reservoir involves numerous processes which cause changes in the physico-chemical quality of the water which feeds into it. Depending on its use, it can be as important to focus on the **change in the reservoir** itself as on the **consequences on the downstream river** when the water is returned to it.

The effect of a reservoir on water quality is first and foremost associated with physical processes which characterise the change from rapid flow conditions (lotic conditions; supplied by the river or surface runoff) to **lentic conditions** in the reservoir, and then potentially lotic conditions again in the downstream river.

The main potential effects of a reservoir on carbon, nitrogen and phosphorus are summarised Figure 17, associated with the lentic conditions that develop within the reservoir and lead to:

1. **Sedimentation** of the solid, mineral or organic particles contained in supply water. The phosphorus, trace metals, cations and some pesticides are sometimes associated with these particles and deposited at the same time. Some of the organic particles, although generally light, can be partially deposited, contributing to carbon sequestration and providing nutrients in an organic form. In addition to this allochthonous OM (organic matter), there is generally autochtonous OM from primary production, and OM from the submerged soil and vegetation. So all these chemical substances are stored in the reservoir for the medium or long term. However, if conditions become anoxic at the bottom of the water column, biogeochemical transformations in reducing environments can lead to their release into the water column in gaseous or dissolved forms (CH_4, NH_4^+, PO_4^{3-}, etc.);
2. Potential **thermal stratification** of the water column in deep reservoirs, due to rebalancing of water temperature and air temperature (warming) in surface layers during the summer. In shallow reservoirs in the summer, the temperature of the water stored in the reservoir and not replaced tends to increase, which reduces the solubility of oxygen in the water. In addition to the development of **reducing conditions** at the bottom of the reservoir and the consequences mentioned above, anoxia favours denitrification, i.e. the transformation of nitrates into inert (such as N_2) or greenhouse (such as N_2O) gases. Stratification controls oxygen gradients, and diffusion, mixing and sedimentation phenomena for dissolved and particulate elements between one layer and another, and the primary production and mineralisation of OM in the water column (**Erreur ! Source du renvoi introuvable.** in Appendix III). This leads to a vertical zoning of dissolved elements, strongly linked to thermal stratification and oxygen gradient phenomena. Two types of trophic structures build on this foundation, using bacterial or fungal decomposers or primary producers. Nutrients, such as nitrogen and phosphorus, and contaminants follow diffusion (dissolved fraction) or sedimentation (particulate fraction) phenomena.
3. Potential development of **primary production** (phytoplankton, plant life). This occurs particularly in spring and summer, when there are abundant nutrients, and in the surface layers of the water column, where temperature and light conditions are favourable. If PO_4^{3-} is abundant, this can lead to eutrophication. By consuming these nutrients, primary production creates a reduction in NO_3^- and PO_4^{3} concentrations. Eutrophication leads to an increase in biomass and therefore OM in the autumn, mineralisation of which will increase the consumption of oxygen and reducing conditions in the benthic zone. The PO_4^{3-} ions released then in turn maintain eutrophication (see chapter The specific case of eutrophication). The NO_3^- deficit can be mitigated by fixation of N_2. This situation encourages cyanobacteria which can do this.

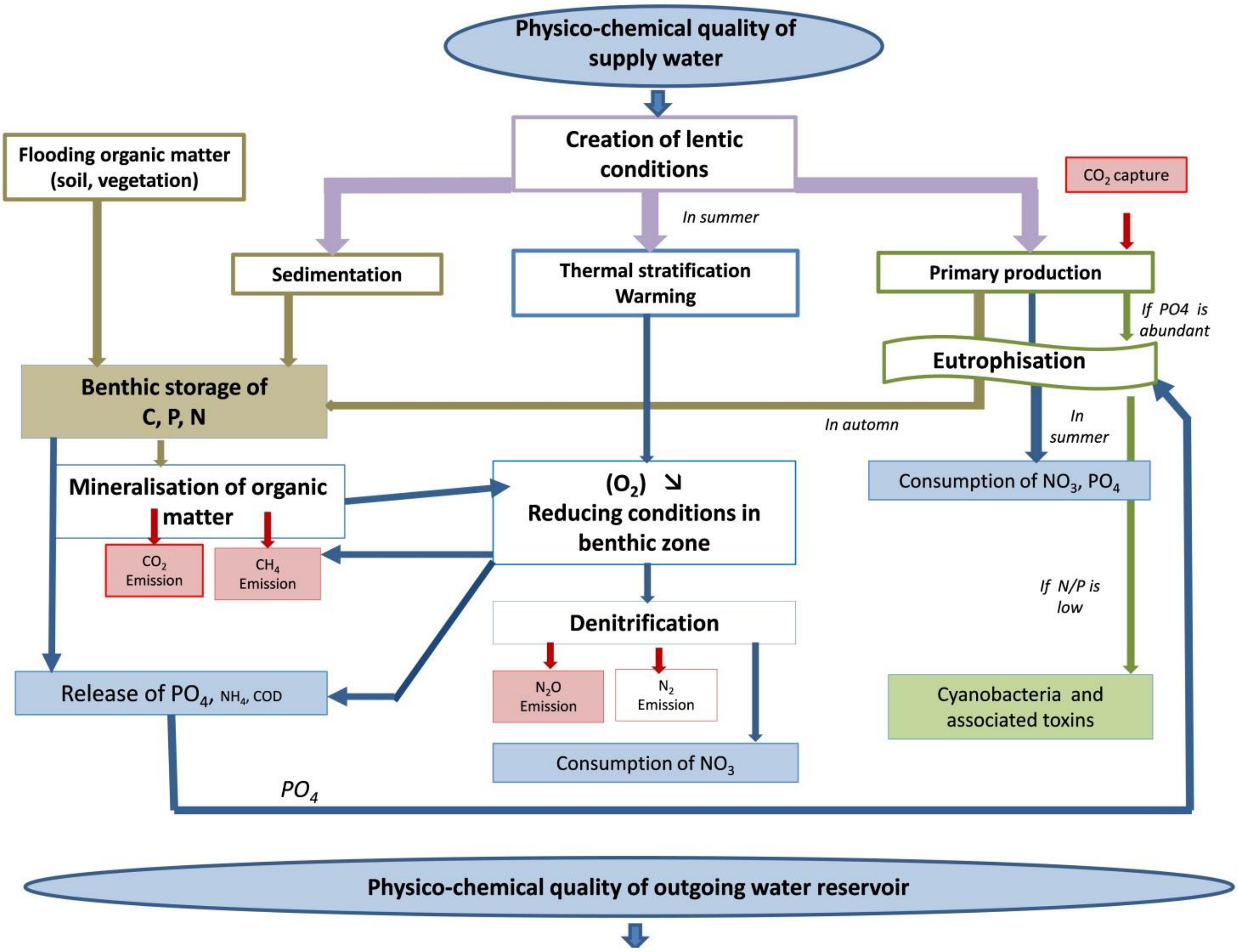

Figure 17 : Main potential effects of a reservoir on carbon, nitrogen and phosphorus within a reservoir. The colours used differentiate between the compartments, flows and processes related to the dissolved phase in the water column (blue), the sediment phase (brown), the gaseous phase (red) and the biomass (green). These potential effects are associated with lentic conditions and do not include the effects during hydraulic regime changes (flood, wind-related mixing, dredging, draining, etc.).

The development of lentic conditions in the reservoir or more generally hydrodynamic conditions therein, is one of the key aspects of how reservoirs function with regard to water quality. Low replacement of water increases the residence time, which can provoke sedimentation and storage of some elements, thermal stratification and anoxia, and therefore some biogeochemical transformations in the water column. In return, in the case of high and fast inflows, or under the effect of wind, mixing of the water column and the resuspension of sedimented particles can lead to renewed mobility of chemical species associated with the particles or a release of some compounds initially concentrated in the benthic pore environment. Mixing can also have effect on the homogenisation of the water column and reduce thermal stratification and oxygen gradients, and on the diffusion of elements within the water column and at the interface with the atmosphere. Finally, the drawdown phenomenon, which is by definition accentuated in reservoirs and leads to alternating anoxic and oxic conditions around their edge, further provokes the release of chemical elements associated with sediment (phosphorus, trace metals, pesticides, etc.).

While the creation of lentic conditions affects the majority of change processes for the physico-chemical quality of water in the reservoir, the manifestation of these processes and their intensity will also depend on a number of determining factors: the specific morphological characteristics of the reservoir (size, shape, depth), its environment (land use, hydrology) in the catchment area and its supply method which all determine inflows, its management which determines outflows, the regional and local climate and the variability thereof over time, and finally the use of the submerged land and the period of time since submersion. All these factors are involved to differing degrees, depending on physico-chemical variables and associated transfer and transformation processes.

Hydrodynamic conditions can present **high variability across all time scales**, and in particular across **seasons.** Temperature inversions from one season to another can lead to stratification of the water column, particularly in deep reservoirs. Seasons are also a determining factor in the cyclical development of primary production (the effect of temperature and light) which consumes nutrients in spring and summer, and becomes senescent in autumn, stored as OM or potentially decomposed, leading to the release of nutrients. Dissolved oxygen can be affected both by respiration, photosynthesis and the decomposition of this primary production. Diffusion, mixing and sedimentation phenomena for dissolved and particulate elements between one layer and another of the water column depend on thermal stratification phenomena and therefore on the location of the thermocline and metalimnion, which are subject to seasonal variation.

A determining factor for the change in a number of the physico-chemical variables described above, which is extensively mentioned in the literature, is the **residence time of water** in the reservoir. However this varies in a complex way, both in terms of time and space in the reservoir, and while the indicators normally used (ratio between the reservoir volume and the inflowing water, or ratio between the reservoir surface area and the area of the catchment area that feeds into it) may give a useful estimate, they cannot reflect this variability. All these effects that take place in the reservoir also have **consequences on the water quality in the downstream hydrographic network**, when the reservoir is located on a river or is connected temporarily or permanently to one. The consequences in the receiving river are a function of the relative magnitude of outflows with regard to inflows into the river, and can still be observed to a significant degree downstream depending on new inflows. For some variables (temperature, dissolved oxygen) the effect of the reservoir can be cancelled out beyond a certain **distance** in the river, particularly due to turbulence created by the return to lotic conditions, and as new inflows into the river mix with outflows. For other elements (nitrogen, phosphorus, etc.) the effect of the reservoir can still be observed depending on the relative size of outflows compared with inflows into the river and whether or not there are tributaries.

The specific case of eutrophication

Eutrophication is a trophic change for aquatic ecosystems. It is caused by an increase of nutrients resulting in a transformation of the structure* and way the biotic community functions, and involves an increase in productivity, an accumulation of biomass and overall disruption in the quality of water. Eutrophication of reservoirs is said to be “cultural”, i.e. it is produced by inflows of water with high domestic, agricultural or agri-industrial nutrients and develops over several decades, or even just a few years. It is therefore radically different from the slow natural aging of a water body due to filling which produces partially analogous symptoms on a thousand-year scale.

An increase in the concentration of assimilable nutrients stimulates the plant productivity of the trophogenic zone (Figure 40 in Appendix III). Assimilable phosphorus (SRB, Soluble Reactive Phosphorus) is very often, in lentic environments, the overall factor which limits this change. The “fertilising” effect generates an accumulation of plant biomass as soon as excess primary production stops being regulated by its consumption in the trophic network (Figure 34 in Appendix III). The synthesised and unconsumed OM sediments and its decomposition contributes to a deoxygenation of deep water layers which sometimes lead to anoxia of the water-sediment interface. This anoxia leads to the reduction of iron and the release in solution of some of the phosphorus associated with iron oxides in the sediment. Eutrophication can then be automatically maintained by this new inflow of dissolved phosphorus (internal load) and the stabilised eutrophic state. In some situations, the excess plant production stimulated by the phosphorus leads to a relative deficiency in nitrogen which can favour the development of N_2-fixing cyanobacteria. Cyanobacteria, plant forms that are very difficult to consume, end up proliferating whatever happens, even in non-limiting nitrogen conditions, due to the shade created by the excess phytoplankton production. These can potentially produce toxins which affect the human nervous or digestive system, and their development can constitute a major risk for water uses (in particular drinking water supply, agri-food and swimming).

VI.2 CUMULATIVE EFFECTS OF RESERVOIRS ON RIVER PHYSICO-CHEMICAL CHARACTERISTICS

The issue of the cumulative effects of reservoirs on water quality is rarely covered and some variables receive more treatment than others. The few studies available focusing on the behaviour of nitrogen and phosphorus will first be presented. The emission of greenhouse gases by reservoirs, which could become an emerging problem given the high number of reservoirs in the world, is dealt with in Box 6. Given the low number of references covering the cumulative effect of reservoirs, we also focused on publications presenting more conceptual approaches on the cumulative effect of wetlands and lakes. These publications are not based on observed data and do not specifically focus on one variable over another.

VI.2.1 Cumulative effects of reservoirs on nitrogen

The methods implemented to study the cumulative effect of reservoirs on nitrogen are based either on measurements at several points in the hydrographic network and sometimes within reservoirs, or on modelling, with models capable of representing a series of reservoirs on the hydrographic network, and varying levels of detail for representing the influence of reservoirs on nitrogen. The “retention” of nitrogen via denitrification is primarily covered, a term used in the literature, but one which is not entirely appropriate, since we are really talking about the release of nitrogen into the atmosphere in gas form.

Some studies go no further than taking measurements at catchment area outlets, and look for correlations between reductions observed and the characteristics of catchment areas studied and the water bodies they contain. Others use the measurements taken on a reservoir to calculate the effect of other reservoirs in the catchment area, and include them in modelling across the catchment area.

Studies based on modelling can be used to explore reservoir location scenarios. They show that reservoirs located downstream near the outlet are more efficient in retaining nitrogen than those placed upstream, and that numerous small reservoirs are more efficient than a single large reservoir. Some studies conclude that dams increase the inter-annual variability of nutrient flows, while others come to the opposite conclusion. When denitrification occurs, the efficiency of reservoirs in reducing the nitrogen load seems higher than for lakes, because ratios between drained area and reservoir area are higher than for lakes, with higher apparent sediment transfer speeds and larger mean inflow loads.

Where **several reservoirs are located in series on the same river**, the upstream reservoir can have a significant effect on nitrogen retention. The intensity of denitrification is a function of nitrogen concentrations, which leads to a nitrogen retention which progressively decreases from one reservoir to another heading downstream. This phenomenon is amplified by the buffer effect of each reservoir on the temporal variability of the physico-chemical quality of water which goes through it. Vertical stratification of the water column becomes less clear from one reservoir to another going downstream, since this is associated with seasonal temperature variations in the inflow water in comparison with lake water, variations which are buffered when they go through upstream reservoirs. The vertical thermal stratification of the water column includes stratification of dissolved oxygen concentrations which govern the denitrification process. This explains the importance of the depth from which outflows come, and the distance between reservoirs, which determines whether it is possible to buffer the temporal variability of the physico-chemical quality of water over the long term. High seasonality is observed, associated with algal blooms and biogeochemical conditions (high temperature and pH, anoxia) in the summer which prompt the biological absorption of nitrogen and denitrification, and is also more significant in upstream reservoirs.

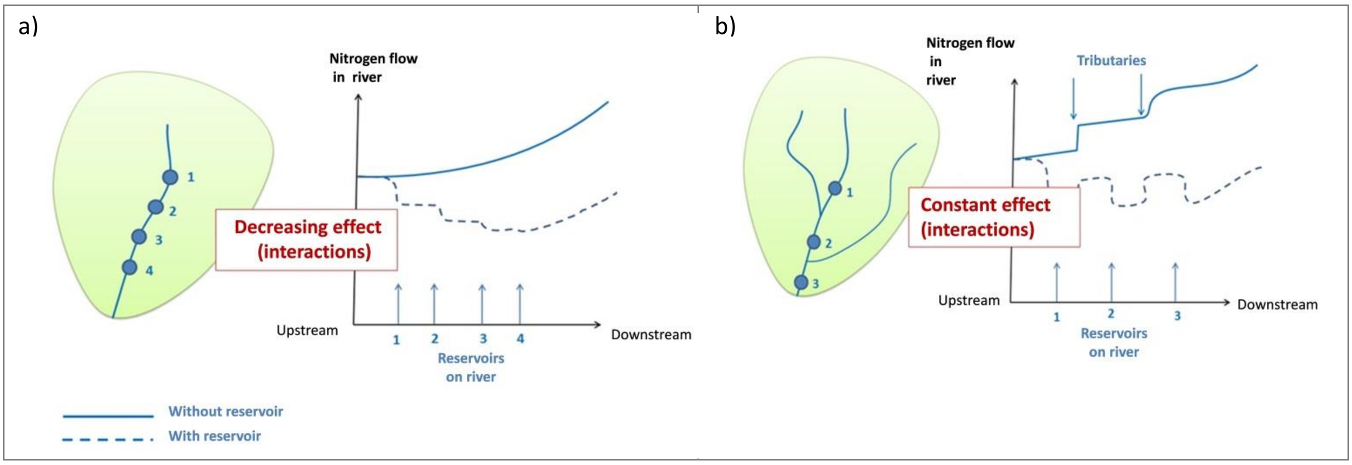

Figure 18: (Conceptual) effect of the position of reservoirs in the catchment area on nitrogen flows in the river: a- reservoirs in series close to one another; b- reservoirs in series spaced out from each other, or with tributaries.

This analysis shows that assessment of the cumulative effect of reservoirs on nitrogen must take into account their distribution across the basin (Figure 18). For reservoirs in series and close to one another on the same river, interactions between reservoirs need to be taken into account, while reservoirs with a less dense distribution across the hydrographic network, or outside the hydrographic network, can be considered independent from each other, and their cumulative effect on N flows can be simply considered in additive terms. Figure 19 thus illustrates, for a sub-basin of the Seine, that the retention of nitrates increases with the surface area of the basin occupied by reservoirs, but levels out beyond a certain threshold, which reflects the interaction between reservoirs when they increase in number and the more they are close together on the hydrographic network.

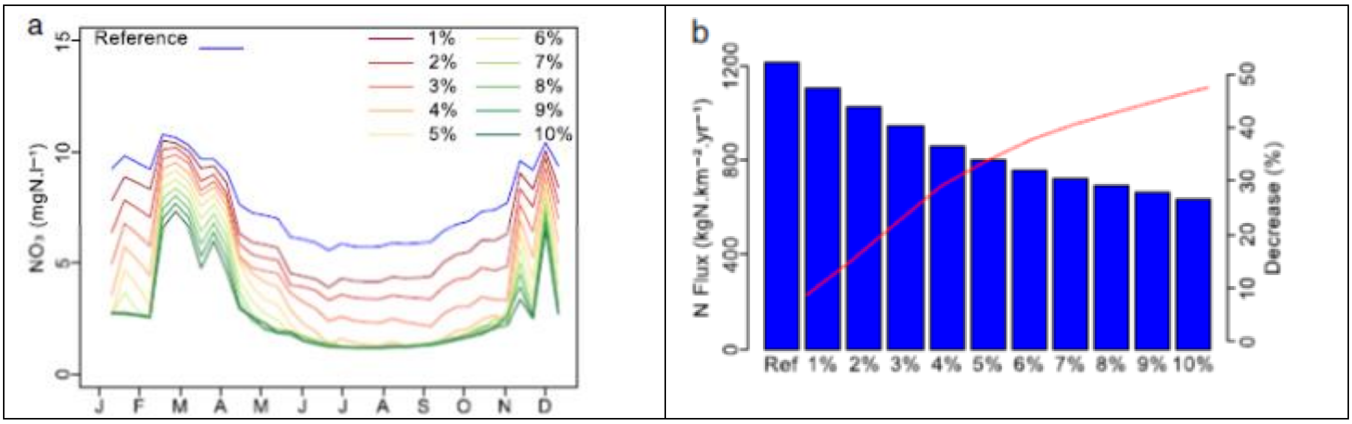

Figure 19: a. Seasonal variation of nitrate concentrations at the Orgeval sub-basin outlet for water year 2006, as a function of the proportion of ponds (in %) in the catchment area. b. Annual nitrogen flow at the Orgeval basin outlet as a function of the percentage of the surface area of the catchment area covered by ponds (2006). The corresponding reduction is marked by the red line. (Passy, 2012).

From the perspective of the model to be used, representation of the influence of reservoirs on nitrogen flows must be consistent with the data available, but also with the underlying hydrological model. A non-distributed hydrological model will only serve to represent the effect of a single equivalent reservoir, a spatially explicit model will serve to represent a reservoir by meshing (which, in some applications analysed, can reach 50 km^2). A semi-distributed model, such as SWAT, serves to represent various reservoirs for a sub-basin, which forms its basic mesh, by distributing them along homogenous hydrological sub-units, but these are not hydrologically connected together, so interactions between reservoirs within a single sub-basin cannot be represented. The model selected to be applied to a catchment area for assessing the cumulative effects of reservoirs on nitrogen transfer **must therefore be adapted to the level of interest in interactions between reservoirs.**

VI.2.2 Cumulative effects of reservoirs on phosphorus

Studies show that multiple dams lead to the creation of a very high internal phosphorus load within the hydrosystem, which can represent a problem for the load release to come. Some series of connected natural lakes lead to an increase in assimilable phosphorus concentrations from upstream to downstream, due to the biogeochemical transformations that occur in lentic environments, while other series instead create a decrease due to a predominance of retention functions. The seasonal effect observed is more significant for nitrogen than for phosphorus. In a chain of connected lakes, if measures are taken to reduce phosphorus inflows, their consequences on water quality (eutrophication) are at a maximum upstream and in summer, and diminish downstream, due to an increasing level of internal recycling going downstream. The differences between reservoirs and natural lakes (internal load created by floods, variation in water levels (whether or not they are synchronous) type of water return (potentially hypolimnetic)) make it impossible to directly transfer results for lakes. Some questions need to be dealt with in order to move forward on this issue:

- What is the incremental effect on phosphorus flows? What functions are additive, linear or subject to thresholds? We could, for example, consider the relationship between nitrogen and phosphorus and the development of cyanobacteria.
- Is there a place in the hydrographic network which would be optimal for a reservoir’s retention and transformation functions? What should be the distance between dams to allow recovery?

- What are the differences in impact associated with the position of reservoirs in a hydrosystem (order of the river)? What parameters or metrics can we use to take into account the effects associated with position?
- For equal volumes, is it best, in terms of the eutrophication risk, to have multiple small headwater reservoirs, or a bigger one further downstream?
- What connection is there at landscape scale between land use and associated phosphorus flows? How can we describe the activity-landscape-reservoir system?

VI.2.3 Cumulative effects of reservoirs on river physico-chemical quality: conceptual approaches

Given the lack of studies focusing specifically on the cumulative effect of reservoirs on river physico-chemical quality, the literature on wetlands and lakes was considered, primarily from the perspective of the conceptual and methodological approaches used. The focus of studies on **wetlands** is assessing the cumulative effects of the loss or degradation of wetlands in a catchment area. Both wetlands and reservoirs are storage compartments for elements adsorbed from particles and reactors for transformation of dissolved elements in reducing conditions, with a potential switchover from particulate to dissolved phase. As with reservoirs, wetland outflows depend on inflows and the capacity for storage or transformation of various pollutants, which depends, among other things, on the residence time. There are therefore numerous similarities between wetlands and reservoirs, and many of the conclusions drawn for wetlands can be transferred to reservoirs.

Studies show that there is no linear relationship between the number of wetlands and their cumulative effect. The sum of the effects of each wetland does not always provide an estimate of the cumulative effects, due to interactions between wetlands. It is important to **define both the space and time scales of the system** to be studied, which depend on the function assigned to wetlands, i.e. their effect on such and such a variable or group of physico-chemical variables. Interactions between wetlands primarily involve exchanges of water (hydrological sequence) and the catchment area is the appropriate unit for identifying these interactions and integrating them for the cumulative assessment, but several scales can be relevant (Figure 20). The time scale must take into account variability across seasons and years, as well as the variability associated with events, and sometimes the long term. The relevance of the time scale considered depends on the type of impact studied - the mean effect over a certain period, peaks during exceptional events, etc.

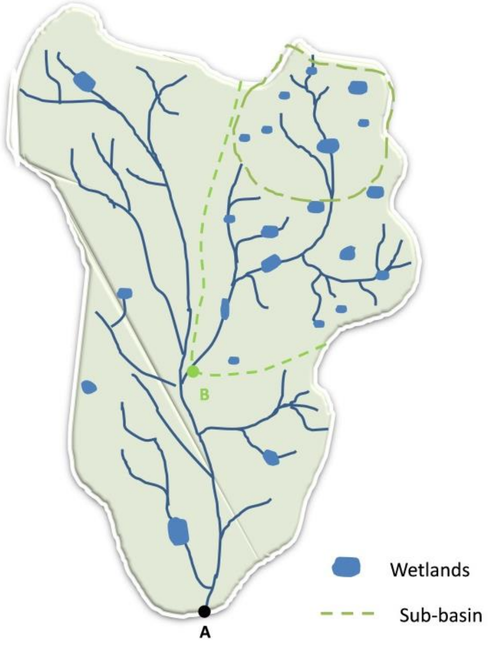

Figure 20: Virtual catchment area showing the different sub-basins in which it would be possible to assess the cumulative effects of wetlands on the storage of floodwater, and their outlets A, B and C.

The position of wetlands in the landscape is, for many authors, a determining factor for the evaluation of cumulative effects, alongside (of course) the characteristics of each wetland, both because their position in the catchment area determines the flows that they receive and because their position in the river determines how they function. Studies conclude that modelling seems to be necessary to assess cumulative effects. Two approaches can be followed, in parallel: a bottom-up approach which integrates each wetland into the hydrological sequence with its own characteristics, and a top-down approach in which (conceptual) models develop a qualitative assessment while identifying opportunities for research in order to build major hypotheses and define data requirements.

However, the development of quantitative assessment methods requires **improvement in the understanding of the factors which control processes** in wetlands, so that functional differences between wetlands can be taken into account.

Research into lakes also shows the importance of their position in the landscape. This determines, in particular, whether they are supplied by groundwater or surface water, which influences some water quality parameters. The position can be described using various semi-qualitative indices, providing information on their water supply/return method, their position in the catchment area and compared to other lakes (Figure 21). A study in Northern Michigan showed that these indices are associated with some water quality parameters, but also with determining factors at a landscape scale, such as the proportion of wetlands in the catchment area and lake morphology. It is therefore difficult to discern which factors really affect water quality.

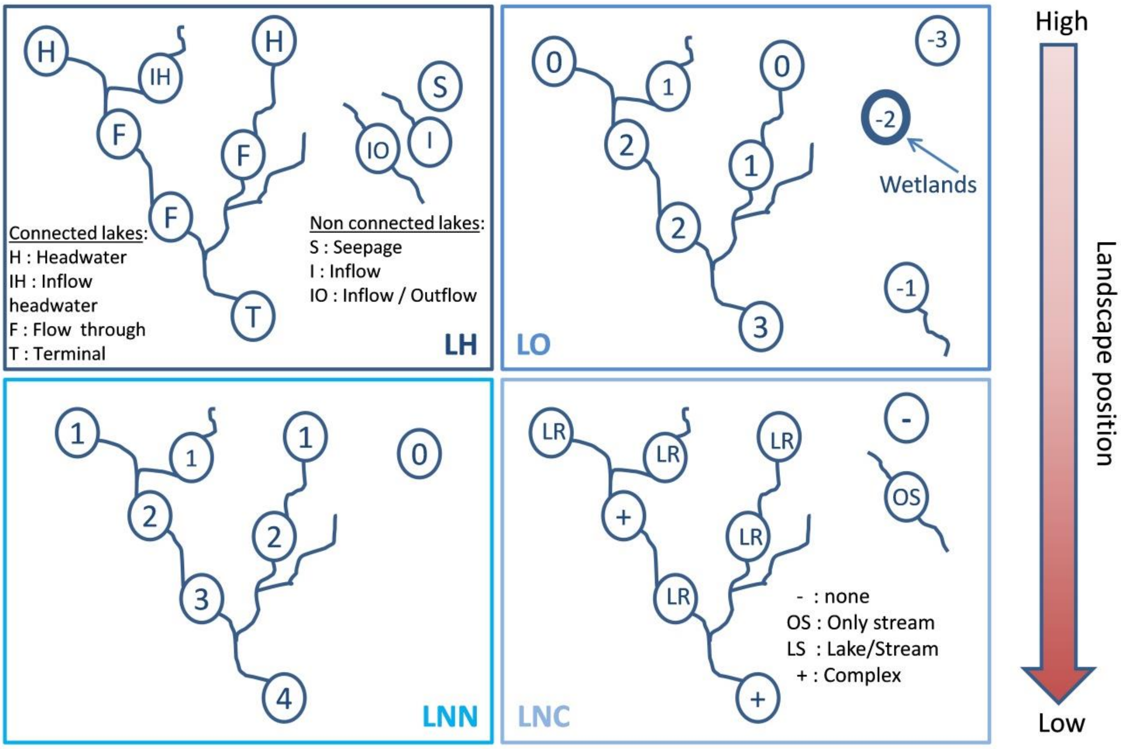

Figure 21: Description of lake position metrics: Lake Hydrology (LH), Lake Order (LO), Lake Network Number (LNN), Lake Network Complexity (LNC). Based on (Martin and Soranno, 2006).

Lakes considered are often in series on a single river, chains of natural lakes or dam lakes. The influence that a lake can have on a river depends on the size of the river, the size and shape of the lake, and the position of the tributary (river feeding into the lake) and the effluent (river fed by the lake) or the management of the dam, where applicable. One of the difficulties highlighted for progress in understanding the cumulative effect of lakes on a river is that lentic and lotic environments are not studied by the same specialists. The use of geographic information systems and network analyses for organising knowledge should make it possible to develop predictive science for aquatic networks.

On the basis of the River Continuum Concept (RCC), which considers that the longitudinal dimension of a river is associated with various physical and biotic alteration gradients, it is possible to study the effect of a series of lakes on a river using the Serial Discontinuity Concept (SDC). This introduces dams as discontinuities which modify abiotic and biotic parameters and processes along these gradients from upstream to downstream. This modification depends on the position of the lakes and dams in the catchment area, partitioned into three contrasting situations: the upstream, middle or downstream of the river (Figure 22). The order of the river depends on the climatic context.

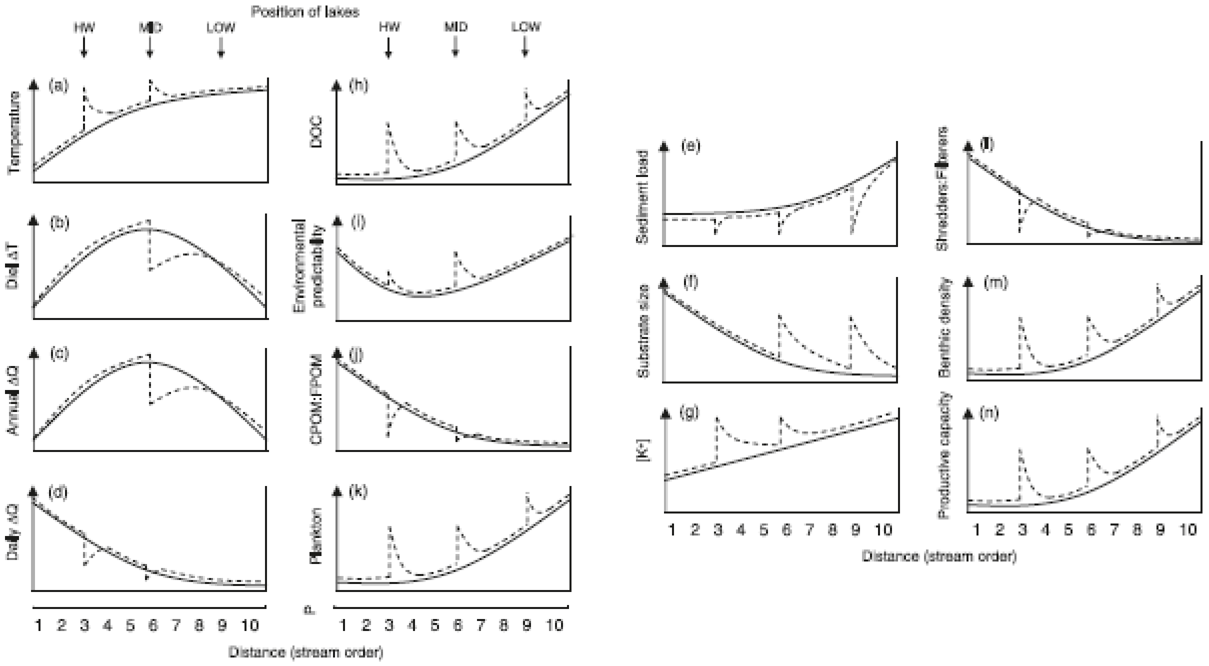

Figure 22: In this figure, the solid line represents the upstream-downstream change of various variables in a river without a lake (temperature, daily temperature variability, annual flow variability, daily flow variability, suspended matter load, particle size of the substrate, potassium concentration, dissolved organic compound concentration, etc.). The dotted line represents the effect of dams depending on their position in the hydrographic network (Jones, 2010).

There are two indicators that should be considered for a given variable: the distance for which the effect of the dams is observed (DD - Discontinuity Distance), and the disturbance intensity associated with its presence. In Figure 23b, water bodies are close enough together for a cumulative effect to be observed, given the extent of individual effects (disturbance intensity) which do not allow a return to initial status as in Figure 23a.. This theoretical diagram does not specify which water quality variable (physical, chemical or biological) it applies to. The changes simulated should differ according to the various variables.

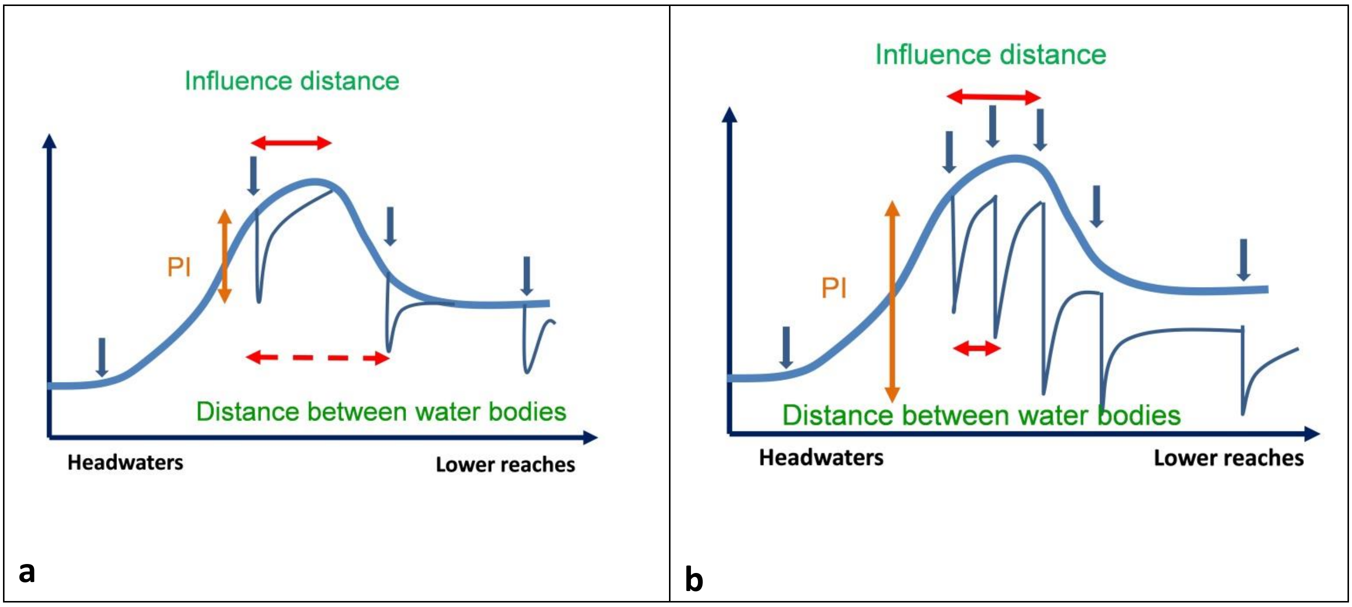

Figure 23: Impact of water bodies on the theoretical downstream behaviour of a variable, a) with no cumulative impact, b) with cumulative impacts (Bergkamp, 2000).

However, taking into account the longitudinal position of lakes on the river is not sufficient, and across the catchment area, the first factor for discontinuity is the branching of the hydrographic network, with often sharp variations at each confluence. Previously we were only focusing on a single longitudinal dimension of the river, with a more or less continuous gradient that was interrupted by a lake, but things become more complicated when there are multiple lakes across a catchment area. The form of the catchment area and therefore the form and hierarchy of the hydrographic network can have an influence. Even if a lake has an important effect on a river, the arrival of a tributary downstream with a high flow rate can cancel out this effect (Figure 24a), while the small effect of a lake located near the outlet of the basin studied is exaggerated (Figure 24b). It seems more difficult to assess the effects of multiple lakes with more complex cases, which appear more realistic than these initial configurations Figure 24d). In addition to the spatial organisation of lakes, the temporal consistency of their responses also need to be taken into account (synchronisation, correlation, delay effect).

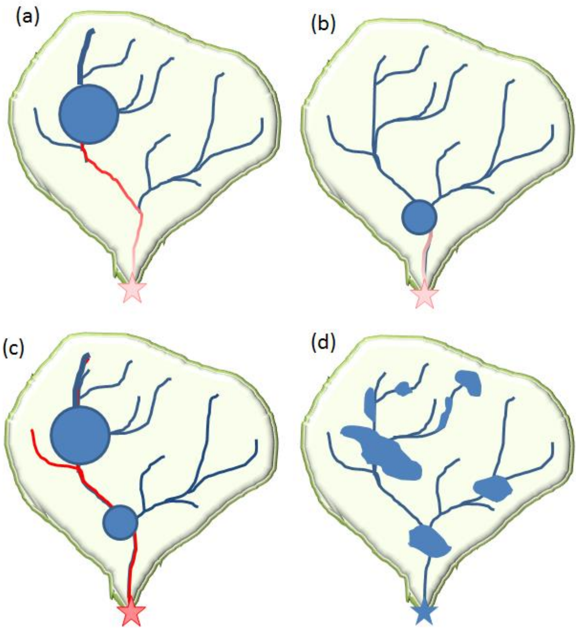

Figure 24: Theoretical distribution of several lakes on a hydrographic network: (a) a large headwater can significantly change river characteristics - a tributary with no lake downstream may dilute this effect; (b) a small lake could have fairly little influence on river characteristics in the downstream network; (c) the combination of two lakes in the network influences the ecological characteristics of the same tributaries; (d) lakes of more realistic positions and sizes - their individual and combined influences are complex and not easy to summarise (Kling *and al.,* 2000).

The cumulative effect of lakes must be studied by comparing the local scale (each lake) and the overall system scale (the catchment area). Some indicators or descriptors, summarised in Table 5, can be used to characterise the influence of a lake, or provide information for understanding their cumulative effect across the catchment area. However, their use in comparing situations remains very dependent on context.

Table 5: potential measurements and descriptors of lake-river networks, including metrics summarising conditions of the entire catchment area, and the potential of a lake to alter the characteristics of the downstream river (Jones, 2010).

Measurement	Specific measurements	Objectives
Metrics for the influence of lakes across the catchment area	Percentage of the basin covered with lakes	A high percentage (over 10%) of the basin covered could indicate a high influence of lakes on the system. However, distribution could be reduced to a large headwater lake
	Position of lakes in the catchment area	Surface area or volume of headwater lakes or lakes in the middle or downstream portion of catchment area
	Percentage of the length of river running through lakes, or percentage flowing as a river	A measurement of the overall effect of lakes
	Distribution of lake sizes in the network	Multiple small lakes have less potential to alter rivers
	Cumulative score of lake effects for the catchment area	A measurement of the influence of lakes on rivers in the network
Potential of a lake to	Area or volume of lake in relation to size (width or flow rate) of the	The characteristics of a small river can be significantly altered when it runs into a large lake with a low flow rate. However, a

alter downstream characteristics	inflowing or outflowing river	large river flowing into a small lake with a high renewal rate will maintain most of its characteristics
	Residence time	Mean time that the water will spend in a given lake
	Size of the inflowing river	The width of the channel or the river flow rate at the banks provides an indication of the size of the river
	Maximum order of rivers flowing into a lake	Provides an indication of river size
	Flow distance between the lake inlet and outlet	A lake with inlets and outlets at opposite ends will alter the attributes of the outflowing river to a much greater extent than if inlets and outlets are close to each other and short-circuit lake effects
	Angle between inlet and outlet	Angle between the lake tributary and effluent
	Number of rivers flowing into a lake	A large number of rivers flowing into a lake can mean a low residence time
	Basin shape	Ratio between the basin surface area and the square of its length
	Distance downstream from a lake	The distance downstream from a lake will determine the magnitude of the lake effect at a downstream observation point. The coefficients and functional form of the mitigation of lake effects downstream are largely unknown

VI.2.4 Conclusion

Some conclusions from the few studies on the cumulative effects of reservoirs, and the rather conceptual literature on wetlands, lakes or large dams, may be relevant to this assessment:

The importance of the space (and time) scale selected for the cumulative assessment

The cumulative effect of reservoirs must be studied by comparing the local scale of each of the reservoirs and the broader system scale (the catchment area). This is linked both (1) to how the various reservoirs function and their internal control factors, which explains the importance of knowledge acquired at an individual reservoir scale, and (2) to their interactions with the environment, the importance and nature of which involve control factors that are external to reservoirs. A broad space scale for cumulative assessment is important, but difficult to define. The same is true for the time scale. They both depend on prior assumptions about the type of impact to take into account, the physico-chemical variable(s) of interest, the place where this impact must be assessed, etc. For greenhouses gases, a global scale should be selected, and the relevant time scale is the year or decade. For other variables, effects will differ depending on whether we focus on small upstream catchment areas or large downstream basins, and the time scale to be considered must take into account hydrological variations (event or season).

The importance of hydrological connections between reservoirs

As with wetlands, there should not be a linear relationship between the number of reservoirs (total surface areas or volumes) and their cumulative effect on the majority of physico-chemical variables. In other words, the sum of the effects of each reservoir does not always provide an estimate of cumulative effects. Two reasons can be given to explain this:

- Some local effects are not found downstream in the landscape, or are mitigated depending on distance. This is the case for effects on temperature or dissolved oxygen.
- Most of the time, the way each reservoir functions in terms of physico-chemical variables depends on the characteristics of inflows. This is the case for denitrification, which depends on the nitrate load in the supply water. However, these inflows can already have been influenced by passing through other reservoirs.

Interactions between reservoirs primarily involve water exchange. It therefore seems essential to identify how reservoirs fit into the water pathway system in the catchment area where cumulative effects are being considered. This depends on the reservoir supply method (see supply types in the introduction), their position in the catchment area with regard to its hydrological functioning, and their management method.

Where reservoirs are located on the water pathway (the most common case is reservoirs located in series on a river), a distance effect can come into play (potential return to the initial characteristics prior to reservoirs via switchover to lotic conditions or "dilution" effect of reservoir outflows into the river).

In some cases (groundwater supplying, no downstream return to the river, large distance between reservoirs on the hydrographic network, etc.) there is no direct interaction between reservoirs. In this case, either the cumulative effects for the whole catchment area are the sum of the individual effects (emission of greenhouse gases, retention of carbon, nitrogen, phosphorus, etc.), or the individual effects remain limited to each reservoir and only have a local impact (summer warming, deoxygenation, eutrophication, etc.).

The importance of the position of the various reservoirs in the landscape

The position of reservoirs in the landscape comes out as an important factor in the literature on cumulative effects. It had already been highlighted as a factor of effect variability across a reservoir, but had not been studied in great detail. There are also a number of other factors of this variability, in particular "internal" control factors, which affect the reservoir's capacity for storage and transformation, i.e. its morphological characteristics, size, shape, management, the position of water inlets and outlets, etc. When focusing on cumulative effects, the position of reservoirs in the landscape also plays a role in the issue of interactions between reservoirs mentioned above.

Following in the steps of many conceptual publications on wetlands and lakes, it could be useful to develop a few landscape metrics, or a list of reservoir types in terms of upstream or downstream position in the catchment area, depending on their relationship with the river. However, this would require more precise knowledge of the effects of these types: are there major trends associated with a particular position with regard to inflows depending on the hydrology of the drained catchment area, land use, reservoir water supply, its capacity for storage and transformation? The idea is to define broader indicators than simply describing hydrological connections. Studies could be performed to statistically link these reservoir position metrics in various types of catchment areas and water quality at the outlets.

Cumulative effect assessment methods

Given the numerous processes involved and the high number of factors of variation, cumulative effects can probably only be assessed using **modelling.** Spatialized models could be developed by integrating the position of each reservoir in the hydrological sequence, their type, size, and capacity for storage or transformation. Representation of the influence of reservoirs must be consistent with the data available, but also with the underlying hydrological model. A non-distributed hydrological model will only serve to represent the effect of a single equivalent reservoir, a spatially explicit model will serve to represent a reservoir by meshing (which, in some applications analysed, can reach 50 km^2), and potentially interactions between reservoirs. The model selected must therefore be consistent with the analysis of interactions between reservoirs.

Currently, the prediction efficiency of such models is debatable, given the wide range of ways in which reservoirs function and the limits of our knowledge on the role of many determining factors. A qualitative approach based on a few contrasting standard types of catchment areas including reservoirs could already be used to identify ways forward for research with a view to developing major hypotheses and understanding the need for knowledge and data. It must be said that there are no research projects focused specifically on the issue of the cumulative effects of reservoirs on the physico-chemical quality of water.

Research needs and gaps

From a scientific perspective, the barriers identified involve first and foremost the scale of a reservoir, with the quantification of a number of processes active in it. Local observations and data are still required, together with sufficiently close monitoring at a space and time level. They need to aim to feed into biogeochemical models adapted to reservoirs, which need to be further developed. Some phenomena which occur specifically in reservoirs need to be quantified and better understood: the initial effect of flooding of organic matter and its long-term influence, the effect of variations in water levels. Furthermore, data that exists or needs to be collected at the reservoir scale could be used in a meta-analysis to identify the numerous factors of influence, and help prepare for transferring results gained.

At the catchment area scale, other models need to be developed for processing the cumulative effect. Since the position of reservoirs in the basin plays an important role (different inputs depending on the area drained and interactions between reservoirs linked to their relative position on rivers), models should be either spatially distributed, or produce a list of types [spatial patterns – physico-chemical effects], which still needs to be developed. It would be good to assess the possibilities for tracking the overall effects of reservoirs via isotopic labelling of carbon and nitrogen, and also potentially phosphates (under development).

Box 6: Effects of reservoirs over large time and space scales

Reservoirs are structures intended to last for several decades. Their effects can therefore be expressed over long periods of time, including a change in climate or development of the catchment area which support them. This is an important point. While the assessment does not deal specifically with climate change or the socio-economic aspects associated with the development of reservoirs, its results must be put into the perspective of predictable climate and land use changes in some regions, which will affect reservoir filling capacity, and their impact on the aquatic environments whose "natural" state will also change.

Moreover, the effects of small reservoirs, primarily covered in this assessment at the level of the catchment area that supports them, can combine with the effects of other developments along the river, and so contribute to effects on estuaries and seas. For example, the reduction of water and sediment inflows can lead to increased salinity, which changes the circulation of marine currents, and the equilibrium of the trophic network, particularly in that such modifications generally involve a change in nutrient inflows. Water turbidity is also affected, with silt plugs that tend to move up the estuary. For large lakes or inland seas, reducing inflows can lead to partial or total drying out of water areas. On a global scale, it is estimated that the impact on the flows of small irrigation reservoirs, which account for around 23% of irrigation worldwide, would correspond to a 5% drop in mean flow rates, 44% in the minimum monthly flow rate, and 2% in the maximum monthly flow rate.

The reduction of annual downstream floods particularly affects the natural productivity of floodplains and deltas. In North America, detailed studies show that the construction of dams is one of the main causes of extinction for freshwater species. Spectacular reductions in bird species have also been observed, particularly in downstream floodplains and deltas. Some reservoirs also provide habitats for birds and other animals, but this often fails to compensate for the loss of downstream habitat.

Another cumulative effect of reservoirs is covered in the literature. This is an issue of global importance – that of overall greenhouse gas emissions (CO_2, CH_4, N_2O). Some studies suggest that reservoirs contribute 7% of greenhouse gases produced by anthropogenic sources. Others highlight the fact that methane (CH_4) emissions are inversely proportional to the size of reservoirs, and that emissions are much higher when their surface area is less than 1000 m^2. Conversely, reservoirs are also considered as locations for organic carbon sequestration. Estimates of annual carbon storage in reservoirs worldwide give orders of magnitude of around 0.15 to 0.6 Pg/year[20] for an estimated total water surface area of between 400,000 and 1.5 million km^2. These flows should be compared, for example, with the flow of Carbon stored in land environments, estimated at between 1 and 4 Pg/year, or the 0.4 Pg/year transported to oceans by rivers.

Reservoirs around the world therefore seem to have a significant role in greenhouse gas emissions responsible for climate change. However, it should be underlined both that there is great uncertainty about the surface area estimates involved, and that emission flows per surface unit are very little known, especially given the fact that a mean value is often considered in the studies, without taking into account the many factors of variability in time and space. As was highlighted for the impact of a reservoir, we cannot disregard the functions of the environments replaced by these reservoirs (river, soil, vegetation, etc.) and their impact in the carbon cycle, which should be another factor of variability between reservoirs.

The spatial scale on which this assessment on the cumulative impact of reservoirs focuses is generally not on a global scale. There may be a contradiction between a local and potential individual gain due to a reservoir use and a global collective environmental cost associated with cumulative effects in some countries. It is important here not to forget this type of impact which should, if shown to contribute to the greenhouse effect, have an influence on the general direction of public policy, and not encourage an increase in the number of reservoirs for a short-term benefit without awareness of this global level of impacts.

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[20] One petagram (Pg) is equal to 10^{15}g.

Chapter VII CUMULATIVE EFFECTS OF RESERVOIRS ON THE RIVER AND CATCHMENT AREA BIOLOGICAL COMPARTMENT

This chapter deals with the effect of reservoirs on aquatic biotic communities and the ecological functions of rivers in general. However, in the light of the low number of studies dealing specifically with small reservoirs, and to an even lesser extent, their impact on river ecology, this chapter is also based on studies covering other systems such as small ponds, ponds, natural lakes or large dams, and sometimes wetlands and beaver dams. In such cases, we nevertheless sought to draw out results that we felt could be, at least in part, extrapolated or applicable to the context of small reservoirs. The nature of the studied object, and its use and management method are not stated for all studies. The literature already known by the experts together with this specific research does, however, provide some knowledge, methods and tools which can be applied to this assessment.

This chapter first presents the influence of a reservoir considered individually on communities of aquatic organisms, and then deals with the cumulative effects of reservoirs on aquatic biotic communities and the functions of rivers in general. It also covers methods and approaches that can be used for analysing and assessing the cumulative impact of reservoirs on this biodiversity in both qualitative and quantitative terms.

Before getting into that, it should be stated, however, that the first impact of creating a reservoir is the disappearance of pre-existing habitats (wetlands, rivers, land habitats, etc.) and associated species. While this question is rarely dealt with in the scientific studies, some research suggests that newly created reservoirs continue to host significantly less biodiversity than pre-existing aquatic and wetland environments.

VII.1 EFFECTS OF A RESERVOIR ON RIVER BIOLOGICAL COMPARTMENTS

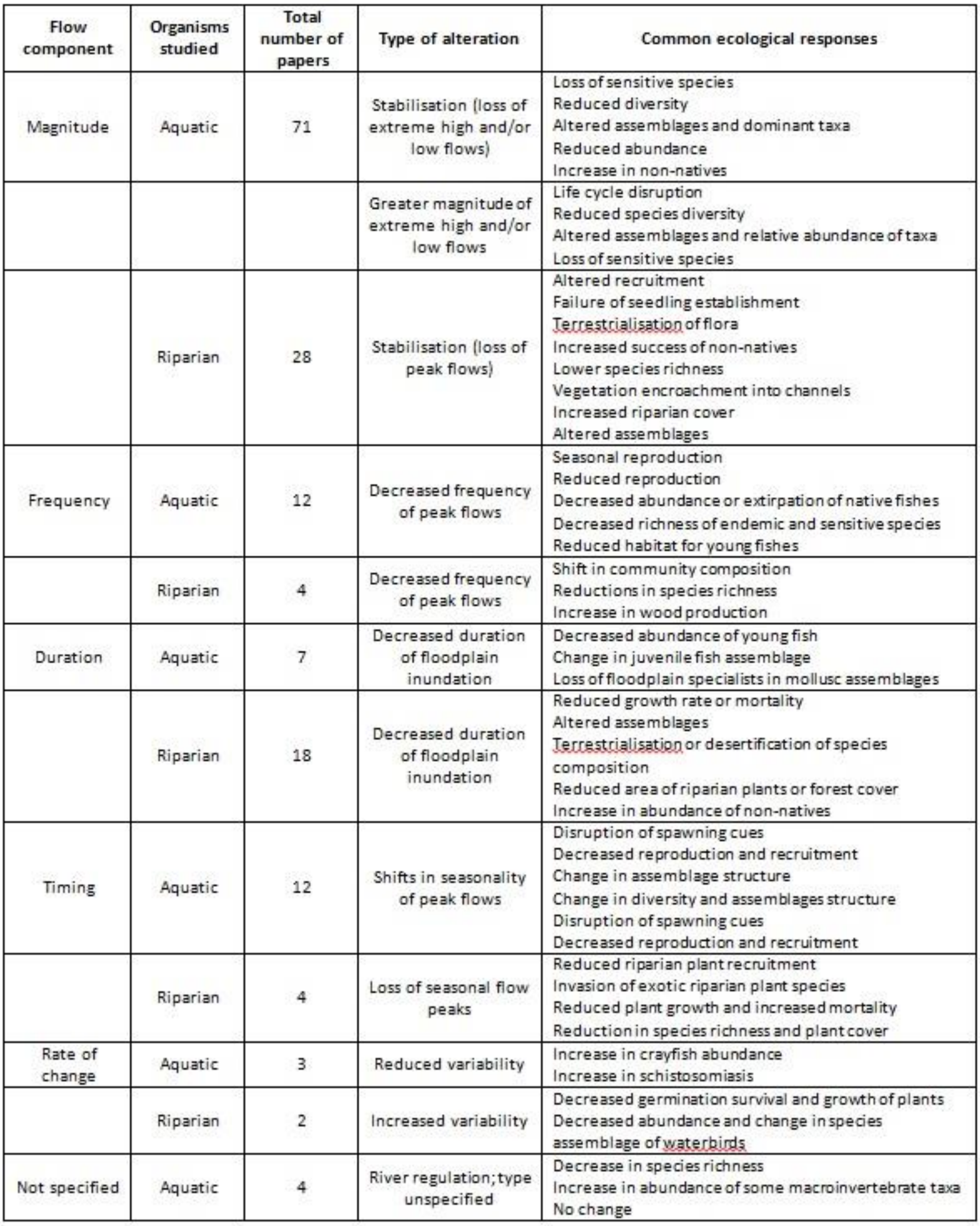
We will first examine the influence of a reservoir on river biological compartments from the perspective of responses to changes in abiotic conditions (hydrology, morphology, physico-chemistry, etc.) covered in a previous chapter, then with regard to processes associated with aquatic organisms (dispersal/distribution), before covering the overall impacts of multiple factors.

VII.1.1 Responses to primary drivers

VII.1.1.a Hydrological changes

The change to the hydrological regime caused by the construction of a reservoir has effects on aquatic fauna and flora whose significance directly mirrors the extent of the hydrological changes. Changes in flows downstream of the reservoir can be detrimental to some species that are strictly dependent on the river and see their habitats restricted and seasonal dynamics changes, and at the same time encourage colonisation by exotic species. A recent summary by Poff and Zimmerman (2010) produced a detailed inventory of different ways in which hydrological regimes are altered and their potential ecological consequences, taking into account both aquatic organisms and those that use river habitats (Table 6).

Table 6: Impacts of flow alterations on aquatic and riparian organisms reported in the scientific literature (source: Poff and Zimmerman, 2010)



Flow component	Organisms studied	Total number of papers	Type of alteration	Common ecological responses
Magnitude	Aquatic	71	Stabilisation (loss of extreme high and/or low flows)	Loss of sensitive species Reduced diversity Altered assemblages and dominant taxa Reduced abundance Increase in non-natives
			Greater magnitude of extreme high and/or low flows	Life cycle disruption Reduced species diversity Altered assemblages and relative abundance of taxa Loss of sensitive species
	Riparian	28	Stabilisation (loss of peak flows)	Altered recruitment Failure of seedling establishment Terrestrialisation of flora Increased success of non-natives Lower species richness Vegetation encroachment into channels Increased riparian cover Altered assemblages
Frequency	Aquatic	12	Decreased frequency of peak flows	Seasonal reproduction Reduced reproduction Decreased abundance or extirpation of native fishes Decreased richness of endemic and sensitive species Reduced habitat for young fishes
	Riparian	4	Decreased frequency of peak flows	Shift in community composition Reductions in species richness Increase in wood production
Duration	Aquatic	7	Decreased duration of floodplain inundation	Decreased abundance of young fish Change in juvenile fish assemblage Loss of floodplain specialists in mollusc assemblages
	Riparian	18	Decreased duration of floodplain inundation	Reduced growth rate or mortality Altered assemblages Terrestrialisation or desertification of species composition Reduced area of riparian plants or forest cover Increase in abundance of non-natives
Timing	Aquatic	12	Shifts in seasonality of peak flows	Disruption of spawning cues Decreased reproduction and recruitment Change in assemblage structure Change in diversity and assemblages structure Disruption of spawning cues Decreased reproduction and recruitment
	Riparian	4	Loss of seasonal flow peaks	Reduced riparian plant recruitment Invasion of exotic riparian plant species Reduced plant growth and increased mortality Reduction in species richness and plant cover
Rate of change	Aquatic	3	Reduced variability	Increase in crayfish abundance Increase in schistosomiasis
	Riparian	2	Increased variability	Decreased germination survival and growth of plants Decreased abundance and change in species assemblage of waterbirds
Not specified	Aquatic	4	River regulation; type unspecified	Decrease in species richness Increase in abundance of some macroinvertebrate taxa No change

The scale and nature of these impacts on biotic communities are shown to depend on context. Based on case studies in varied geomorphological contexts, it was shown that the denser the hydrographic network in which the river is located, the faster the hydrological alterations of reservoirs and the resulting biological impacts generated are buffered. In the same way, in Oklahoma (USA), it was demonstrated that the effect of reservoirs (used for managing flows and water supply) on the hydrological regime and ultimately on fish communities was felt much more strongly in a river in a semi-arid area, which is naturally intermittent, than in a river in a sub-tropical context. However, even if the hydrological alterations and their ecological consequences vary strongly from one situation to another, it is clear that for organisms such as fish, benthic invertebrates and aquatic plants, the most generally applicable ecological effects are associated with (1) alterations in low water and flood flow rates over several tens of percentage points, (2) flood alterations during reproduction periods or just after young fish have emerged, or (3) management practices for reservoirs with sluice gates (hydroelectricity) or draining.

Research suggests in particular that ecological impacts are especially significant when the reservoir leads to desynchronization of the hydrological regime from the natural regime, especially with regard to high water and low water periods, since the new hydrological conditions do not allow species to complete their life cycle in satisfactory conditions. From this perspective, reservoirs that serve to keep up low water levels, which are generally considered beneficial for the ecological functions of rivers, in that they reduce the severity of low water levels, can generate significant impacts on biological compartments. The artificial maintenance of high summer flow rates is harmful for the reproduction of fish and the early growth stages of fish.

Negative consequences of changes to the seasonality of flows generated by reservoirs have also been observed for populations of amphibians, through damage to reproduction conditions, like for example with the North-American frog, *Rana boylii*.

Intermittent rivers which are home to limited local diversity (low alpha diversity*: the number of species observed in a given locality is low) but high regional diversity (high beta and gamma diversities*: the species observed vary strongly from one locality to another, and the number of species observed across the region is therefore high) (Figure 25) are also especially sensitive to alterations in flow seasonality. In such contexts, the hydrological changes generated by reservoirs can have a high ecological impact on rivers with fauna and flora that was initially adapted for dried-out periods. For these naturally intermittent rivers, which are numerous in the country, particularly in potential reservoir construction areas, effects on the extent, frequency and duration of dried-out periods must therefore be quantified before analysis.

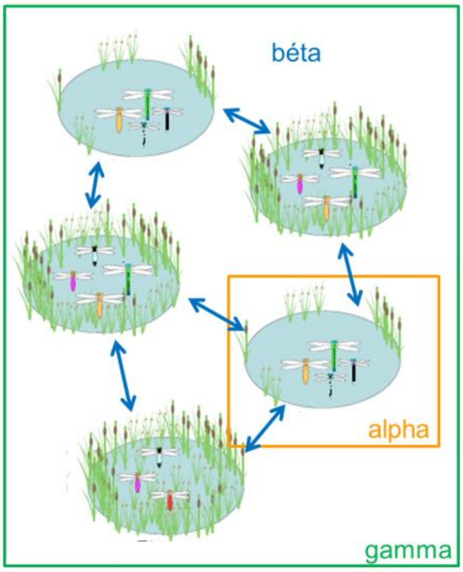


Figure 25: Illustration of three different specific biodiversity space scales (Source: © hepia).

VII.1.1.b Geomorphological changes

Sediment is an essential compartment for biological activities (habitat for many invertebrates, spawning ground for lithophilic fish, substrate where plants can take root, etc.). However, reservoirs on rivers trap sediment and also seeds and plant propagules, resulting in a high reduction of abundance and diversity* of these groups of flora downstream. A study on the Elwha River (US Pacific Coast), prior to the removal of dams there in 2014, showed that the abundance of riparian plant seeds trapped dropped by 90%, and diversity by 84%, in the same way for both surface and bottom trapping.

Moreover, changes in the substrate have also been observed downstream of reservoirs. They lead to a sediment supply deficit and potentially armouring of rivers downstream of reservoirs, which can have significant impacts on animal communities, and particularly fish populations. For example, the reproduction of lithophilic fish species (e.g. salmonids) can be seriously affected by the gravel deficit downstream of dams. Alteration of the substrate downstream of reservoirs is also harmful for aquatic flora which prefers to develop on fine sediment.

However, during draining operations, mineral and organic sediment trapped in reservoirs is resuspended, potentially leading (in particular through the massive increase in concentrations of suspended matter and ammonia, and in consumption of dissolved oxygen) to high levels of mortality among aquatic organisms. These kinds of one-off operations can generate long-term modifications (over several years) for biological communities, especially for more long-lived organisms with relatively low fecundity, such as some fish species (see Box 5).

VII.1.1.c Physico-chemical changes…..

Biological communities are also likely to be influenced by changes to the physico-chemical parameters of water following construction of a reservoir. These abiotic changes and their repercussions on animal and plant species occur both on the scale of the reservoir itself and of the downstream reach of the river concerned.

1.c.i …..in the reservoir

Aquatic biotic communities are significantly influenced by the **temperature** of the water, which indirectly affects the **concentration of oxygen dissolved** in the water. In general, species diversity increases in correlation with the temperature and the potential for thermophilic species to be established. However, temperature also has a strong influence on the range of species encountered, with species requiring the highest water oxygenation levels not found in the warmest reservoirs.

Furthermore, many studies show that biological communities respond strongly to **nutrient concentration**, with a maximum diversity of species in environments presenting intermediate concentration ranges. However, this general trend is likely to vary strongly from one biological group to another, or depending on the geographical or hydroclimatic context of the reservoir, making it impossible to set generally applicable quantitative thresholds. Where eutrophication processes occur, the anoxic conditions created are very harmful to most animal communities. As for **pH**, this is a parameter that affects the selection of organisms, because many of them cannot survive under acidic conditions. The species diversity* of benthic macroinvertebrates and macrophytes reduces significantly in acidic conditions. Finally, pesticides and trace metals in reservoirs, transferred via runoff in particular, can potentially have a toxic effect on animal and plant species. Mesocosm studies have shown, for example, that high concentrations of trace metals can reduce the reproductive success of amphibians both directly and indirectly, by modifying the algae present.

1.c.ii …..downstream of the reservoir

Reservoirs have a thermal impact on the downstream river which varies depending on reservoir size and water return method. Fish and macroinvertebrates downstream of reservoirs are most impacted by thermal changes, but to highly varying extents, depending on the type of reservoir and its management method. In general, for small or larger reservoirs, when surface water is returned, warming of the river in spring and summer occurs, which generates significant impacts on biotic communities such as the local disappearance of cold water species (salmonids and cottids), colonisation by thermophilic species, and alteration of life cycles associated with changes to the thermal regime. Benthic macroinvertebrates are also affected by this warming of water in the downstream river with a clear reduction in diversity of EPT (ephemeroptera, plecoptera, trichoptera). Conversely, due to the stratification of large reservoirs, the return of their hypoliminic water with low dissolved oxygen leads to a cooling of summer water downstream which can have significant consequences on biotic communities there. These consequences can lead to the establishment of cold water species (such as salmonid populations which then serve for amateur fishing) and the reduction and even disappearance of warm water species.

VII.1.2 Reservoirs prevent dispersal…

The dyke, weir or dam that creates reservoirs can have a long-term impact on biotic communities in rivers by creating a discontinuity within the hydrographic network that some, but not all, organisms can cross. Species are impacted differently depending on their biological or ecological characteristics (mobility, size, dispersal strategy, etc.). Fish or crustaceans that are strictly dependent on the aquatic environment will potentially be much more affected by the discontinuity represented by a reservoir than an aquatic insect with a land or air dispersal phase.

Creation of the structure and the reduction, or disappearance, of dispersal and recolonization processes can lead to a reduction in species diversity or a drastic decline in some populations upstream of reservoirs. The impact of fragmentation is particularly high and fast when it affects a population whose habitats required for completing its life cycle (breeding, feeding and rest habitats) are disconnected from each other by the reservoir. Anadromous fish species (amphihaline species which reproduce in freshwater) are especially impacted, in that, where reservoirs cut off access to spawning grounds, they can lead to the extinction of populations across whole catchment areas (downstream of reservoirs too).

However, beyond this, reservoirs, by isolating formerly interconnected populations, can affect many other animal and plant groups with varying degrees of dependence on the rivers. In this way, large reservoirs have provoked genetic isolation effects on a riparian species (*Myricaria germanica*) in 4 alpine streams in Europe, highlighting the fact that the effect of this type of barrier can also be observed on riparian plants.

Furthermore, it has been shown that the vulnerability of species to the discontinuities generated by reservoirs could be exacerbated by some river characteristics, for example on naturally intermittent rivers. Moreover, it has been demonstrated that the smaller the individual basin, and the longer the period since it was disconnected, the higher the probability of extinction of a population.

In these individual basins, the risk of local extinction is also reinforced by the rarity and degradation of available habitats. So in a portion of a basin isolated by a reservoir and with no nearby opportunities for recolonization, the community of fish can experience gradual erosion of species diversity over long periods of time.

VII.1.3 …support biodiversity

Small water bodies, such as small ponds, are generally bastions of biodiversity which host numerous species, some of which may be rare or endangered at a national or European level. However, this protective role with regard to heritage species particularly relates to environments with highly natural characteristics, which is rarely the case for reservoirs, especially when their management method is focussed on irrigation or leisure purposes.

With regard to amphibians, the regional significance of the biodiversity hosted by some manmade water bodies was highlighted by a number of authors. Small water bodies can serve as favourable environments for avifauna and aquatic birds, which are particularly attractive because natural aquatic environments are rare or degraded. However, these artificial areas are less attractive to avifauna than natural aquatic areas, which is why their potentially positive role for the preservation and development of this fauna group must be viewed from the regional context, in particular when the construction of reservoirs involves the destruction of pre-existing wetlands.

Small farm ponds are also able to host a certain level of biodiversity for other groups such as invertebrates or macrophytes. An Australian study showed, for example, that these artificial habitats can help support regional macroinvertebrate biodiversity. The benefit of these environments for biodiversity is particularly important when natural aquatic environments are rare, as in, for example, arid or highly developed regions.

VII.1.4 …but are a source of exogenous and often invasive species

Regardless of their size, reservoirs contribute significantly to the development of a whole host of calm water species that were initially not or little represented in the river, and which can then colonise the adjoining river upstream and downstream, altering the natural distribution of species along the upstream-downstream gradient. This phenomenon is all the more concerning in that it often involves exotic invasive species, which can belong to a range of groups, including fish, macrophytes, macroinvertebrates, amphibians, etc.

On a tributary of the Colorado River (USA), where fish assemblages were almost exclusively made up of native species, observations 5 years after the construction of a reservoir revealed that exotic species made up 90% of numbers in the reservoir itself, and around 80% in the downstream river.

In Mediterranean Spain, reservoirs (primarily intended for irrigation and water supply purposes) host more exotic fish species than native species, and for the Guadiana River basin, 40% of reservoirs only host exotic species, with no autochtonous species observed.

Recent summary research work has tried to set out the reasons why artificial reservoirs are particularly attractive and favourable to exotic and invasive species by comparison with analogous natural environments. There seem to be three major causes:

- artificial reservoirs receive high propagule flows via physical connections or anthropogenic activities which transfer organisms;
- reservoirs are environments with a high increase in nutrients and strong variations in environmental conditions;
- the intensity of anthropogenic pressures and the newness of these environments mean that communities and their simpler biotic interactions are more vulnerable to invasion.

Furthermore, there are positive connections between the intensity of anthropogenic pressures (understood via proxies as varied as land use, numbers of visits to water bodies or the density of roads) and the extent of the colonisation of reservoirs by invasive species, which confirms the fact that the dispersal of species by man and artificial development of environments encourages the establishment of exotic species in a reservoir. This seems to mean that the more reservoirs involve artificial development and are located in areas of high anthropisation, the more sensitive they are to biological invasion (putting autochtonous species more at risk).

VII.1.5 Examples of multi-factor responses: responses of benthic invertebrate communities to a reservoir

It is often difficult to dissociate the abiotic and biotic factors set out above to explain the overall response of communities following creation of a reservoir.

In general, the taxonomic diversity of invertebrate assemblages in a reservoir (lentic habitat with low diversity) is lower than in the upstream sector (diverse lotic habitats, often spread out across upstream sectors). High sedimentation and/or a high level of contamination by nutrients can explain a lower sensitivity of invertebrates to pollution in some water bodies, and a reduction in the number of trophic groups. Taxonomic diversity also varies between water bodies, and even within water bodies. The diversity of invertebrate families (total for ephemeroptera/plecoptera/trichoptera and for coleoptera) can also be used as an indicator of the ecological status of the water body. The taxonomic diversity of a reservoir can vary with the characteristics of the catchment area which feeds into it [altitude, proportion of grassland areas, land use, whether or not there are tributaries with strong hydrodynamics (e.g. torrents) serving as refuges].

Downstream of the reservoir, higher temperatures, a less mobile substrate and higher availability of nutrients generally contribute to a proliferation of periphyton, which leads to a change in the trophic resources available for secondary producers, and can create an increase in the number of diatom taxa downstream of a dam. However, benthic diatoms do not respond much to hydrological disruptions.

The response of the “taxonomic diversity” metric downstream of the reservoir depends on the taxonomic group considered and the local context. However, it often falls for microinvertebrates or macroinvertebrates, especially for assemblages of primarily rheophilic* and pollution sensitive species, such as assemblages of ephemeroptera, plecoptera and trichoptera. But this metric can increase for groups of species that are generally more limnophilic* and pollution tolerant. This change can be explained by fine sedimentation. Variations in the abundance and diversity of macroinvertebrates can be observed downstream of small structures, even if there are no significant variations in physico-chemcial variables.

The hydroperiod* seems to be a determining factor, both within a reservoir and downstream.

Ultimately, a reservoir is likely to impact all aquatic organisms, both in the reservoir itself, and downstream and upstream, in particular via the changes in abiotic conditions that it generates. The scale and nature of these impacts are, however, context-dependent, and therefore vary depending on such things as the type of reservoir, what it is used for, its management method, and the natural context in which the reservoir fits, as shown in the figure below.

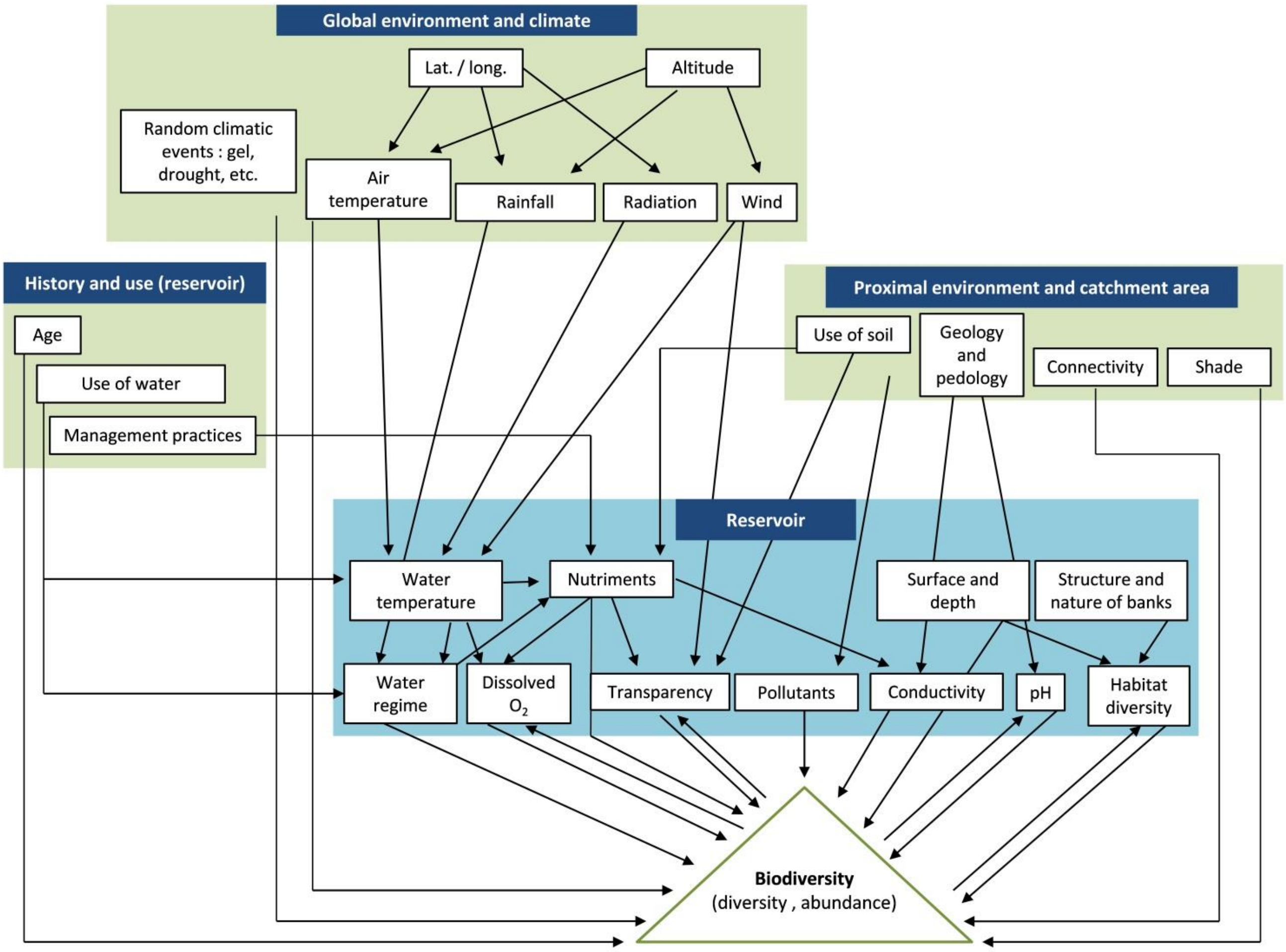


Figure 26: Biodiversity control factors within a reservoir. Based on (Oertli and Frossard, 2013).

VII.2 EFFECTS OF RESERVOIRS ON THE RIVER AND CATCHMENT AREA BIOLOGICAL COMPARTMENTS

Over time, concepts in ecology have developed to take into account anthropogenic pressures, and in particular dams that pose problems for many aquatic ecosystems. From a functional perspective, these structures create a disruption of the hydrological continuum conceptualised by Vannote et al. in 1980 as the River Continuum Concept (RCC)[21]. This was too generic and theoretical, and was later expanded in order to take into account not only pedo-climatic factors, but also anthropogenic disruptions. This is why James V. Ward and Jack A. Stanford developed the idea of "serial discontinuity" (Serial Discontinuity Concept - SDC - conceptual model) to present the conceptual framework of fragmented rivers.

Both the "SDC" and the "RCC" provide an overall system approach, without taking into account the individual responses of organisms to disruptions. **Figure** 27 provides an example, showing that the response to creation of a reservoir depends on the biological group involved and the position of the dam on the upstream-downstream continuum. For aquatic macrophytes, the response reflects an increase downstream of the structure, but mainly when it is located in the downstream river. Macroinvertebrate diversity responds very differently. It tends to increase, albeit modestly, when the structure is located upstream or downstream. However there is a strong negative response when the structure is located in the median portions of the river.

By comparing the SDC with empirical data since 1983, the authors highlighted the main challenge, which is to untangle the effects of fragmentation due to discontinuity from dams, from those of other environmental parameters that characterise lotic ecosystems in the context of regulated rivers. This is why they suggest a change of scale in order to

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[21] This principle considers the alteration of biological communities in natural lotic systems in a continuous physical conditions gradient.

better take into account the effects of multiple dams and their consequences on a large scale, by focusing on the landscape and riverscape context. Riverscape metrics can be used to start exploring how geomorphological structures influence lotic habitats by taking into account the connectivity, fragmentation and spatial distribution of these habitats.

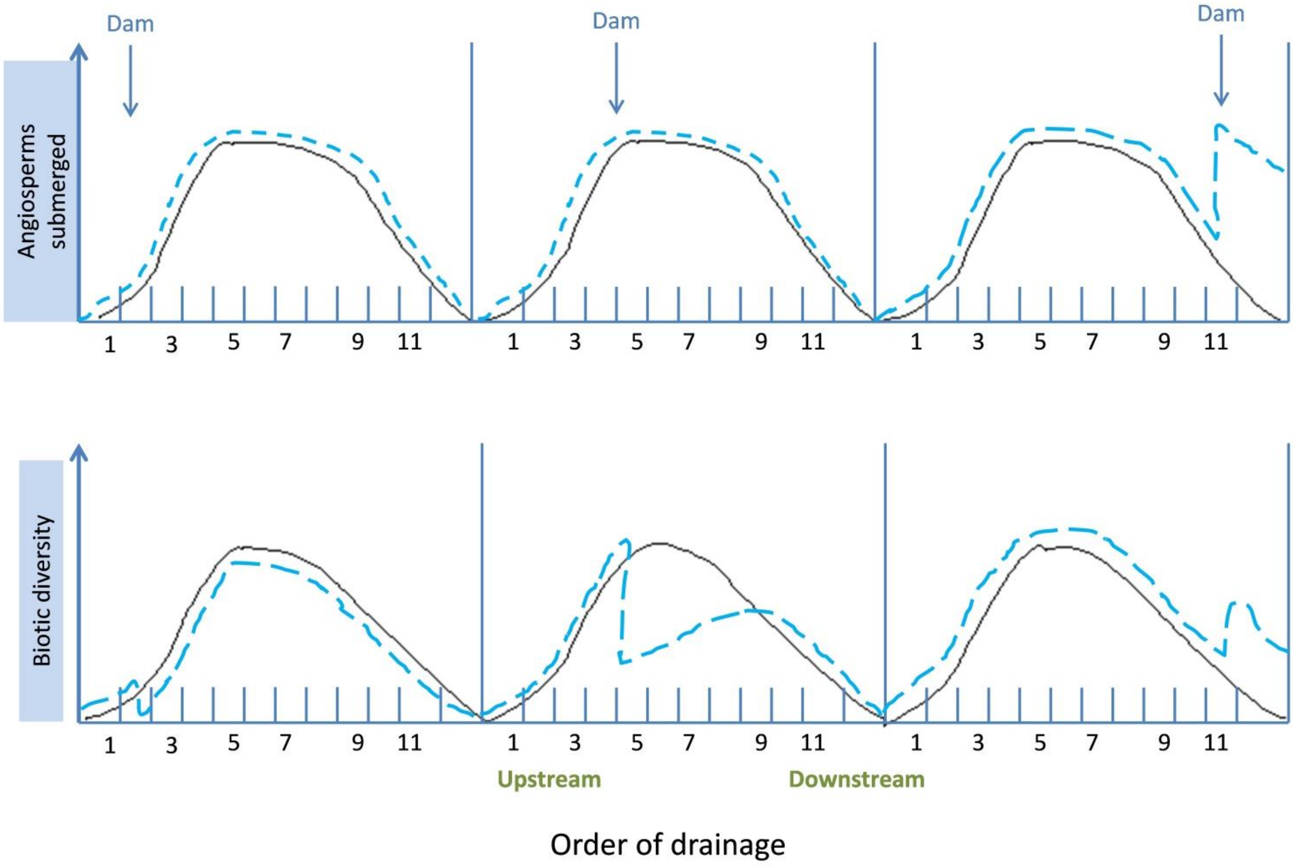

Figure 27: Relative change in biotic diversity (macroinvertebrates) and macrophytes based on Ward & Stanford's interpretation (1983) of the natural river continuum theory (solid line) and estimated effects (dotted line) of a dam according to its position on the gradient.

VII.2.1 Effects are significantly linked to the density of reservoirs in a catchment area

Catchment areas in South Africa that have a high density of reservoirs (small farm dams) show low national biotic index values (Average Score Per Taxon – ASPT; Armitage et al., 1983) based on benthic macroinvertebrates. Opportunistic taxa which tolerate pollution (e.g. molluscs, heteroptera) and are able to use various kinds of habitats (e.g. chironomids), as well as those which prefer slow currents increase, while taxa that are sensitive to pollution and disruptions decrease in numbers (e.g. trichoptera).

Other research has shown that even relatively small reservoirs can have profound effects on the biological integrity of rivers. The local effects on macroinvertebrates are an increase in the density of filters, such as some chironomids or some hydropsychids, at points located downstream of reservoirs, and an increase in the abundance and diversity of EPTs in areas directly upstream of structures. For ephemeroptera in particular, an increased abundance of baetids and caenids has also been documented for high densities of reservoirs. One study attempted to quantify the physical, chemical and biological effects of a series of three successive dams which operate differently (in terms of volume and water return regime) on an Australian river using the data obtained from 25 sites distributed along the main river and its tributaries. Assemblages of benthic invertebrates downstream of dams presented relatively more pollution tolerant taxa (chironomids, oligochaetes, acari) and relatively fewer pollution sensitive taxa (EPT), with almost full recovery observed 4 km downstream of the reservoir for the intermediate dam. The authors believe that the "barrier" effect of dams, combined with the maintenance of low flow rates, are the key factors that determine the abundance and diversity of invertebrate communities, especially in the first kilometre downstream of each dam.

With regard to fish communities in rivers, significant responses to the increase of water bodies in catchment areas are frequently documented, such as an increase in tolerant omnivorous species like the common carp. For fish, the cumulative impact of structures generally goes beyond a simple additive effect and follows more complex patterns. A study on over 13,000 sites in Wisconsin (USA) showed that the diversity of fish species was negatively affected by an increase in structures downstream, and particularly in headwater streams (Strahler number of 1). In the context of European rivers, other studies have shown that the higher the number of structures in a catchment area and the smaller the distance between structures in the area studied, the smaller the proportion of rheophilic species in the assemblage (the opposite has been observed for limnophilic species).

On another level, with regard to organisms in the water bodies themselves, many studies show that the abundance of some taxa or the composition of communities in a water body depends in part on the density and proximity of water bodies in the area, thus demonstrating the key influence of the exchange of organisms between water bodies in the same region. So a study of 76 ponds and small ponds in a semi-urban landscape in the UK demonstrated that the occurrence of some invertebrate taxa depends on factors associated with the water body itself (e.g. the size and abundance of vegetation) but also on other spatial factors reflecting the proximity of other water bodies.

VII.2.2 Fragmentation of habitats and changes to the connectivity of the environment profoundly influence aquatic biotic communities

In fragmented landscapes, movements between habitats (e.g. river segments) and therefore their connectivity, play a key role in the persistence of populations by ensuring genetic flows, the potential for recolonisation after local extinction, and the connection between different complementary habitats for reproduction or resource acquisition. By altering the dispersal options for aquatic organisms, reservoirs on rivers increase the fragmentation of the hydrographic network, which is considered to be one of the most serious threats to species diversity. Furthermore, the separation of habitats also has genetic consequences.

VII.2.2.a Fragmentation of the hydrographic network, genetic consequences and effects on the viability of populations

Within hydrographic networks, populations of fish frequently present longitudinal genetic organisation marked by a loss of genetic diversity from downstream to upstream. This situation can be explained, in particular, by a disproportionate relationship in the flow of organisms and therefore genetic flows. In natural conditions, upstream-downstream flows are more frequent than downstream-upstream ones. By strongly limiting the dispersal options for organisms, particularly from downstream to upstream, reservoirs, dams and other obstacles tend to exacerbate these spatial patterns and increase the genetic differentiation between populations (Figure 28). So by comparing rivers fragmented by reservoirs or small dams with non-fragmented rivers, studies have shown, in very different contexts - including in terms of time since fragmentation (from several decades to a few centuries), that the fragmentation of hydrographic networks has indeed led to a drop in genetic diversity (reduction in allelic diversity) in some species, and greater genetic differentiation between populations. Other studies have confirmed the influence of artificial obstacles in the genetic organisation of populations by showing, for example, a positive link between the genetic distance between populations and the number and size of reservoirs that separate them or the age of structures.

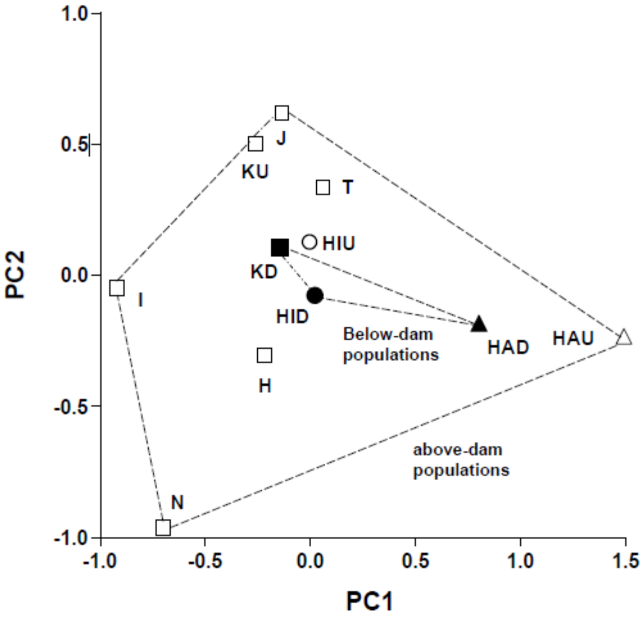

Figure 28: Genetic characterisation of salmonid populations (*Salvelinus leucomaenis*) (principal component analysis of allelic frequency data from 5 microsatellite loci) depending on the fragmentation of the hydrographic network (populations isolated by dams vs. interconnected populations). Isolated populations upstream of dams present low genetic diversity (reduced number of alleles) but are also strongly differentiated from each other. Conversely, interconnected populations present strong genetic diversity (high number of alleles) but similar characteristics due to the number of individuals exchanged between them (source: Yamamoto *and al.,* 2004).

Furthermore, it seems that small populations, once they have been isolated by reservoirs, are particularly vulnerable to a loss of genetic diversity due to an increased sensitivity to the genetic drift phenomenon. Moreover, fragmentation of the hydrographic network by reservoirs, leading to the genetic impoverishment of populations, can thereby increase their vulnerability to extinction processes through its impacts on factors such as fecundity, growth rate, survival or ability to compete.

In situ monitoring rarely allows the long-term effect of reservoirs to be studied. Dynamic or population viability models are therefore also used in order to predict outcomes for populations over the long term following the creation of a reservoir. Based on a simple metapopulation model (sub-populations of a single species interconnected through the exchange of individuals), taking into account both a constant annual extinction rate across a patch of habitats (i.e. a river segment) and the potential for recolonisation from neighbouring patches, theoretical work has shown the following facts: first, in natural conditions[22], dendritic networks generate less risk of extinction for the metapopulation and are therefore more resilient than linear networks; second, when recolonisation processes only occur from upstream to downstream (the predominant situation for systems fragmented by reservoirs, since active movements from downstream to upstream are restricted by obstacles), the likelihood of extinction of the metapopulation increases significantly and linear systems are therefore more resilient (less risk of extinction) than dendritic systems (Figure 29).

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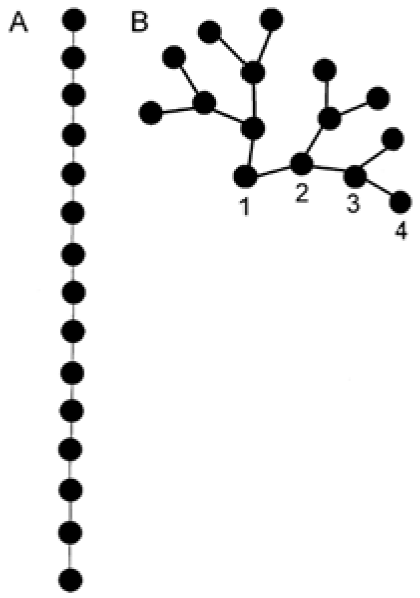
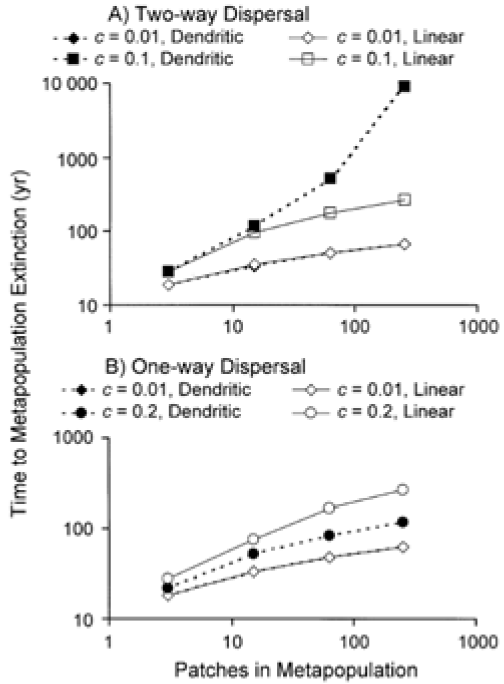
[22] With potential for recolonisation from upstream and downstream.



a) Alternative geometries for metapopulation dynamics: linear arrangement of patches for (A) and dendritic arrangement, with a 4-level hierarchical network for (B). The black circles represent patches of habitat, and the segments represent potential dispersal paths.



b) Mean lifetimes of metapopulations for systems of patches arranged in linear or dendritic networks. The probabilities of colonisation for each time step are given by parameter c (c = probability of being recolonised by dispersal from an immediately neighbouring patch). In all cases, the probability of extinction for each patch and time step was 0.1, and the initial conditions corresponded to full occupation of all patches. In case A, dispersal can occur both upstream and downstream at the same time. In case B, it can only occur downstream.

Figure 29: Changes in metapopulations according to network configuration and dispersal method. Based on Fagan, 2002.

Other studies show that the more structures are located downstream of the hydrographic network, the higher the potential impact of hydrographic fragmentation due to dams on a trout population, and that an increase in the number of reservoirs has a cumulative effect on population dynamics (Figure 30). Furthermore, once the upstream population has been isolated, it is likely to begin different evolutionary processes from those of the downstream population, which can go so far as to generate ecological or biological differences, especially for life history characteristics[23] associated with genetic divergence.

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[23] Life history characteristics are defined as a set of characteristics associated with the life cycle of a species which describe certain specific properties and functions of individuals in a population, such as size at birth, age of maturity, number, the size and sex-ratio of young produced, reproduction frequency, survival rate as a function of age, longevity, etc.

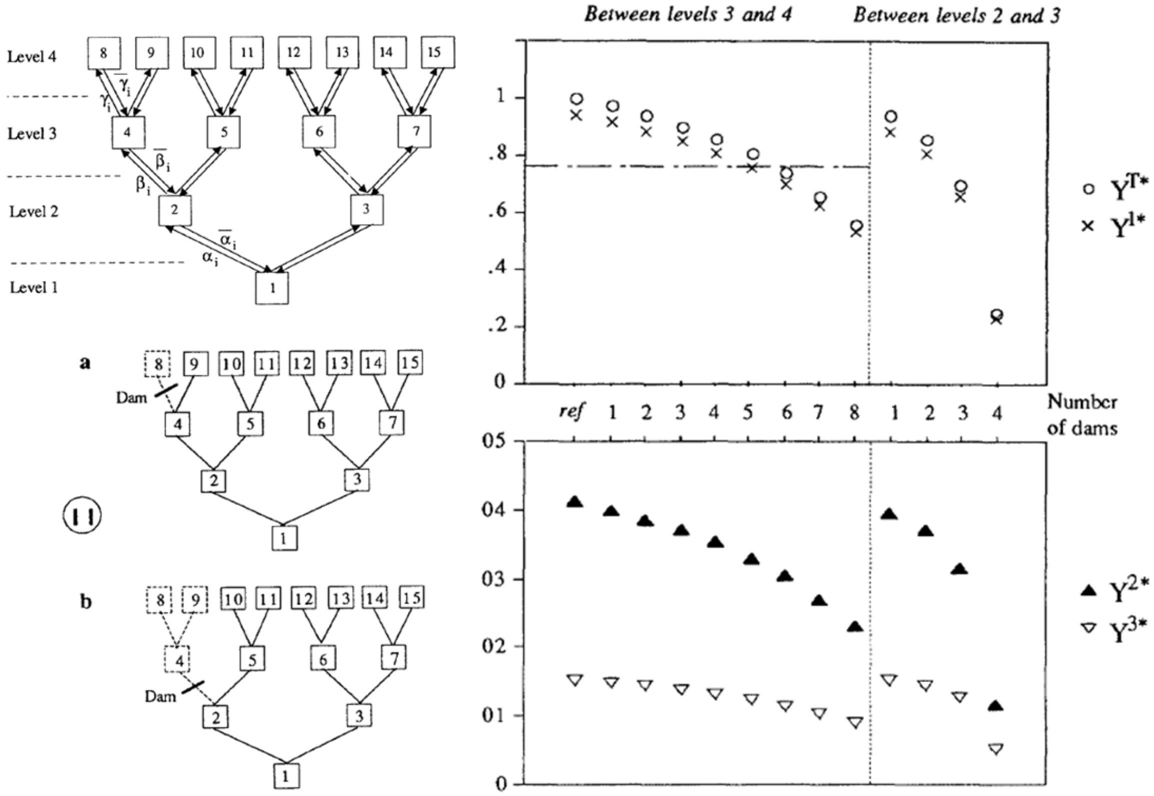

Figure 30: Simulation of the effect of the creation of dams on trout population dynamics in a fictional dendritic hydrographic network. The graphs show the effect of a gradual increase in the number of dams on the equilibrium state of the overall population (Y^T*), young fish from that year (Y^1*), juveniles (Y^2*) and adults (Y^3*). The terms Y^T*, Y^1*, Y^2*, Y^3* are indices of overall trout density (at different stages) in the hydrographic network. Based on Charles, 1998b.

VII.2.2.b Connectivity, a sign of the permeability of landscape matrix

In order to assess the cumulative impact of reservoirs on aquatic biotic communities, it seems essential to consider the system from a broader space scale, and to take into account the connectivity between different local habitats, given that most aquatic species are organised in metapopulations. For organisms with a capacity for dispersal, connectivity makes the landscape matrix permeable.

Ecological connectivity is physical, hydraulic connectivity, as stated above. For species that depend heavily on the river, reservoirs will break up habitats and thereby reduce or destroy this physical connectivity, with significant consequences for plant and animal species. For lentic species adapted to reservoirs, hydraulic connections between small water bodies can favour their dispersal across the basin and thus modify biodiversity on a local (alpha diversity) and regional (beta and gamma diversity) scale. It needs to be underlined, however, that this impact is less significant than at first it seems, in that it can affect both heritage species and potentially invasive exotic species.

Connectivity also makes the landscape matrix permeable for organisms capable of moving around in it (e.g. amphibians, aquatic insects). Connectivity potentially favour all biological groups, but the implications for the structure* of metapopulations probably depends on their dispersal strategy. For amphibians and macroinvertebrates (in terms of abundance, diversity and population dynamics), the composition of the landscape and surrounding habitats is a very important factor. For fish, and more generally for organisms that are strictly dependent on water, connectivity is primarily established via permanent or temporary aquatic systems. For example, the work of Olden et al. (2001) shows that the composition of fish assemblages from natural lakes in Ontario (Canada) is explained more by connectivity between lakes via the hydrographic network than by the physical or chemical characteristics of the lakes themselves.

The **distance between small water bodies** and **the number of them** also play a predominant role in the maintenance and development of populations of species associated with environments. For example, a study in Switzerland shows that the presence of newts (*triturus helveticus, triturus alpestris* and *triturus cristatus*) shows a positive correlation with the number of small water bodies in a surrounding area of 50 ha, underlining the importance of exchanges between sub-populations.

The spatial arrangement of small water bodies, and the distance between two sites, also plays a major role in the distribution of species and their dynamics.

Reservoirs can modify landscape permeability for some species and play an important role as migration corridors and stopover points for some of them. This stepping stone role can favour species in decline that are dependent on lentic environments. But this phenomenon also plays a part in the establishment and expansion of invasive species such as the American bullfrog in Japan.

VII.2.3 Tools and methods available for covering ecological impacts

There is currently no approach that can be used to understand and, most importantly, anticipate the overall cumulative effects of reservoirs from an ecological perspective. However, potentially useful qualitative or quantitative methods, or methodological approaches, do exist, and some of them could be applied to the issue of reservoirs in order to cover different aspects of their ecological impacts. Furthermore, new methods are being developed all the time to deal with issues of spatial organisation of communities and their dynamics. In terms of the overall analysis framework to be adopted, it seems important to reconcile both available observations and predictions made through modelling. Although it is fairly general, this analysis framework can serve to support decision-making for managing environments and thereby make it possible to consider non-additive effects.

VII.2.3.a Assessment methods for first order impacts to support public decision-making

3.a.i Bioindicators and functional metrics that respond to reservoirs

As stated above, whether or not there are reservoirs in a catchment area, and how many there are, leads to modifications of species distribution and the composition of communities in and around rivers. So we would expect current bioindicators that take into account the state of biological communities or the functional metrics that make them up to respond to the presence of reservoirs to differing degrees. The responses of bioindicators such as IPR+, I2M2, or IBD to the presence of reservoirs or to the changes that can be caused by them (e.g. changes to hydrology or thermal dynamics) have been demonstrated. However, these tools have been designed for their integrating characteristics (capacity to log a large range of pressures) and they do not provide optimal sensitivity for the issue of reservoir impacts.

3.a.ii Assessment method for hydrological impact risks

The issue of changes to flow rates can be approached and quantified using existing tools that are not specific to reservoirs. It is important to state that using these ecohydrological methods requires prior knowledge of hydrological alterations, particularly where these are significant and/or the biological stakes are high. Furthermore, these methods only cover hydrological / hydraulic alteration effects downstream of structures, which account for just some of the effects of reservoirs, and are sometimes secondary. These quantitative tools are based on two types of complementary technical approaches which are usually used to guide the definition of environmental flows for river reaches and catchment areas:

- “**Hydrological” approaches** such as the ELOHA approach (“Ecological Limits of Hydrological Alteration”, Poff, Richter et al. 2010), which is the most fully developed and widely used because it covers several biological groups: fish, macroinvertebrates, riparian plants. The authors recommend adopting multivariate models for predicting ecological responses, taking into account both hydrological variables and additional variables not linked to flow rates (temperature, substrate, type of disruption, etc.)

- "**Hydraulic and habitat" approaches**, targeted at low to medium flow rates, combine hydraulic models and biological models to express some hydrological alterations as changes in the quality of hydraulic habitat for organisms. They are widely used in France, and material is available for fish, such as EVHA or Estimhab, both available online (http://dynam.irstea.fr). For significant changes in habitat, this type of approach has made convincing predictions about the effects of changes to low water flow on communities of fish and macroinvertebrates.

Neither of these technical approaches directly provide environmental flow values, and even less so, values in terms of the number and surface area of reservoirs than can be supported by a catchment area. But they do provide relevant information to support decision-making, by comparing the ecological effects of various management scenarios. Since these methods apply to the catchment area scale, they require, first and foremost, ecological modelling/extrapolation across the basin. There are a number of potential strategies for doing this. The first involves identifying representative sites for the problem posed and/or with high environmental stakes on which to base the habitat modelling. This was the option selected for the "abstractable volume" studies in the Rhône basin. A second solution is to estimate the hydraulic functioning of the basin in order to model habitat alterations across it.

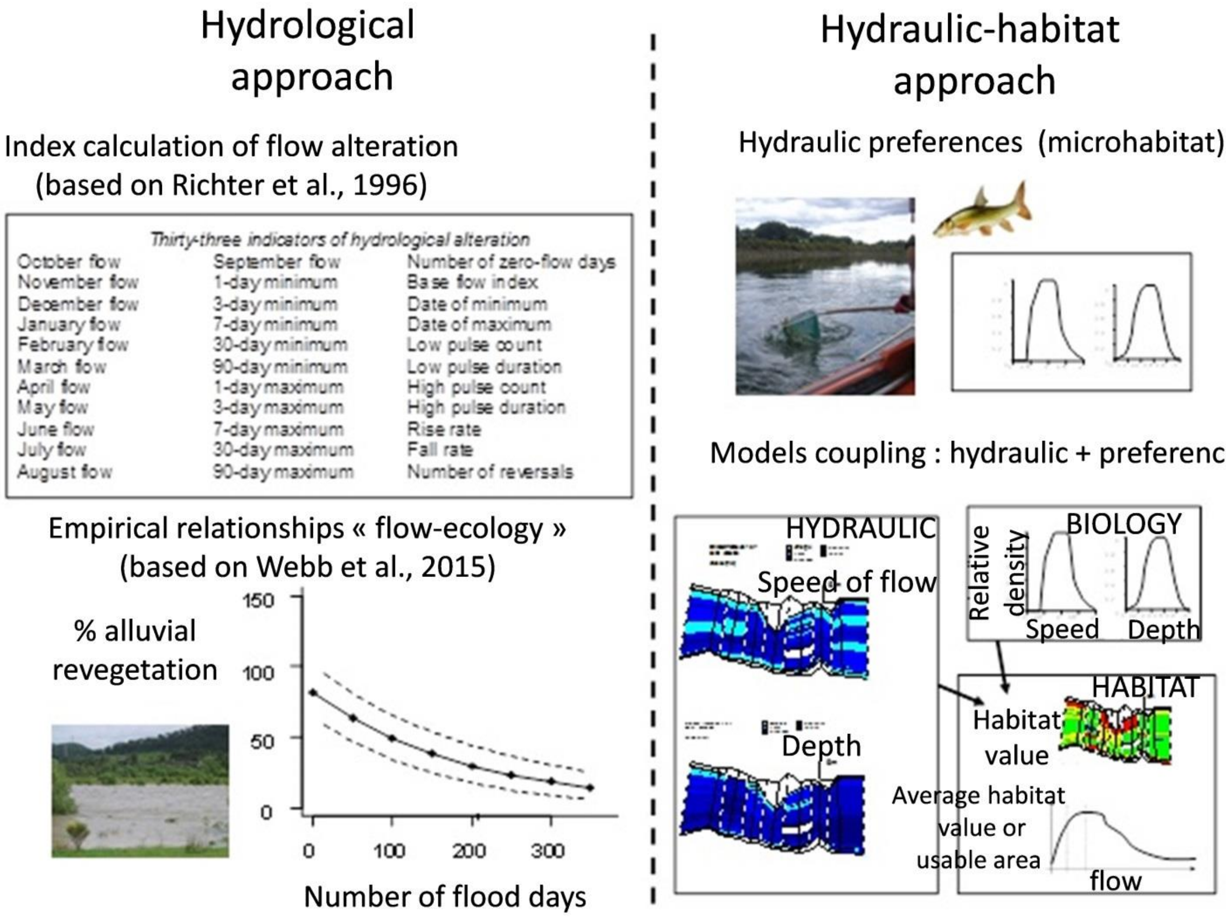

Figure 31: Simplified representation of "hydrological" and "hydraulic and habitat" approaches used to define environmental flows. The hydrological approach quantifies the distance from the natural regime for a range of variables reflecting all aspects of the regime, and then looks for empirical "flow-environment" relationships. The habitat approach targets low to medium flows, and uses a hydraulic model to describe the hydraulic characteristics of species microhabitats (e.g. water speeds, heights); combined with biological models for hydraulic preferences, this model estimates the positive value changes in the habitat or surface areas within the river reach. Drawn from Lamouroux *and al*.

For the definition of environmental flows, some of the literature focused on defining approaches for combining available expertise and tools, due to both ecological and hydrological uncertainties. These approaches are generally based on a technical comparison between management scenarios, and involve: (1) description of the natural and current hydrological context, current uses and planned management scenarios (2) description of the overall ecological context, (3) identification of relevant metrics (hydrological and/or habitat and/or others) to describe the impacts of scenarios (modifications of uses, environmental changes) and (4) comparison of scenarios (Figure 31).

3.a.iii Method focused on key species

One methodological framework proposed by Vander Zanden and Olden (2008) can be used to assess the vulnerability of water bodies (including reservoirs) with regard to three invasive species: a fish, a bivalve and a crustacean (Figure 32). Their approach involves separately taking into account (1) species' capacity for dispersal and accessibility of sites, (2) capacity of sites to allow the development of invasive species and (3) potential negative impacts of invasive species on the receiving ecosystem. This approach seems like it could be fairly easily adapted to other geographical contexts, although it does require detailed knowledge of the species concerned (ecological niche, dispersal capacity) and potential receiving ecosystems.

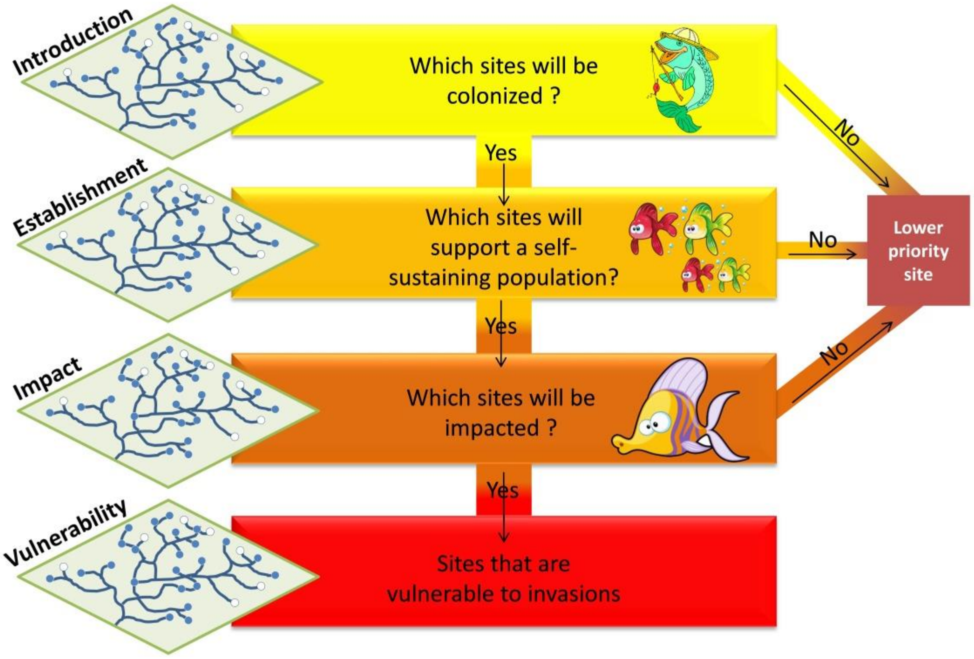

Figure 32: A conceptual framework for assessing site vulnerability on a landscape comprised of several lakes. The approach separately assesses potential for introduction, establishment and adverse effects of a given specific invasive species for each of a series of lakes. Assessment of vulnerability for individual lakes can help guide the targeting of invasive species prevention and management efforts. Vander Zanden and Olden (2008).

3.a.iv Method focused on identifying the structures with the highest impacts

Based on a specific case in California, Grantham et al. (2014) proposed an approach for assessing the ecological risks posed by reservoirs, focusing particularly on the issue of hydrology, with the ultimate objective of producing an overall assessment of all reservoirs in the region, and generating operational recommendations in terms of management, and, if appropriate, the removal of some reservoirs. This approach proposes several stages for selection and assessment. First, reservoirs on significant catchment areas are identified (the authors ignore reservoirs that control less than 1 km^2 of catchment areas of on the grounds that below this limit, hydrological impacts are negligible). Next, information with varying degrees of precision (depending on availability of data) on the potential or demonstrated hydrological impact of each reservoir is collected. Finally, the environmental risk is assessed, taking into account whether the river on which the reservoir is established hosts fish species that are potentially vulnerable to hydrological modifications, or whether local extinctions of this species group have been observed. Based on this information, the authors suggest ranking reservoirs by the ecological risk they represent, identifying reservoirs that could be removed and carrying out further studies if required.

VII.2.4 Assessment methods for predicting the development of communities across a region

4.a.i Metapopulation models and potential impact of hydrographic network fragmentation

The potential impact of hydrographic network fragmentation is covered by models in varying stages of development that include the concept of metapopulations. Using this type of approach and taking into account theoretical hydrographic networks, it becomes possible to test hypotheses and scenarios for the impact of fragmentation generated by reservoirs on the sustainability of populations. Theoretical studies have shown that the impact of fragmentation on population dynamics can vary strongly depending on the structure of the hydrographic network, and that the potential impact of reservoirs depends, of course, on how many there are, but also on their position in the hydrographic network.

These population dynamic model approaches can also apply to more specific cases. Jager et al. (2001) developed this type of approach for improving understanding of the consequences of hydrographic fragmentation in the Snake River (USA) on long-term outcomes for sturgeon populations (*acipenser transmontanus*). To this end, the authors combined very concrete considerations (hydrographic network structure, position of reservoirs and state of current populations) with more theoretical or uncertain information (population dynamic parameters, dispersal capacity) to identify the most vulnerable sub-populations and the most damaging structures, and better appreciate the key processes involved in long-term maintenance of populations.

4.a.ii The notion of metacommunities*

The concept of metacommunities (in the sense of a series of local communities connected together by the movement of potentially interactive species) seems particularly useful for dealing with biological interactions on a catchment area scale between rivers and the stagnant environments generated by reservoirs with varying degrees of connection to hydrographic networks or other reservoirs. However, these approaches are still in the development stage.

4.a.iii Modelling of ecological networks

Many studies that have covered the issue of ecological process modelling in hydrographic networks have tried to integrate exchanges and flows between various landscape elements. It seems that dendritic systems are more appropriate for this than the more traditional two-dimensional systems used for terrestrial ecosystems due to restrictions associated with movement of organisms. A theoretical framework proposed by Fuller et al. (2015) can be used to take reservoirs in the hydrographic network into account. To this end, they identify “river” habitats, fragmentation agents (e.g. dams), habitats created by the fragmentation agent (e.g. the water body formed by the dam) and surrounding habitats. Although these proposals are very recent and exploratory, they should lead to developments that could eventually be applied to reservoirs in the fullness of time.

VII.3 CONCLUSION

In general, the international academic literature has been shown to be relatively light on the issue of small reservoirs and their impact on river ecology, in comparison with the abundance of literature dealing with large reservoirs, and particularly hydroelectric dams. Other environments similar to reservoirs, such as small water bodies like ponds, small ponds, large dams and beaver dams were therefore studied in addition to the literature already known by the experts. Analysis of these various scientific studies has provided some key aspects of knowledge, methods and tools which can, at least in part, be applied to this assessment.

Reservoirs are likely to impact all biological compartments, via modifications in environmental conditions (with regard to hydrology, morphology, physico-chemistry, etc.) but also by affecting connectivity and organisms' dispersal processes. The scale and type of these impacts depend on context, and are particularly affected by: (1) the type of reservoir and its management method, (2) the natural context, (3) the type of communities present and their major biological/ecological characteristics, and (4) the relative degree of anthropisation of relevant systems. Unlike impacts on abiotic compartments, which generally occur downstream of reservoirs, biological impacts can also be observed upstream and across regions, in connection with the specific dispersal options for organisms. Furthermore, these impacts occur over the long term, e.g. the processes of extinction associated with landscape fragmentation (as perceived by species) via reservoirs which spread over several decades/centuries. Some examples show that these biological communities keep evolving 20 years after construction of a reservoir. But the majority of studies cover these questions from a short-term perspective (a few years after construction of reservoirs), and it is therefore likely that they only provide a partial overview of the real ecological impacts. The issue of reservoir removal has not been covered as such in this assessment, but there do seem to be some heritage effects. Once a reservoir has been removed, the river and its biological communities do not necessarily return to conditions before the reservoir. This suggests that the ecological impact of reservoirs can last long after they have disappeared.

There is currently no approach that can be used to understand and, most importantly, anticipate the overall cumulative effects of reservoirs from an ecological perspective. However, potentially useful tools are available, including bio-indicators or metrics that are sensitive to reservoirs, tools or approaches for covering impacts associated with hydrology, fragmentation or the risk of invasive species, etc.

Chapter VIII CONCLUSION

This assessment confirmed that reservoirs have real, complex, and diverse effects of varied intensity on aquatic ecosystems. By storing and diverting water, reservoirs change the natural distribution and movement pathways of water and transported materials. They therefore influence flow regimes and sediment, nutrient and contaminant transfer, particularly by extending the amount of time they spend in water and modifying their physico-chemical characteristics, the interaction conditions between transported compounds and the intensity of primary production, with related ecological impacts.

Effects of an individual reservoir

The analysis of the effects of an individual reservoir proved to be an essential step prior to the analysis of the cumulative effects of several reservoirs. This step was used to examine how the processes involved are understood, to reveal the various interactions between these processes and identify a number of influencing factors. It provided precisions on estimates, for instance for losses from infiltration or evaporation. During the exploratory phase, there was substantial uncertainty concerning these two aspects in the water balance of the reservoir. Reservoirs act as reactors linked with the creation of lentic conditions, separating the upstream portion from the downstream portion of rivers (or the hillslope and the river in the case of a hillslope reservoir). They modify the volume, nature (change in speciation for some elements) and temporal dynamics of flows carried downstream and can significantly impact the way the downstream reaches of the river function from a hydrological, morphological, physico-chemical and ecological standpoint.

Two compartments therefore need to be considered to understand the effects of a reservoir: (i) **the new aquatic environment created by the reservoir** and (ii) **the river** - the downstream portion that is more or less the direct receptor, and the upstream portion for biology.

(i) **The conditions created within the reservoir stimulate certain biological, physical and chemical processes**. The reservoir is an area of increased evaporation and sometimes of significant infiltration, and always traps sediment. It can also be conducive to denitrification, or the degradation of some agricultural chemical molecules, the development of eutrophication, greenhouse gas emissions, the creation of difficult to manage reserves of phosphorus, trace metals or pesticides that can become resuspended and released over the long term. Particular attention should be paid to the risk of eutrophication. It is widespread in all catchment areas, particularly due to flooded soil, can jeopardize various uses of the water body and can amplify or mitigate the effects of other pollutants. From a biotic standpoint, the reservoir also represents a new environment that may become the home to a host of other species not found in the river and which could colonise the hydrographic network and interact with existing species. Reservoirs can be favourable habitats for some heritage species but can be particularly favourable for many problem species, especially exotic invasive species.

(ii) **The presence of a reservoir influences all the functional characteristics of the downstream river**, by modifying the volume, dynamics, nature and temporal aspects of flows in terms of hydrology, sediment transport, morphological changes in the stream bed induced by its modification, or the physico-chemical characteristics of water. These modifications to the abiotic conditions downstream of the reservoir lead to changes in biological communities depending on the biological and ecological characteristics of the species. When eutrophication develops, it can spread downstream through changes in the bioavailability of phosphorus and the nitrogen-phosphorus ratio.

Furthermore, by creating an obstacle that is sometimes unpassable, thereby limiting or preventing exchanges of individuals between sub-populations, a reservoir built on a river is likely to generate ecological impacts much further upstream from where it is located. These impacts include the loss of genetic diversity (genetic drift) and long-term decline that may lead to the extinction of isolated populations.

The effects from reservoirs are very context-dependent and influenced in particular **by the combined effect of the following three elements,** which are closely linked:

- **inflows into the reservoir.** These depend on the reservoir's catchment area: geomorphology, soil, hydrological functioning, climate (rain, evaporation), land use and cultural practices, position of the reservoir in relation to the river,

- **the specific characteristics of the reservoir itself:** size, morphology, volume and abstraction dynamics (depending on uses), water return method, which influence what happens to inflows (and chemical elements already present). For the physico-chemical characteristics, the amount of time the water spends in the reservoir (residence time) is a key factor,
- **the method in which water is returned downstream,** if applicable: spill, depth of intake, whether or not compensation water is maintained. If water is returned, the influence of the reservoir depends on the volume of flows and water concentrations returned compared to those of the downstream river, this means the position of the reservoir in relation to the hydrographic network of the catchment area in question (upstream or downstream of the basin, whether it is directly connected to the river or not – hillslope reservoir), whether there is compensation water or a diversion, whether there are major tributaries or inflows further downstream, and the vulnerability of the environment.

Complex and non-linear interactions between these three elements make it difficult to directly transfer results from literature, especially since the geographic, climatic and land use contexts are often quite different from the situations in mainland France. For the same reasons, indicators that have been developed either directly on the effects of a reservoir on a given variable or, for example, that connect the surface area and capacity of a reservoir, cannot be directly applied. Table 7 summarises the various impacts that can occur in or downstream of the reservoir. Although the major tendencies are known, it is difficult to directly quantify the effects of a reservoir on a given functional characteristic of the aquatic environment only using findings from literature. It should also be underlined that aspects related to the management of the reservoir such as water uses and abstraction dynamics, the water return method or whether there is compensation water, are rarely cited in literature on reservoirs. However, analysis of the determining factors involved in the effect of a reservoir show the importance of these factors along with the results of the exploratory phase that took place before the assessment.

Table 7: Different types of impacts (1st, 2nd and 3rd order impacts, as presented in the introduction) in and downstream of the reservoir (based on Bergkamp *and al,*. 2000).

Position in relation to the dam	**Impact Category**	**Impact**
Upstream (in the reservoir)	1st order impact	Modification of the thermal regime; risk of deoxygenisation Sediment accumulation in the reservoir; flooding Changes to the physico-chemical characteristics of water Groundwater around the reservoir
	2nd order impact	Plankton and periphyton Growth of aquatic macrophytes; risk of eutrophication Riparian vegetation
	3rd order impact	Invertebrates, fish, birds and mammals
Downstream	1st order impact	Daily, seasonal and annual flow rates Reduced sediment fluxes Changes to the morphology of the channel, flood plain and coastal delta Groundwater in the riparian zone Water temperature, thermal pollution Ice formation
	2nd order impact	Plankton and periphyton Growth of aquatic macrophytes Riparian vegetation Carbon fluxes, distortion of the cycle
	3rd order impact	Invertebrates, fish, birds and mammals Estuarine impacts Marine impacts

Cumulative effects of reservoirs

The cumulative effects of reservoirs are rarely discussed in scientific literature apart from in hydrology, where there are more studies. The reservoirs discussed in literature are almost always reservoirs on rivers. In light of this, literature on large structures, lakes, wetlands and ponds was also consulted as it often contains scientific research on cumulative effects. Consequently, depending on the different sets of functional characteristics (related to hydrology/hydrogeology, sediment transport, physico-chemical properties, and ecology), the water bodies considered differ in their geographic context (climate, topography in particular) and in type (artificial reservoir or natural lake, use, size, etc.) and some are quite different from the reservoirs considered in this assessment, as defined in the introduction. Widening the types of water bodies considered seemed necessary to move the discussion forward, at least from a methodological standpoint. It should also be noted that research on cumulative effects are often conceptual and the findings are often methodological. When results from observations or models are available, it is important (more so than for individual reservoirs) to examine the possibility of extrapolating them on a case by case basis depending on the environmental and structural context and the parameter in question.

One point that is essential for all the elements considered **is the distribution of reservoirs within a catchment area, the hydrological and ecological connectivity**[24] between reservoirs, catchment area zones and different stretches of the hydrographic network in question.

The impacts of reservoirs accumulate from upstream to downstream for hydrology, with a reduction in flows along the entire hydrographic network, all the way to the sea. This influence on rivers can, however, be "diluted" further downstream, with inflows from other areas that function in a less anthropised manner. This **underlines the importance of the scale at which the cumulative effects of reservoirs are assessed.** These effects can vary significantly depending on the size of the catchment area considered in some contexts: catchment area made up of highly contrasting areas where the effects can offset each other.

As for sediment transport, in most cases reservoirs trap sediment and especially the coarse sediment load. However, the sediment deficit that occurs downstream can, depending on the context and if the substrate allows, lead to a bed incision that partially offsets the deficit. On the whole though, a network of reservoirs limits the spread of sediment downstream.

For chemical elements where water acts as a vector, the influence of a network of reservoirs on the downstream river is more complex. It can be expressed in terms of concentrations, speciation and flow depending on whether the cumulative effect on flows for the entire catchment area (which can add up just as for hydrology) and/or the effects on water quality (speciation and concentrations) in the downstream aquatic environment are being examined. One important concept for assessing the cumulative effect is the distance of influence. This term designates, for a variable characterising the physico-chemical quality of water, the distance required downstream of each reservoir so that the variable in question returns to the level if there was no reservoir. It is typically several dozen metres for the dissolved oxygen content, but can reach several hundred metres for the temperature. If the distance between two reservoirs is greater than the distance of influence, there is no interaction between the effects generated by each reservoir. Otherwise, these interactions need to be taken into account and the effects can spread from upstream to downstream. Hydrological connectivity between the reservoirs is therefore a determining factor as well. The distance of influence varies with the variable considered, the degree to which it is modified in the reservoir, the water return method, and the changes in the variable downstream, linked to physical and chemical processes or hydrological conditions: diffusive supply of the river or presence of tributaries. This concept is relevant for temperature, dissolved oxygen content and concentrations of nutrients or contaminants. It does not apply when flows are considered.

The case of ecology is more complex. The presence of reservoirs at least partially disconnects the various stream reaches from the catchment area. However it generates new connections between current habitats and stagnant environments and affects the dispersal dynamics of species. Here to, the influence of a network of reservoirs depends on whether some tributaries (or other landscape structures such as hedges, rainforests, etc.) remain sufficiently linked to enable the exchanges required to maintain species (metapopulations and metacommunities).

The presence of reservoirs also affects the **temporal aspects of the hydrosystem:** flows transferred into the system (water, nitrate, different forms of phosphorus, coarse sediment) evolve in terms of both accumulation (e.g. on an annual scale) and temporal dynamics. These changes are particularly linked to the reservoir filling and abstraction dynamics for water, flooding dynamics for sediment, and seasonal dynamics for physico-chemical properties. These changes can sometimes delay processes, diminish the temporal variability or accentuate it. The signal amplitude is often affected as well. In the presence of several reservoirs, these changes, attenuations/amplifications should be considered on the scale of the landscape and their consequences on evaluated organisms.

The assessment highlighted the need to take **long periods** into account in the analysis, whether this involves the morphological change of rivers, the mobility of certain stored chemical elements such as phosphorus, trace metals or

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[24] Connectivity is understood as the degree of connection between the entities considered. It encompasses the degree of branching of the hydrographic network, the distance between reservoirs and whether they are located on the river, and the degree of fragmentation of the hydrographic network created by the reservoirs.

pesticides, or changes to populations of organisms linked to the aquatic environment. In reality, these processes can be expressed over several decades. In the same way, the combined change to the footprint of reservoirs on the basin, land uses (farming practices), and the resulting way in which the catchment area functions, in terms of both hydrological behaviour and the export of sediments, nutrients and pollutants is a phenomenon that must be expressed over the medium to long term. In the long term, there are obviously legacy effects. In other words, the disappearance of reservoirs does not necessarily mean that their impacts will immediately vanish. On the contrary, they could continue to exist for several decades or centuries. These long-term issues are hardly addressed in literature.

In addition to the idea of time and long-term changes, it seems necessary to occasionally review the assessments of cumulative effects in order to update them by integrating the determinants affecting the functioning of the basin (particularly land use and climate changes) and changes to the state of the aquatic environment: **the assessment of cumulative effects must be an iterative process.**

Lacking data and on-going research

The assessment did not bring to light any cumulative effects or threshold indicators (such as reservoir density) that could be applied as is to determine if there are too many reservoirs in a catchment area. However it did identify metrics that seem important to include in generic impact and cumulative effect studies, such as longitudinal variations of proportions of different categories of invertebrates. This would help identify discontinuities or gradients in these metrics along the hydrographic network in order to better characterise the effect of reservoirs on these components depending on the context, and eventually lead to a predictive approach.

The need to acquire data was identified at two complementary levels:

(i) efforts must be made on characterising reservoirs (size, morphology, position in the catchment area and regarding the river, water use and return method) and data needs to be capitalised on, as was already underlined during the exploratory phase of the assessment. Although these efforts have already been made in some catchment areas, it has not been done everywhere. Remote detection techniques are offering rapidly evolving solutions in this field. However, their use requires equipment and skills that are not always available in the operational field;

(ii) knowledge must continue to be increased concerning the cause and effect relationships of reservoirs on the various functional characteristics of the river, as information is still lacking in mainland France. It is particularly necessary to **jointly study all the functional characteristics, their interactions and their response to the presence of reservoirs on a few “workshop” catchment areas with contrasting characteristics.** This type of approach seems to be the only way of developing an organised and quantified body of knowledge on the cumulative effect of reservoirs on all the functional characteristics of rivers, leading to the development of validated models, tools and indicators that can be applied to similar contexts and contribute to informed decision-making. Existing studies on lake networks, wetlands, large reservoirs or small ponds could provide methodological elements and suggest indicators that could be useful if adapted to the context of reservoirs. Furthermore, the assessment did not provide further insight into the influence of the reservoir management method on their effects. Although the results of the exploratory phase led to the assumption that the management method has a strong influence (whether there is compensation water, water return method – overflow or drawdown, abstraction dynamics – associated with the land use and farming practices, abstraction substitution), there are no references on this aspect. It is therefore essential to acquire reference data on this subject.

Modelling seems necessary to formalise and organise knowledge and study scenarios related to the location of reservoirs and their management, for instance, or explore the year-to-year variability of situations in a catchment area. The modelling approach comes with the traditional problem of the balance between available data and the level of sophistication required for the models to be used. Several types of hydrological models exist, which differ in the representation of the spatialization associated with reservoirs. The findings for other functional characteristics of the hydrosystem examined in this assessment (ecology, physico-chemical aspects, etc.) suggest that a completely distributed approach would be useful to identify the interactions between different reservoirs. The results of the assessment do not currently make it possible to determine which type of modelling is necessary depending on the contexts. To move forward in this approach, it appears necessary to use different types of models and evaluate related uncertainties on catchment areas where available data makes this possible.

Time and space scales: two key concepts for assessing cumulative effects.

The spatial and temporal scales to be used to assess the cumulative effects must incorporate all expected effects. As far as the spatial scale is concerned, theoretical considerations on cumulative effects assessments stress the interest of using a **two-pronged approach** (as was suggested after the exploratory phase), which would make it possible to focus greater attention on certain areas of the catchment area that are more sensitive or subject to greater pressure, while maintaining a global view of the way the basin functions. For example, based on this proposal, a **study related to a given project** would be based on a **prior study, carried out on the scale of the entire basin** (e.g. scale of the SAGE plan) used to characterise the overall hydrological functioning, identify zones with important biological, water quality and use issues and with strong pressures (water abstraction, land use, other types of anthropic pressures). More in-depth studies could be conducted in these sensitive zones. Studies for new projects would be based on these contextual factors in order to better identify the methods to be implemented and the issues to be taken into account.

Some effects can occur over the long term, such as geomorphological changes to rivers, the storage-release of phosphorus or certain contaminants, or changes to certain populations, depending on the dynamics of the species in question. They can also occur on broad spatial scales, with reduced water and sediment inflows into the sea or global greenhouse gas emissions. If a study on the cumulative effects of a group of projects cannot explore these scales, these aspects should still be taken into account.

The issue of scale comes down to the issue of governance. Studies agree on the importance of having cumulative effects assessment conducted by an entity acting at a greater scale than the projects in question. This ensures the transparency and consistency of choices concerning the environmental components to be preserved and the metrics and thresholds used to determine if the effects are acceptable for a vast area. This type of approach also allows data to be collected in a harmonised manner, guaranteeing that they can be capitalised on, shared, and reused.

The assessment focused on the cumulative effects of reservoirs on the environment. It did not address the economic and social aspects associated with their use. The results provide greater insight into the study of the ecosystem uses, services and disservices associated with a hydrosystem modified by reservoirs and help gain a more objective assessment of the overall interest of these structures in a catchment area, including economic and social aspects.

GLOSSARY

Accretion: Accumulation of sediment

Aggradation: Increase in land elevation of the channel bed or alluvial plain due to the deposition of sediment

Alteration of a river: Change in the shape of a river or stream reach under the effect of a change in external (solid or liquid flow) or internal control factors (plant colonisation)

Alpha diversity: Number of species present in a uniform habitat of a fixed size at a given time. It corresponds to the diversity on the local scale (e.g. station, grid, etc.)

Artificial pond: Manmade water body built outside the river and supplied by groundwater or river pumping.

Beta diversity: Rate of species diversity between different locations (stations, grids, etc.) within a given geographic area.

Bedload: Coarse sediment particles that make up the bed of a river which are transported by rolling or sliding along the bed

Dam: Artificial barrier used to create a reservoir that generally blocks a river

Eddy Covariance: Measurement of evaporation by calculating vertical turbulent fluxes on the evaporation surface

Fitness (or selective value): Ability of an organism (and therefore of a population) to maintain its biomass over several generations. It is used to measure the reproductive success of a genotype according to its frequency variations in a population from one generation to the next.

Gamma diversity: Total number of species in a broad geographic area. It therefore corresponds to the diversity on a regional scale and depends on both the alpha diversity (mean number of species on a local scale) and beta diversity (ratio between regional and local species diversity).

Hydrochory: Plant seed or diaspore dispersal through water.

Hydroperiod: Seasonal pattern of water levels in a wetland area. It mainly describes the period during which a wetland is covered with water.

Incision: When the channel bed or valley is cut downward through the effect of sediment erosion

Limnophila: Organisms that thrive in calm or stagnant water.

Lithophila: Organisms that lay their eggs on a mineral substrate such as pebbles/gravel.

Small pond: Stagnant aquatic environment that is generally small and shallow with well-developed vegetation resulting from rich organic matter.

Metacommunity: Set of local potentially interacting communities of species in a broad biogeographic region. In other words, a metacommunity integrates all metapopulations present in a given landscape.

Metapopulation: Ecological concept that defines a set of populations of individuals of the same species spatially or temporally separated and interconnected through dispersal.

Pan evaporation or evaporation from Class A evaporation pans: Evaporation of a volume of water subjected solely to local meteorological conditions. This evaporation differs from potential evapotranspiration, which corresponds to evapotranspiration from a grass-covered surface not limited by water. The standard for measuring pan evaporation is to use Class A pans. Although it involves measuring open water evaporation, pan evaporation differs from evaporation from a reservoir due to the fact that the micrometeorological parameters are influenced by the immediate environment of the pan.

Pond: Natural or artificial body of stagnant water that is generally smaller and shallower than a lake

Potential evapotranspiration: defined as the amount of evaporation from a sufficiently large surface of short grass with a sufficient water source. **Actual evapotranspiration** is the quantity of water transferred from a surface into the atmosphere through evaporation and plant transpiration. Actual evapotranspiration is the quantity of water that actually evapotranspires given the plant cover and quantity of water available, as opposed to potential evapotranspiration,

Psychrophile: Organisms whose spatial distribution is limited by high temperatures. Their optimum growth temperature is less than 20°C (sometimes 15°C for benthic macroinvertebrates).

Q10, Q90: Q10: flow rate exceeded 10% of the time; Q90: flow rate exceeded 90% of the time.

Reduction: Reduction in the width of the low-water channel (or active channel) of a river.

Reservoir: Any lentic body of water of anthropic origin.

Rheophile: Organisms that prefer habitats in fast moving water currents.

Species diversity: Refers to the number of species present in a given environment. Simplest measurement of the biodiversity in all or part of an ecosystem.

Scintillometry: Technique used to measure evapotranspiration by determining latent heat fluxes, based on the scintillation of an electromagnetic wave that crosses the atmosphere.

Taxonomic structure (or specific structure when examining the structure of a community of the same “species”): Refers to the numerical organisation of the population. This expresses a type of biological organisation that has ecological implications in terms of functioning or types of interactions.

Thermophiles: Organisms requiring high temperatures to develop.

VCN3, VNCx: Minimum flow rate or low water flow rate recorded over 3 (or x) consecutive days.

Water body: Any lentic body of water of natural or anthropic origin.

ACRONYMS

ASPT: Average Score Per Taxon

BRGM: *Bureau de Recherches Géologiques et Minières* (French geological survey)

CACG: *Compagnie d’Aménagement des Coteaux de Gascogne* (Gascogne area planning and development Board)

CAMS: Catchment Abstraction Management Strategy

CEA: Cumulative Effect Assessment

CEC: Cumulative Environmental Change

CEQ: Council on Environmental Quality

CLE: *Commission Locale de l’Eau* (local water commission)

DOC: Dissolved Organic Carbon

DD: Discontinuity Distance

DE: Discriminatory Efficiency

DOE: *Débits d’Objectif d’Etiage* (low water regulating flows)

DDT: *Direction Départementale des Territoires* (Decentralised government department for territorial management)

DMF: Decision Making Framework

DREAL: *Direction Régionale de l’Environnement, de l’Aménagement et du Logement* (Decentralised Ministry of the Environment department in the regions)

DTM: Digital Terrain Model

EPT: Ephemeroptera, Plecoptera, Trichoptera

EVHA: *Evaluation de l’Habitat* (a model for assessing habitats)

GIS: Geographic Information System

I2M2: *Indice Invertébré Multimétrique* (a multi-metric invertebrate-based index used as an indicator of water quality)

IBD: *Indice Biologique Diatomées* (a diatom-based biological index - an indicator of water quality)

INRA: *Institut National de la Recherche Agronomique* (French National Institute for Agricultural Research)

IPR: *Indice Poissons Rivière* (fish river index - an indicator of water quality)

Irstea: *Institut de Recherche en Sciences et Technologies pour l’Environnement et l’Agriculture* (French National Research Institute of Science and Technology for Environment and Agriculture)

LEMA: *Loi sur l’Eau et les Milieux Aquatiques* (French water and aquatic environments act)

MEEM: *Ministère de l’Environnement, de l’Energie et de la Mer* (French Ministry of the Environment, Energy and the Sea)

OM: Organic Matter

ONEMA: *Office National de l’Eau et des Milieux Aquatiques* (French National Agency for Water and Aquatic Environments)

OUGC: *Organisme Unique de Gestion Collective* (single joint management body for irrigation users)

PET: Potential Evapotranspiration

RCC: River Continuum Concept

SAGE: *Schéma d’Aménagement et de Gestion des Eaux* (French water resource development and management plan)

SDAGE: *Schéma Directeurs d’Aménagement et de Gestion des Eaux* (French strategic water management plan)

SDC: Serial Discontinuity Concept

SRP: Soluble Reactive P

SYRAH-CE : *SYstème Relationnel d’Audit de l’Hydromorphologie des Cours d’Eau* (Hydromorphology audit relational system - a model designed by Irstea)

VCN: Minimum flow rate over x consecutive days

VEC: Valued Ecosystem Component

WFD: Water Framework Directive

ZRE: *Zone de Répartition des Eaux* (water distribution area)

APPENDICES

APPENDIX I: JOINT ASSESSMENT STUDY REPORT ON THE CUMULATIVE IMPACT OF RESERVOIRS

Background

In 2008, a reform aimed at reducing quantitative deficits resulting from water abstraction was introduced. In all basins in quantitative deficit, prefects were asked to determine the **abstractable volume** of water for all uses in order to ensure the proper functioning of corresponding aquatic environments and compliance with **low water regulating flows (DOE) for eight out of ten years.** They were also asked to revise abstraction authorisations so that the total authorised volume is at most equal to the abstractable volume by 2014, 2017 or 2021 depending on the river basin.

The Circular of 3 August 2010 pertaining to the restoration of quantitative equilibriums with respect to water abstractions specifies that returning basins with a large deficit (discrepancy between abstractable volume and the volume abstracted in the driest year out of five on average greater than a threshold of about 30%) to quantitative equilibrium is based on a set of measures that aim to **encourage water saving and, under certain conditions, to create new resources, i.e. reservoirs**.

In some river basins (particularly Adour Garonne, Loire Brittany and Rhone Mediterranean and Corsica, the reform on quantitative management of water requires the creation of new **substitution reservoirs**. These are planned for catchment areas that generally already have a wide variety of structures located directly on rivers or nearby: hillslope reservoirs supplied by runoff and disconnected from rivers, reservoirs built on rivers, artificial lakes located outside the river and supplied by pumping from rivers, diversion or from groundwater, etc. Only structures disconnected from rivers and filled outside low-stress periods by pumping from rivers or groundwater are considered as substitution reservoirs.

In 2011, at the request of decentralised government departments and directly concerned stakeholders, the French Directorate for Water and Biodiversity published guidelines with the aim of providing a legal framework for avoiding procedural errors concerning external legality (form and procedure) in reservoir construction files. The guidelines iterate that the environmental impact report to be submitted by the petitioner in its **declaration or authorisation file must include the cumulative impact of the planned structures.** This obligation is also stipulated in Article R122-5 of the French Environmental Code (as amended by Decree no. 2011-2019 of 29 December 2011 pertaining to impact studies). Furthermore, certain **SDAGEs have made provisions asking government services to ensure that the cumulative impact of all reservoirs present in a river basin is taken into account when a project is examined**. In this case, checking the compatibility of the project with the SDAGE plan may require a cumulative impact assessment of the reservoir project(s) with those that already exist in the basin in question.

The cumulative impact of successive storage structures in the same catchment area is currently poorly understood by government services responsible for examining projects and applicants themselves. **A methodology has yet to be implemented at the national level, however the issue is gaining momentum with the reform of abstractable volumes.** It is becoming all the more essential as the latest available studies on the evaluation of climate change impacts show that it will have major impacts on the hydrological regimes of rivers, and subsequently on reservoir filling. Climate change and the expected retreat of the snow line could also lead to an increase in the number of reservoirs for snowmaking, which could have a significant environmental impact in mountain regions.

Purpose of the assessment study

The purpose of the assessment is to provide operational methodologies for improving the quality of examination procedures:

- Improve environmental impact reports and impact studies prepared by applicants in order to assess the cumulative impact generated by their reservoir project, taking into account similar existing structures in the catchment area in question. This involves defining methodologies for improving these documents while taking into account, if relevant, hydrogeographic contexts to be organised into types.
- Improve and facilitate water policing services in evaluating the quality and relevance of environmental impact reports and impact studies prepared by applicants as part of their declaration or authorisation files, particularly by defining analysis criteria to be taken into account.

One of the essential challenges of examining reservoir project files is to ensure that the quality of water bodies is not degraded, as stipulated in the Water Framework Directive. The Directorate of Water and Biodiversity, which commissioned the assessment, underlines that this does not mean defining the number of reservoirs that could be built on each catchment area or giving recommendations on water management.

In this context, the assessment will focus on knowledge, ways and methods of characterising and quantifying the additional impact resulting from the creation of a new reservoir in catchment areas already equipped with several reservoirs. This means defining how to assess the cumulative impact of a new reservoir while taking into account the cumulative impact of reservoirs already existing in a catchment area (coherent process management area), with, a priori, no limit on the size of the catchments taken into consideration. The assessment will therefore also provide insight into the impact of reservoirs that already exist in a catchment area.

The ultimate goal of the assessment is not to develop models of specifications or directly operational tools for evaluating the cumulative impact (models). However the assessment will help define the areas in which advances need to be made in research and development to create this type of tool. It will also gather and provide perspective on the methodologies that can already be used, probably by using a classification of the main environments and situations encountered.

The assessment should also provide recommendations required to develop SAGEs and other planning documents concerning the policies to be pursued for the creation of new reservoirs.

The impacts to be taken into account concern the entire life cycle of the reservoir, from construction to operation and maintenance. The assessment must cover different types of impacts related to the various components involved in the functioning of water bodies taken into account in the assessment of the state of waters under the WFD:

- physico-chemistry (particularly nutrients, pollutants and temperature)
- hydromorphology (hydrological regime, sediment and biological continuity, morphology)
- biology (fish, macroinvertebrates, flora, phytoplankton).

Methods used to evaluate aspects related to the safety of structures already exist and this field will not be considered in the assessment.

All types of already existing reservoirs or those set to be built are to be considered, in particular reservoirs located directly on rivers or to divert water, hillslope reservoirs supplied by runoff, substitution reservoirs supplied by pumping from the river or groundwater in the winter, and probably reservoirs for snowmaking (the inclusion of these types of reservoirs is subject to reflection).

Coordination of the assessment study

Irstea was asked to conduct and organise the assessment in close partnership with Inra and Onema. Nadia Carluer, a researcher from Irstea, was charged with overseeing the assessment.

Irstea and Inra are sharing their expertise and providing the human resources needed for the assessment in order to create a joint project team to facilitate the work of experts (bibliographic research, document provision and archiving, logistical support for visit and discussion meetings, oversight of the group of experts) and ensure that the rules of the assessment are followed.

Some efforts need to be made by the two institutions in order to align their procedures.

The costs of the assessment will be covered by Irstea based on a forecast budget (logistical costs for the various groups and expenses for project team agents) under the Irstea-Onema agreement.

Organisation of the assessment

The assessment is organised around 4 committees, using a traditional joint assessment model.

1 – A steering committee with the role of:

- ensuring that the assessment is conducted in accordance with the order and its objectives;
- ensuring that the expertise of the group of experts is consistent with the objectives of the assessment;
- facilitating the work of experts within their institution;
- defining the methods for publishing and communicating the results of the assessment.

This committee is made up of representatives from the institutions in charge of the assessment (Irstea, Inra and ONEMA) and the commissioner (The Ministry of the Environment's Directorate for Water and Biodiversity). The steering committee meets at the key stages of the assessment at the request of the coordinator.

2 – A project team made up of people working with the project coordinator, with the following roles:

- overseeing the group of experts with the coordinator of the group of experts;
- conducting bibliographic research required for the assessment;
- organising the meetings and discussions of the group of experts and monitoring their work;
- providing documents ensuring that the expertise of the group of experts is consistent with the objectives of the assessment;
- publishing and communicating the results of the assessment.

The project team is made up of a research engineer, a design engineer and several researcher assistants.

3 – **A committee of experts** (see Appendix) with the role of drafting the various reports.

This committee of experts is made up of specialists from various fields with a strong applied research component. To cover all aspects of the issue, the committee of experts will pool all the required expertise (see Appendix).

Each expert will be mandated and receive a letter of appointment for this purpose.

4 – A monitoring committee with the following objectives:

- ensuring that all operational issues are taken into account at the start of the assessment;
- ensuring that the final report is complete from an operational standpoint;
- ensuring that the final report is readable and useable.

This monitoring committee will be made up of qualified individuals from the French government services and public institutions involved in the creation of reservoirs, and particularly in examining declaration and/or authorisation applications, and drafting SDAGEs and SAGEs:

- ○ representatives from the Ministry of the Environment, Directorate for Water and Biodiversity, the commissioner of the assessment;
- ○ representatives from the decentralised services of the Ministry of the Environment (DDT, DREAL), representatives from water agencies, especially those affected by the problem (Adour Garonne, Loire Brittany and Rhone Mediterranean and Corsica);
- ○ representatives from Onema (DG, DiR and SD).

Timeline for the assessment

Without prejudice to the reflections of the committee of experts, several methodological aspects seem essential for obtaining the most useable results possible:

- make optimum use of examples of catchments with reservoirs where there is enough data for feedback;
- use representative cases in order to obtain results that can be easily generalised. For this, a classification of the most frequent cases could be created based on the different types of existing structures (associated with

management methods) and different biogeographic contexts in which the majority of cases are found (Adour Garonne basin, Rhone Mediterranean Corsica basin, part of the Loire Brittany basin);

- conduct interviews with stakeholders and people involved in management. These interviews will be used to include stakeholders in the reflection. These stakeholders include applicants and engineering consultants commissioned to prepare the files.

In order to gain a comprehensive view of scientific and operational aspects, the assessment will be carried out in 3 phases that will each form the subject of one or more documents. These phases will successively feed into the following:

Preliminary period *(February to August 2014): acclimatisation of the coordinator with the problem, initial contacts with operational players. Identification of experts.*

Phase 1 (September 2014 – April 2015): this phase is an exploratory phase to examine operational issues. The aim of this phase is to determine all the questions based on discussions with managers / operational players and by analysing existing practices and available operational literature. The report must explain methodological aspects that can be considered as acquired, uncertainties and discrepancies regarding the problem and existing practices. It must also identify best practices. Finally, the phase must define scientific fields where efforts should be invested to further the development of methodological aspects in areas where information is lacking, in preparation of the second phase (development of bibliographic reference requests). The phase report will present the first operational elements without fully analysing existing international references.

Phase 2 (April 2015 – March 2016): this second phase corresponds with a traditional joint scientific assessment. It consists in defining scientific knowledge and the fields of research requiring further development based on the survey of international scientific literature. This phase is organised based on the results of the first phase and will feed into the last phase. The report for this phase will correspond to a state of the art of research on the various uncertainties and areas of controversy identified during the first phase.

Phase 3 (March 2016 – December 2016): this third and final phase corresponds with the creation of the final report. This will involve creating a document that is as usable as possible, backed by a scientific analysis. The report will focus on:

- existing best practices;
- existing tools that can be easily adapted to meet needs;
- methods that can improve impact studies and the way they are examined;
- fields of knowledge that are still unclear;
- research and development avenues that need to be furthered to improve practices at different time scales.

Findings of the assessment and publication

A single report will be drawn up for the first phase of the assessment with the aim of assessing (from an operational standpoint) acquired knowledge, usable methods and existing methods for addressing the cumulative impact of reservoirs in impact studies or environmental impact reports. It will also identify knowledge requiring further insight in the second phase and areas in which efforts would be worth investing in order to develop methodologies that would lead to progress on this issue. Two different reports will be prepared for the second phase. The first will be the full report of the joint scientific assessment, compiling the results of research conducted by the experts in each field. The second will be a summary report covering the key points from research. For the third and final phase, a report will be written proposing methodologies for operational services.

The details for releasing these documents (scope, medium, form and follow-up) or document excerpts must be defined at the end of each phase. Particular attention must be paid to the release of findings from Phase 1 which, by nature, could include preliminary results.

Research seminars will be held in conjunction with the release of findings. The first will take place at the end of the second phase to debate results and will be open to civil society. Three other regional research seminars for operational services and engineering consultants may be organised at the end of the third phase in each of the major river basins of the three water agencies most affected (Loire Brittany, Adour Garonne, Rhone Mediterranean and Corsica).

Appendix: Committee of experts

This committee of experts is made up of specialists from various fields with a strong applied research component. To cover all aspects of the issue, the committee of experts will pool expertise in the following areas:

River and stream hydrology: the expert(s) must be able to understand how hydrological regimes are altered within catchment areas by the management of different types of reservoirs (particularly during the filling and drainage phases). This alteration must be evaluated with respect to the physico-chemical and biological functioning and hydromorphological dynamics of rivers in a catchment area, with corresponding specialists. The expert(s) must be capable of understanding and taking into account the various issues related to how rivers work. Particular attention should be paid to the relationship between hydrology and morphology, and between hydrology and aquatic habitat.

Keywords: hydrology, catchment area, flow regime, runoff, variability, modelling, low water, flood, rural catchment areas, environmental impact, hydraulics, habitat.

Hydrogeology: the expert(s) must be able to make a correlation between the short-and medium-term changes to the state of groundwater and the different impacts directly or indirectly resulting from the operation of reservoirs throughout an entire catchment area (e.g. direct groundwater pumping, partial interception of runoff, flood control).

Keywords: hydrogeology, catchment area, runoff, natural variability of groundwater, groundwater recharge, modelling, rural catchment areas, low water, flood.

Physico-chemistry of rivers and water bodies: the expert(s) must be able to analyse the various physico-chemical processes that occur in reservoirs after they are filled. They must also be able to characterise the various impacts on physico-chemical properties, and particularly temperature, concentration levels of nutrients, suspended matter and different pollutants (agrochemicals) in rivers resulting from changes to flow regimes. They must also be able to evaluate the contribution of reservoirs to greenhouse gas emissions.

Keywords: chemistry, biogeochemical cycles, temperature, nutrients, organic matter, agrochemicals, greenhouse gases, hydrology, reservoir, water body.

Ecotoxicology: the expert(s) must be capable of making a correlation between changes to the bioavailability of contaminants in the aquatic environment as a result of reservoirs (liquid phase, sediment, in reservoirs and downstream, in standard operation and the drainage phase) and their ecotoxicological effect on aquatic organisms.

Keywords: ecotoxicology, contaminant, sediment, bioavailability, hydrology, reservoir.

Hydromorphology and sediment transport in rivers: the expert(s) must be capable of defining how hydromorphological dynamics (sediment transport, erosion, sedimentation) can be impacted by the functioning of a reservoir in a catchment area. The correlation must be made between changes to flow regimes as a result of the functioning of reservoirs, the hydraulics of rivers and their state of morphology. The medium- and long-term changes to habitats caused by changes to hydrological regimes (from runoff to the flow regime) and hydro-sedimentary equilibriums (erosion/sedimentation) must be taken into account for an entire catchment area.

Keywords: hydromorphology, sediment transport, habitat, flood, bankfull discharge, runoff and erosion.

Ecology: the expert(s) must be able to understand the short- and medium-term responses of biological compartments to changes in hydrological regimes, the hydromorphological functioning and physico-chemical characteristics of rivers resulting from the management of reservoirs. The primary biological compartments to be taken into account are fish, macroinvertebrates and flora (macrophytes). The impacts on protected species and their habitat must also be taken into account, especially for areas submerged from the construction of a reservoir. It is essential to be able to understand the link between hydrology, hydraulics, habitat and biological compartment. In addition to the local impact on habitat, the concept of ecological continuity in a river must also be considered, whether for local, migrating or invasive species.

Keywords: fish habitat, macroinvertebrates, flora, temperature, hydraulics, modelling, biochemical cycle, ecological continuity, invasive species, migratory species.

Agronomy: the expert(s) must be able to understand the causal role played by the use and management of reservoirs on agriculture. They must also be able to understand water runoff in catchment areas and onto cultivated land.

Keywords: runoff, reservoir management, irrigation, crop rotation, cultivars, water stress, nutrients, agrochemicals.

Sociology: the expert(s) must be able to understand the sociological issues related to the development of reservoirs in catchment areas and shed light on the way groups of stakeholders react to development projects. This aspect may prove essential when authorisations are subject to public enquiry or when municipalities and local water commissions are consulted.

Keywords: sociology of movements, agriculture.

For most fields, it is best if experts are able to understand the various processes on the scale of each structure as well as on the scale of an entire catchment area. The main relationships and interactions between the different processes must be able to be taken into account. The experts must therefore be capable of interacting with fields other than their own. They should be knowledgeable in the way small and medium rural catchment areas function, as the impact of reservoirs are mainly felt in these types of catchments. It is essential that the experts be able to bring operational perspective to these issues, as the aim is to produce methodologies that can be directly used by stakeholders involved in preparing and examining authorisations.

APPENDIX II: LIST OF EXPERTS

Surname, First name	Affiliation	Position	Field
BABUT, Marc	Irstea Lyon-Villeurbanne – UR MAEP (Aquatic Environments, Ecology and Pollution Research Unit) – Ecotoxicology laboratory	ICPEF	Ecotoxicology (micropollutants, emerging compounds, bioaccumulation, etc.)
BELLIARD, Jérôme	Irstea Antony / Hydrosystems and Bioprocesses Research Unit.	Research Engineer	Ecology of aquatic systems, ecology of communities, bioindicators
BERNEZ, Ivan	UMR (Joint Research Unit) ESE0985 INRA-Agrocampus Ouest	Research Engineer	Restoration ecology / Ecology of communities
BURGER-LEENHARDT, Delphine	INRA – UMR 1248 Agir (Joint Research Unit – Agroecology, Innovation and Territories) – Département SAD (Science for Action and Development Department)	Research Director	Territorial agronomy, agronomy of cropping systems
DORIOZ, Jean-Marcel	INRA Thonon / UMR CARRTEL (Joint Research Unit – Alpine Research Centre on Trophic Networks of Limnic Ecosystems)	Research Director	Physico-chemistry (Diffuse pollution, eutrophication, phosphorus); Ecology, agropedology, catchment areas
DOUEZ, Olivier	BRGM	Engineer	Hydrogeology
DUFOUR, Simon	Université Rennes 2 - LETG Rennes COSTEL - CNRS UMR 6554 / Geography Department	Lecturer	Geography, geomatics applied to hydrosystems (Remote sensing and Geographic Information Systems), alluvial landscapes
GRIMALDI, Catherine	UMR INRA-Agrocampus Ouest 1069 SAS	Research Director	Physico-chemistry of rivers and water bodies
HABETS, Florence	CNRS Paris / UMR Metis (Environmental environments, transfers and interactions in hydrosystems and soil joint research unit)/ Université Pierre & Marie-Curie	Research Director	Hydrology
LE BISSONNAIS, Yves	INRA Montpellier / UMR LISAH	Research Director	Sediment transport
MOLENAT, Jérôme	INRA Montpellier / UMR LISAH	Research Director	Hydrology of catchment areas, hydrology of hillslope reservoirs, groundwater recharge, hydrological modelling
ROLLET, Anne-Julia	Laboratoire LETG Caen GEOPHEN UMR 6554 CNRS	Lecturer	Study of the current physical functioning of river systems and their restoration
ROSSET, Véronique	Irstea Lyon-Villeurbanne - UR MAEP – Dynam Laboratory	Research Engineer	Ecology of ponds and water bodies (macroinvertebrates, adult odonata)
SAUVAGE, Sabine	Ecolab Toulouse / UMR 5245 CNRS-UPS-INPT ENSAT	Research Engineer	Modelling, hydrodynamics, contaminant transfer
USSEGLIO-POLATERA, Philippe	Université de Lorraine - UMR 7360 - LIEC	Professor	Ecology of communities (benthic invertebrates)

Julien TOURNEBIZE, Agricultural and Environmental area engineer (IDEA) at the Hydrosystems and Bioprocesses research unit (UR HBAN) at Irstea Antony, contributed to the chapter on the physico-chemical quality of water and the effect of reservoirs on pesticides and pesticide transfer.

APPENDIX III: INFLUENCE OF AN INDIVIDUAL RESERVOIR ON PARAMETERS CONTRIBUTING TO THE PHYSICO-CHEMICAL QUALITY OF WATER

This appendix presents, for each of the variables of interest, the processes involved within a reservoir, the methods used to study them, and the orders of magnitude for the effect of the reservoir on the variable in question, both within the reservoir and downstream. It attempts to identify the influencing factors in order to transfer the results to other situations as much as possible, as recommended during the exploratory phase of the assessment. However, the diverse situations and interactions between variables make this step difficult.

VIII.1.1 Influence on temperature and dissolved oxygen content in water

These two parameters are often addressed together in literature because they are closely related. **Temperature** acts as an important regulating factor in most physical, chemical and biological processes. In particular, it controls primary productivity along with the seasonal availability of nutrients and light conditions. The level of dissolved oxygen is important because it controls key chemical and biological processes. The concentration level is highly dependent on temperature (the solubility of oxygen decreases when temperature increases) and physical processes (wind, current, etc.), enabling water-atmosphere exchanges.

VIII.1.1.a Reservoirs are heat regulators...

In aquatic environments, temperature variations are significantly attenuated in comparison with variations in the atmosphere, which occur according to daily and seasonal rhythms. These variations, resulting from solar radiation, only concern a thin layer of liquid on the surface of stagnant water. However, in general, the action of the wind and currents mixes the water and creates an even temperature further below the surface. However, in deeper lakes, typical thermal stratification can occur due to the fact that the temperature of maximum density is 4°C. Water at temperatures below or above 4°C therefore have a tendency to rise to the surface. Thus, at least in temperate lakes, the water temperature follows an even cycle throughout the year. In the summer, the sun heats the surface water, and cold and denser water remains at the bottom of the lake. In this case, three thermal layers form: i) a warm, well-mixed surface layer, with temperatures of up to 25°C in the summer (the epilimnion); ii) a cold, dense, even bottom layer where the temperature can be up to 10°C below that of the epilimnion (the hypolimnion); and iii) a middle layer with a high temperature gradient (metalimnion for limnologists), a thin transition area of a few metres. The high temperature gradient (2°C per metre) can create a specific habitat in the metalimnion that is either particularly rich in oxygen if light can penetrate into it and activate photosynthesis, or with low oxygen levels in nutrient-rich lakes where decomposition of organic matter consumes oxygen, which is not regenerated due to stratification. In temperate areas, water can be mixed and create even temperatures when the epilimnion cools in the autumn or gradually warms up in the spring (**Erreur ! Source du renvoi introuvable.**). In deep water bodies, there may not be enough circulation to homogenize the water column. Stratification is therefore permanent. Shallow reservoirs respond more quickly to atmospheric fluctuations and are less likely to become stratified. Despite everything, a gradient of conditions can occur between the surface and deeper layer. Strong winds can quickly affect the metalimnion, as well as flows in the reservoir or mixing during flooding.

Reservoirs therefore act as heat regulators, storing heat and capable of modifying seasonal and short-term fluctuations, typical of numerous natural rivers.

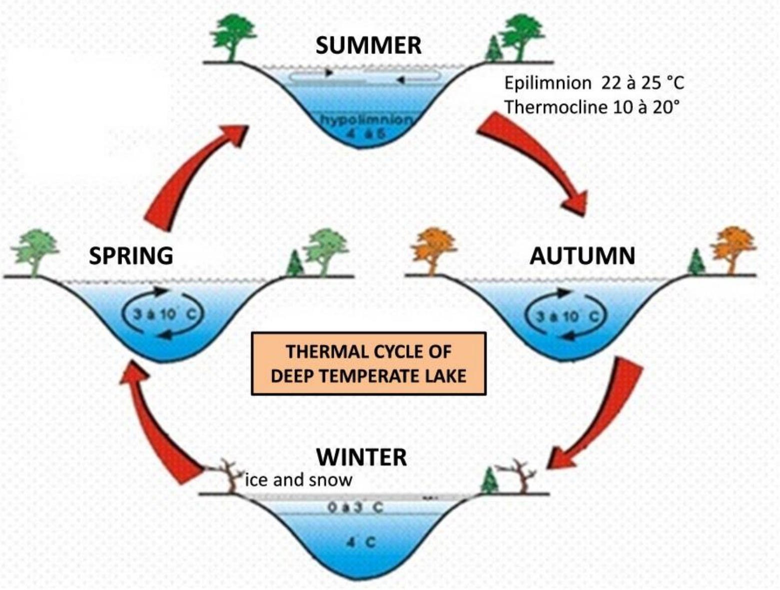

Figure 33: Thermal cycle typical of dicmitic temperate lakes (two stratification periods). Based on G Bourbonnais (http://ici.cegep-ste-foy.qc.ca).

VIII.1.1.b …that also influence dissolved oxygen content

A possible consequence of the lentic conditions established in a reservoir and the increase in residence time is the decrease in **dissolved oxygen** levels. The reservoir receives allochthonous organic matter (OM) in the form of suspended solids, downstream via the river or laterally via runoff, and autochthonous matter via senescence of primary production in the reservoir. This OM can settle on the bottom and its mineralisation consumes oxygen. Thermal stratification, which reduces the exchange of elements between surface and deep waters, can ultimately lead to anoxic conditions at the bottom of the reservoir. Figure 34 shows typical temperature and dissolved oxygen profiles in a deep temperate lake in late summer. The bottom of the reservoir is anoxic, and the oxygen level increases in the hypolimnion, as oxygen consumption is low, and solubility is relatively high (low temperature); when the temperature increases towards the surface, oxygen solubility decreases, and mixing increases the concentration of oxygen at the surface. Anoxic conditions are also often encountered in new reservoirs, where recently flooded land and vegetation can act as a source of OM for a short time, consuming oxygen as it decomposes. However, in the springtime and summer, due to the presence of macrophytes or bloomer phytoplankton, photosynthesis can lead to high dissolved oxygen levels in the surface layers of reservoirs (oversaturation of dissolved oxygen between 300% and 400% for reservoirs with algae in tropical regions). In the autumn, this biomass produces OM which then consumes oxygen.

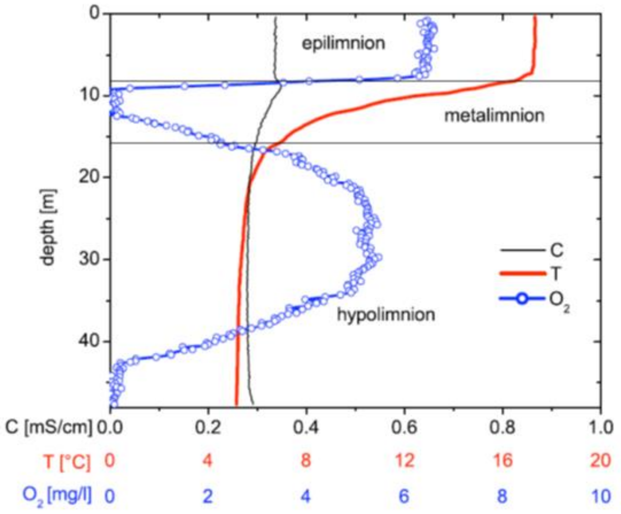

Figure 34: Profile of temperature (T), conductivity (C) and dissolved oxygen levels (O_2) in Lake Arendsee (Germany) on 6 September 2000. Boehrer and Schultze 2008.

In short, oxic and anoxic zones depend on thermal stratification (which itself depends on physical and hydrological conditions in the reservoir), the presence of algal blooms and OM concentration levels in the biodegradation phase. Figure 35a shows the distribution between the oxic and anoxic (oxycline) compartments in different types of lakes.

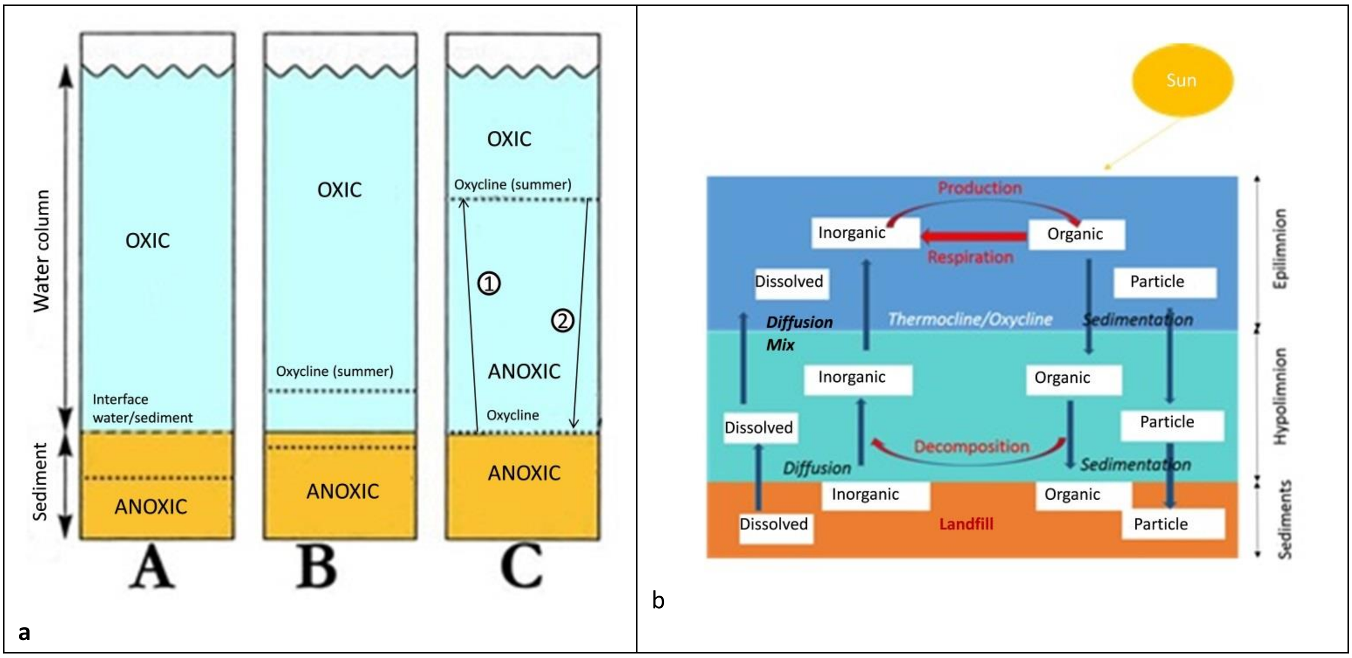

Figure 35: a. Distribution between the oxic and anoxic compartments in different types of lakes. (A): oligotrphic, oxycline is still in sediment; (B): mesotrophic, in the summer, only deep water becomes anoxic; (C): eutrophic, in the summer, anoxic waters invade the water column (development of anoxic waters in the spring, reoxygenation of deep water in the fall or during flooding) (based on to J.-F. Gaillard, 1995). b. Main potential effects of temperature and oxygen gradients.

Figure 35 summarises the effect of the temperature and oxygen gradient on processes concerning elements and contamination, whether they are organic or inorganic, for both dissolved and particulate fractions, depending on thermal stratification and oxygen gradient phenomena.

VIII.1.1.c The influence of reservoirs on downstream rivers depends highly on the water return method

The influence of the reservoir on temperature and dissolved oxygen levels in the downstream river depends highly on the water return method. The quality of water released from a stratified reservoir depends on where it comes from in the water column. If it comes from the deepest layer, it can be cold and have low oxygen levels, especially during thermal stratification periods. If, on the other hand, the water returned comes from the surface layers of a stratified reservoir, it is hotter in the summer and has relatively high oxygen levels. Reoxygenation of the downstream river occurs more quickly if the river is turbulent, shallow, and has a steep gradient. The distance it takes for these variables to return to the levels they had in the upstream river is a few hundred metres for oxygen, but may reach several hundred kilometres for temperature in the case of large reservoirs and deep major rivers.

In the downstream river, water depleted of dissolved oxygen is not only a problem in itself that affects various aquatic organisms (e.g. salmonidae), but it also has less ability to biodegrade household and/or industrial waste. Temperature changes in the river can also have consequences on fish fry, such as the growth rates and periods for many species.

VIII.1.2 Influence on nitrogen

The issues concerning nitrogen can occur in the reservoir itself, particularly with respect to its complex role in the risk of eutrophication (which will be discussed below), or in the downstream river when water is returned, related to the biological quality of water and compliance with regulatory nitrate limits. The studies that were analysed often concern major dams, however some discuss small reservoirs. Some reservoirs are built to act as artificial wetlands in order to reduce nitrate concentrations and fluxes via denitrification. However, there are not enough of these reservoirs to take any specific interest in them.

VIII.1.2.a Multiple processes at play in reservoirs

The **primary source of nitrogen** in a reservoir is **the water supply**, which is often nitrate-rich, especially for reservoirs supplied by rivers or groundwater in agricultural regions. **Atmospheric nitrogen** can also be fixed by autotrophic and heterotrophic bacteria in phytoplankton. Phytoplankton production is linked to the abundance of N and P nutrients in the photic zone of the reservoir and is enhanced in shallow reservoirs (< 1 m) where light can penetrate, or when the residence time is long. **Mineralisation of OM** is another source of nitrogen. OM comes from the decomposition of biomass in the reservoir (that generally decomposes easily) or is carried by ground runoff or with suspended solids by the upstream river (often more resistant). Its mineralisation produces ammonium (NH_4^+) which transforms into nitrate (NO_3^-) in oxydising conditions (Figure 36).

The nitrogen present in the reservoir can be **absorbed** by the aquatic vegetation in a shallow reservoir or by phytoplankton in an open water reservoir. This consumption of N in the form of NH_4^+ or NO_3^- only traps it temporarily, since the biomass then transforms into organic matter that can mineralise itself. Part of the OM can be **stored** in sediment at the bottom of the reservoir when the conditions are not conducive to mineralisation. In a reservoir, **denitrification** is considered as the essential process that eliminates part of the nitrates in the water, in the form of gas that returns into the atmosphere. The transformation cycle is as follows: NO_3^- -> NO_2^- -> NO –> N_2O –> N_2. If transformation is not complete, N_2O, a powerful greenhouse gas, is produced. This process is mainly due to bacteria that use the oxygen in nitrate ions for anaerobic respiration. Denitrifying bacteria need organic carbon and nitrate as substrates, hypoxic or anoxic conditions and their activity is stimulated by an increase in temperature and neutral pH. All these conditions are often met in farm ponds. The processes at play and their determining factors are well known. However there are many control factors, making it difficult to develop strong models for predicting denitrified quantities. Finally, an NH_4^+ oxidation process in anaerobic conditions called anammox also produces N_2 gas. The process was recently discovered and measured in a reservoir in a tropical environment, where it was considered of little significance.

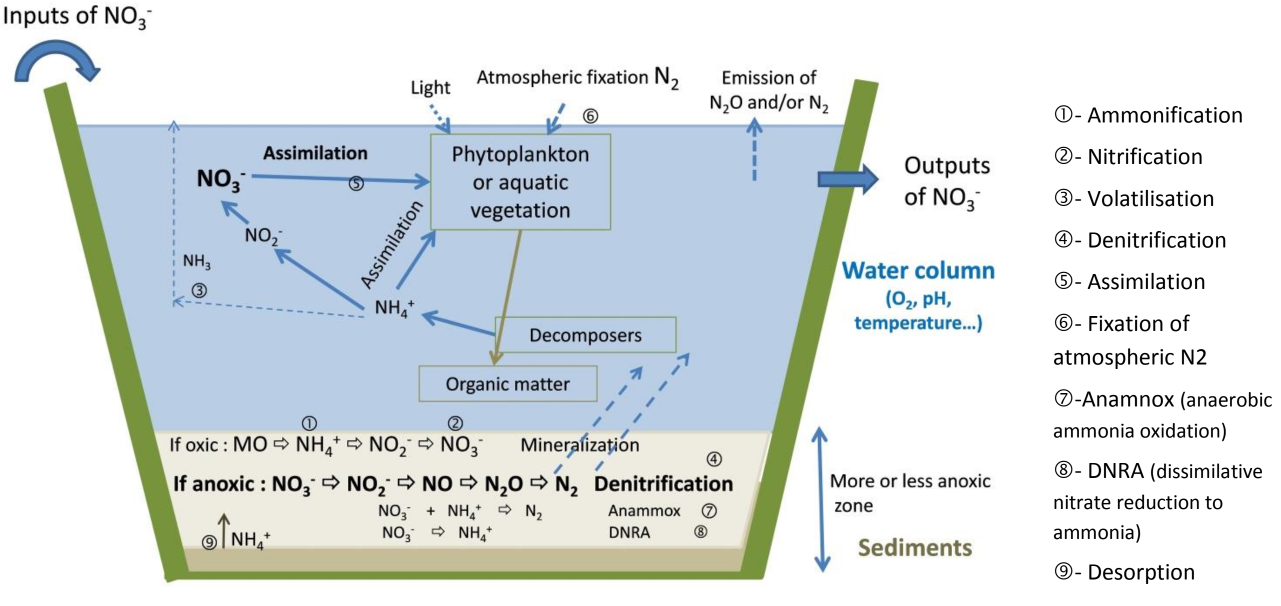

Figure 36: Diagram of the Nitrogen (N) cycle in a reservoir with or without anoxia at the bottom.

VIII.1.2.b Variable observed effects for numerous control factors

It is often accepted that reservoirs, like other lentic environments, are nitrogen sinks: particulate nitrogen stored with organic sediment and especially nitrate via denitrification. **In terms of method,** this sink function can be assessed by estimating nitrogen input and output balances, either using **flux measurements,** or only using **concentration measurements,** for the nitrate form and sometimes ammonium. Exchanges with the atmosphere are therefore neglected. This assessment can also be carried out based on **modelling.** This approach therefore includes simulating flows entering the reservoir, then changes to nitrogen fluxes (generally nitrate) between the reservoir upstream and downstream reaches by modelling active processes in the reservoir. Modelling input fluxes is connected to modelling nitrate fluxes in catchment areas, which is not specific to the field of reservoirs. Some models have been developed to represent the processes at play in a reservoir based on input fluxes and the specific characteristics of the reservoir. Their complexity must be consistent with available data. An alternative method for measuring the effect of a reservoir's nitrogen sinks is to **directly measure denitrification** within the reservoir. Several methods are available, the most well-known being the acetylene inhibition method. However, all of them face the problem of spatial and temporal variability of the process, which makes it difficult to evaluate overall denitrification for the entire reservoir. The atmospheric fixation of nitrogen can also be estimated using the acetylene reduction assay method.

The quantities of nitrogen eliminated through denitrification are extremely variable: retention[25] estimated between 15-20% and 96%, for denitrification from 13 to 90% for large lakes and reservoirs. The retention of N estimated via input-output balance can be insignificant (if input flows are low), or even negative (for instance if old sediment plays a source role). There are numerous control factors for denitrification that do not necessarily have a specific order of significance: nitrate, dissolved organic carbon, dissolved oxygen content, as well as temperature and pH. Other control factors are added in the case of nitrogen sinks via plant absorption or phytoplankton: phosphorus concentration, light and temperature.

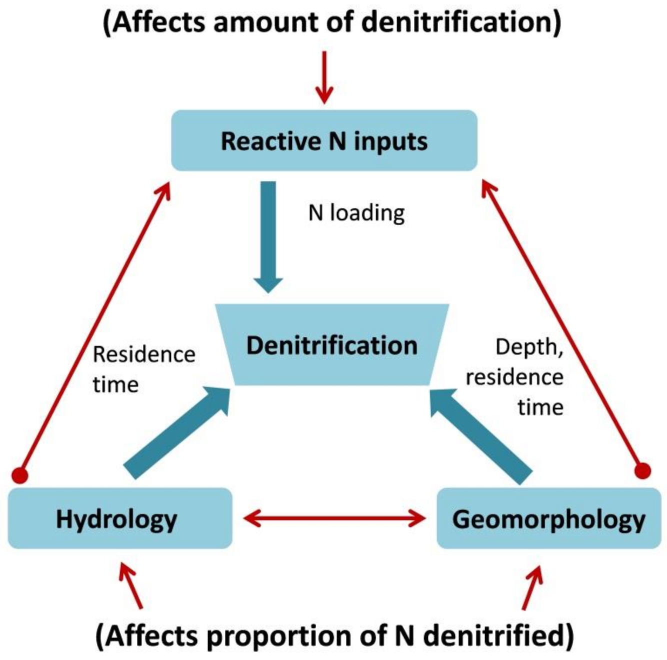

Figure 37: Diagram of the interaction between hydrology, geomorphology and nitrogen load on denitrification. According to Seitzinger 2006.

Some of these control factors vary depending on the depth of the reservoir (oxygen, temperature, light) and are therefore sensitive to potential stratification of physico-chemical conditions. However, it seems that **the greater the inflow loads and the longer the residence time, the greater the role of nitrogen sinks in the reservoir.** The residence time is the most influential control factor. It integrates many others (cited above) for which it reflects changes. However, it varies within the reservoir (depending on flow characteristics), and over time (annual and event-related flow dynamics). It can nevertheless be approximated by the ratio between the surface area of the reservoir and the surface area that it drains, or between the reservoir volume and the intake flow. The depth of the reservoir is also cited as a factor that influences denitrification as deep waters are favourable to anoxic conditions (Figure 37).

Denitrification has a highly seasonal nature related to temperature and the seasonal dynamics of nitrate concentrations in the water that supplies the reservoir or to the mineralisation of OM. Denitrification is heightened in dry years, as a result of higher residence times.

Reservoirs are often referred to in literature for their role as nitrogen sinks, particularly via the reduction of nitrate levels through **denitrification,** and sometimes for their potential contribution to the **risk of eutrophication** (linked to phosphorus). Both these processes share common determining factors: high nitrate concentrations, temperature, and long residence times. When reservoirs have conditions that are favourable to denitrification, the N/P ratio in the water decreases, which favours the development of cyanobacteria with the ability to use atmospheric nitrogen, which increase eutrophication-related health risks. On the other hand, eutrophication in reservoirs increases oxygen consumption from the respiration of organisms that thrive in them and from the decomposition of organic matter. The resulting anoxia favours denitrification, which intensifies the lack of N compared to P, which causes cyanobacteria to develop. These two processes interact with each other and should be studied together, which is generally not the case.

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[25] Retention refers to the amount of nitrogen dissipated between when water enters the reservoir and when it leaves (denitrification, storage in sediment, abstraction via macrophytes or periphyton).

VIII.1.3 Influence on phosphorus

The primary issue concerning phosphorus is eutrophication in the reservoir itself, as well as P fluxes and concentrations downstream (trapping in the reservoir). The majority of studies on this element in reservoirs seek to characterise its cycle in the reservoir, its storage and changes to its speciation, in order to assess the risk of eutrophication in the reservoir and sometimes downstream. Studies focus mainly on large dams, and rarely small reservoirs, often in comparison with natural lakes.

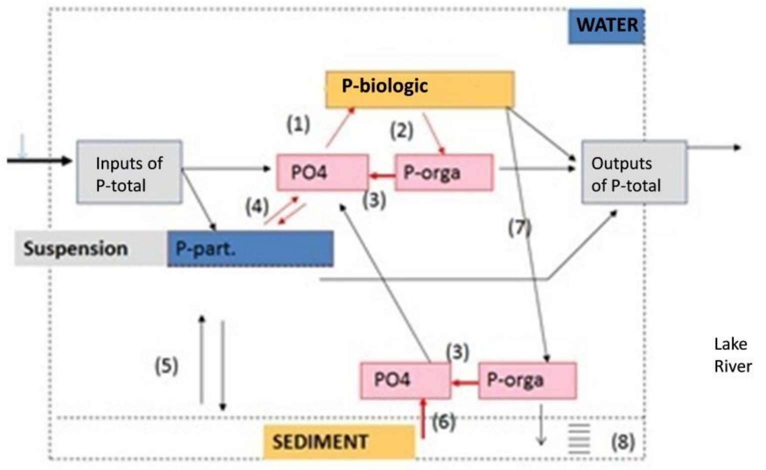
Box 7: Phosphorus and its complex cycle in reservoirs

The general cycle of P is characterised by the almost complete absence of the gaseous form. Total P therefore "persists" in soil and aquatic environments. In a reservoir, biogeochemical transformations are phase changes, between dissolved and particulate state, and/or chemical changes, between dissolved mineral and organic state. P always shows a **strong affinity for the solid phase,** which varies depending on pH, redox potential (Eh), the minerals present and organic matter concentration. P is also relatively rare in water in comparison with plant needs and therefore plays a key role in **controlling the productivity of aquatic ecosystems.**

Phosphorus speciation is relatively complex. In the total P of water, the following are traditionally identified: (1) filterable forms at 0.45 or 0.7µm including **SRP** (**Soluble Reactive P**, often assimilated with **PO4** ions), in addition to organic compounds and fine colloids; (2) particulate forms in particulate phosphorus (PP). PP and its speciation are extremely diversified (PP can be sorbed, precipitated, co-precipitated, in primary minerals, organic material, etc.). Speciation determines the mobility and what becomes of P in the environment, especially via its **bioavailability**. **This** expresses the capability of a phosphorus load in water, soil or sediment to provide and maintain a flux of SRP in response to abstraction by plants and algae. The complexity stems from the fact that besides SRP (100% bioavailable), the quantity of bioavailable phosphorus is associated with neither a specific form of P (particularly for PP), nor a finite quantity: all forms of P contribute and the quantity extracted depends on the length of interaction. This quantity can therefore vary from 10 to 90% for sediment.

VIII.1.3.a Processes at play in water bodies

Most of the total P in a water body comes from the catchment area that feeds into it. Only **SRP can be directly assimilated** by algae or macrophytes, some other dissolved forms are after enzymatic action. It is initially supplied by the external load from the water supply, which contains a dissolved fraction and particulate fraction that can easily release SRP (particularly through desorption). Biological absorption creates a reserve of organic particulate phosphorus, part of which is later likely to settle. Outside biological periods, SRP is not readily assimilated and, like other dissolved forms, can be captured by suspended (sorption) or precipitated or co-precipitated (mainly with Ca, $CaCO3$) particles, which are then sedimented (Figure 38). Conversely, release of SRP from so-called **"internal load"** sediment exists, in the case of mixing and particle resuspension or when anaerobic conditions are established for a long time at the water-sediment interface, allowing SRP to be released and potentially resulting in a diffusive flux into the water. Other interface zones are hot spots in the cycle as they produce SRP from particulate forms: alternating humectation/desiccation and flooding/drying in zones where water levels rise and fall are favourable to the release of SRP.



(1) Absorption – Photosynthesis
(2) Mineralisation
(3) Exoenzymatic hydrolysis
(4) Sorption/precipitation – dissolution: "exchangeable form"
(5) Sedimentation – Resuspension
(6) Release Mixing
(7) Decantation
(8) Diagenesis (lakes)

Figure 38: Phosphorus cycle in an aquatic environment: fluxes, transport and compartments. Based on *Traité de Limnologie* (Pourriot et Meybeck, 1995), amended version.

The particulate P of the external or internal load can either settle and create a potential source of SRP in the long term (release or resuspension of the forms cited above), or in the photic zone, interact with plants or microorganisms by supplying them with a flux of SRP for biological assimilation. Sedimentation is accompanied by mineralisation of certain organic forms. The SRP produced diffuses into the water column and into the sediment mineral solid phase where it can be absorbed by the roots of macrophytes, which grow in shallow zones, especially if the environment is oligotrophic.

Given these processes, it can be assumed that reservoirs play the same role in the phosphorus cycle as a natural water body: (i) sediment and biological retention of P (building reserves of P); (ii) production of organic forms; (iii) conversion: recycling and transformation of speciation potentially producing SRP; (iv) partial dissolved/particulate separation. The characteristics of fluxes exported by reservoirs are controlled by these different functions.

VIII.1.3.b Effects of reservoirs on phosphorus dynamics in hydrosystems

The studies analysed seek to identify certain components and factors in the phosphorus cycle and input-output balance with respect to the risk of eutrophication. They therefore set out to characterise internal or external fluxes in the water column and at interfaces, or reserves, while usually focusing on characterising the speciation of phosphorus, its variability and its evolution. Various methods are used and are based on measurements of concentrations (in the water column or in sediment) or fluxes (in the water column or at the water-sediment interface), or on modelling to estimate inflow and outflow from the system.

Phosphorus retention is observed in all water bodies and it varies considerably, from a few per cent to 90% depending on local conditions. It seems quite lasting on the scale of reservoir or dam management, although it varies from year to year, with maximum retention for rainy years with high loading. Sedimentation dominates retention, which is largely governed by the same factors. It is positively correlated, although non-linearly, with the residence time and external loading, and sometimes with its concentration. However, concentration levels seem influential mainly for natural water bodies. Biological absorption, which creates organic PP in the photic zone, which settles mainly at the end of the season, also contributes to retention and redistribution to sediment.

However, **release of SRP** combined with the reduction of iron in mineral carrier phases, at the water-sediment interface in anoxic conditions, reduces retention. Eutrophic conditions, which generate high biomass production, favour these anoxic conditions at the benthic level and lead to the release of SRP, positive feedback which maintains the process and tends to stabilise eutrophication over time.

Assessment of the **benthic P reserve** must take into account settled phosphorus and phosphorus in place when the reservoir is filled. Very few studies seek to **evaluate the total P reserve**, which is actually important data for evaluating the **long-term effect of the reservoir**. In general, research focuses on the spatial variability of P speciation in the surface layer of sediment, which is supposed to control the flux at the water-sediment interface. Studies generally show extremely high phosphorus concentrations in this surface layer, with control via the geology of the catchment area and land use, and via the maximum trophic state of the water body in case of eutrophication. The fine fraction (fine silt and clay) is the most loaded with P, especially when it is associated with iron oxides. The phosphorus in sediment can become bioavailable if the water-sediment interface is anoxic. This benthic release therefore depends on hydrodynamic factors which control the concentration of dissolved oxygen. These factors should be studied along with the potential of sediment transfer into the water column to estimate effective fluxes.

Changes in water level and wave action, which potentially lead to bank erosion and alternating flooding/drying and oxidation/anoxia conditions, can also influence phosphorus dynamics by redistributing particulate phosphorus (linked with dissolved organic carbon) on the bottom of the reservoir, and by releasing SRP in the water column.

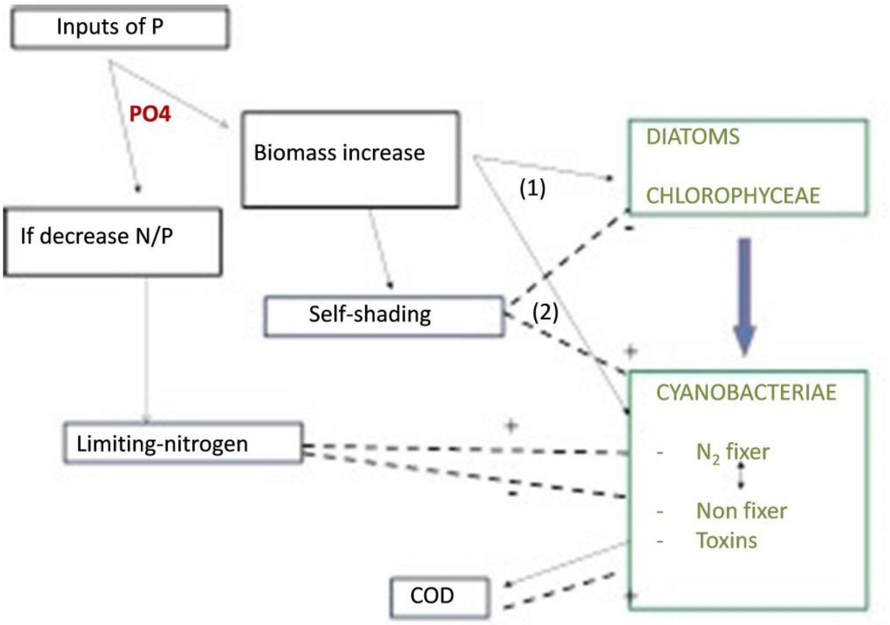


Figure 39: Algal successions resulting from phosphorus enrichment.

One of the major risks associated with reservoirs is eutrophication, a phenomenon where phosphorus plays a key role. Since nitrogen interacts with P in the development of eutrophication, this process is mainly covered in the section on interactions (VI.I.1). It is important here to provide just a brief explanation of how it works. In continental waters, P is considered as the factor that triggers cultural eutrophication. This is a transformation of the structure and function of aquatic biocenoses in response to excessive, accelerated and anthropic nutrient enrichment. The trophic change modifies the dynamics of biocenoses (Figure 39): through the development of phytoplankton, macrophytes and biofilms during seasons that are favourable to plant growth, with an accumulation of plant biomass (Figure 40). The development of eutrophication depends on the concentration of SRP in water. The OM produced with its P content settles. Its mineralisation, which includes the mineralisation of its organic phosphorus, returns SRP to the water column and sustains the process. Eutrophication is triggered for relatively low SRP concentrations: in a natural lake, 20 to 50 µg/L is enough (i.e. 2 to 4 times the mean natural level in surface water). SRP concentrations observed in French rural streams are at levels that can produce eutrophication.

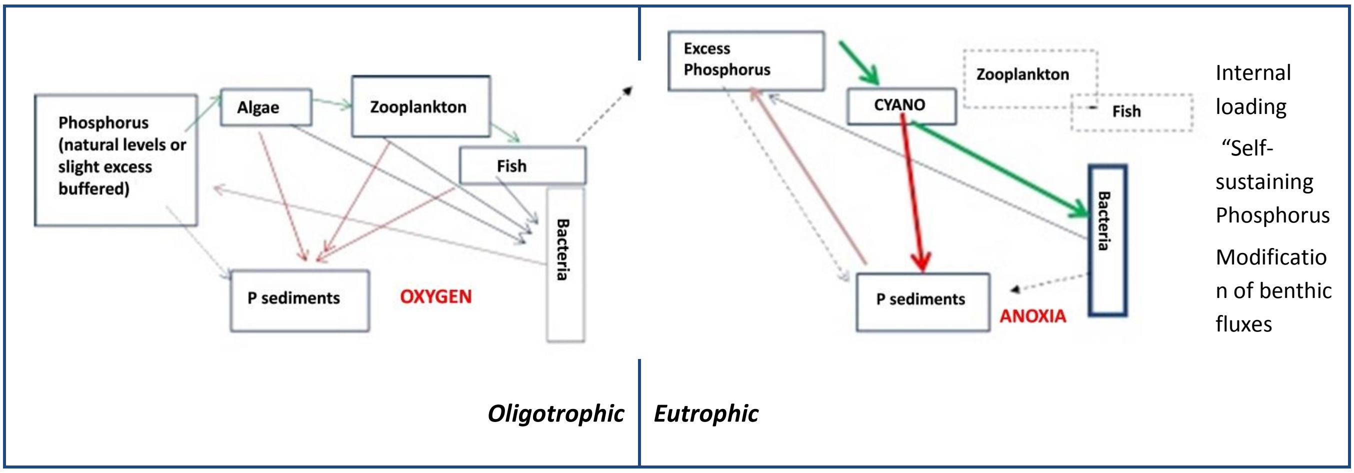


Figure 40: Modification of trophic networks.

As far as the **influence of water bodies on the downstream river** is concerned, studies focus on the differences between input and output flows, on concentration or their variability, and/or on P speciation. In general, fluxes decrease for natural lakes, but dissolved and organic forms (including organic PP) contribute more, less markedly for lakes at the head of the basin. This selective transfer also includes less variability of concentrations (especially PP) and delayed effects which depend on the size, depth and morphometry of the water body. These results apply for natural lakes. Due to a lack of equivalent studies, we can attempt to extrapolate them to reservoirs, with the following expected effects:

- Modification of phosphorous fluxes and speciation in the downstream hydrographic network, with a likely drop in total P but a better supply of SRP on average during low-water periods, constant injection of organic PP and more bioavailable forms overall;
- Increased productivity of the river and its heterotrophic/autotrophic ratio, particularly during low-water periods and at the head of the basin;
- A change (increased or decreased) risk of eutrophication of the overall aquatic system, connected to the changes in bioavailable phosphorus and nitrate.

These changes are interpreted by some authors as a change to the entire river, “virtually” increased due to the presence of a reservoir upstream. The return to normal in-stream phosphorus dynamics conditions is estimated over a short distance (approximately 1 to 4 km), after a large lake or dam reservoir (> 300 km²).

In the end, many of the studies analysed concern lakes and not anthropic reservoirs or dams. It seems that **as far as phosphorus is concerned, the same processes take place in lakes and reservoirs and are subject to similar control factors.** However, some differences appear concerning: (1) phosphorus retention, which is greater in lakes, (2) the spatial distribution of the sediment reserve and its properties, (3) the existence of an initial internal load for reservoirs (flooded land and vegetation), which absolutely must be taken into account.

Depending on the strength of the overall internal load that produces SRP phosphorus for accumulated reserves, the intensity of exchanges between the different compartments of the system and reserves, **reservoirs can act as a sink or source** of total P, or as a source of easily bioavailable phosphorus with strong eutrophication capability. Given the change in the benthic P reserve and the gradual development of anoxia, P is not necessarily stored for a long time. The chemical composition of sedimentary phosphorus is therefore a key indicator. Because the composition is partially inherited from the catchment area and its land use, these parameters must be taken into account in order to predict the risk of eutrophication, or mitigate it through the choices of the reservoir’s morphometric characteristics whenever possible. It is also useful to take them into consideration for the long-term management of the reserves that are created.

VIII.1.4 Influence on trace metal concentrations

The issue of trace metals[26] in reservoirs is mainly addressed for dams or retention and settling basins, often in terms of geochemical processes at work, mainly in sediment, linked with the bioavailability of trace metals. A number of trace metals are “priority substances” under the Water Framework Directive 2000/60 (WFD) and their associated risks should be evaluated and their impacts minimised.

VIII.1.4.a Elements essentially associated with particles, under various forms

The sources of trace metals in reservoirs are mainly atmospheric deposition, leaching from fertilised soil (including from wastewater treatment sludge), urban runoff, inflow from the upstream catchment from rivers feeding into the reservoir. Atmospheric deposition accounts for little in comparison with inflow from the upstream catchment area. The reservoir acts as a “particle filter”, where **trace metals, associated with suspended solids,** settle and are likely to be resuspended during flooding or when the reservoir is drained. They can also be accumulated by plants, invertebrates, and fish (Figure 41). From a geochemical standpoint, the distribution of trace metals between water and sediment is controlled by their **speciation**, which is focussed on in studies. Trace metals are cations that can be associated with five fractions:

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[26] Trace metals are usually defined as metals where the mean natural concentration in the upper continental crust is less than 1000 mg.kg^{-1}. Some, called micronutrients, are essential to biological processes. However at high concentrations, they can be toxic for various life forms (e.g. Cu and Zn). This also applies for other trace metals whose essential nature has not been proven (e.g.: Cd, Hg and Pb).

exchangeable (F1), bound to carbonates (F2), bound to iron-manganese oxides (F3), bound to organic matter (F4), residual (mineral, geogenic – F5). Fraction F1 is considered the most unstable, i.e. available.

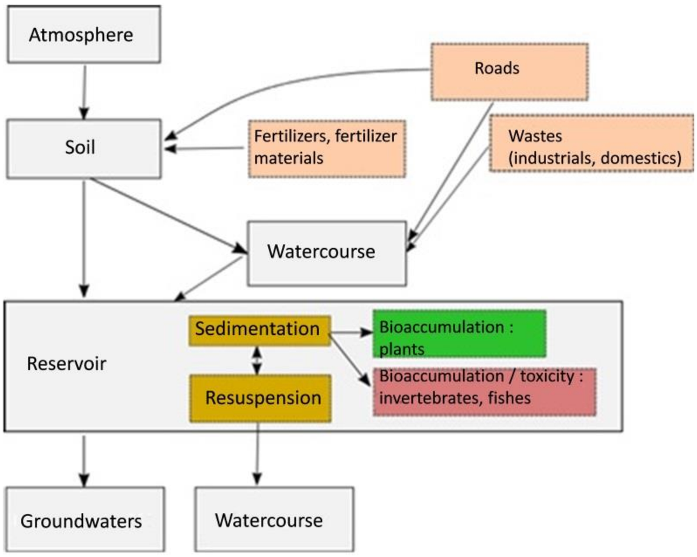

Figure 41: Sources and behaviour of trace metals in a reservoir.

Trace metals can be measured in different trophic links (biofilm, invertebrates, fish), with higher concentrations in the first links (biofilm, invertebrates). Measurements are based on sediment sampling and the analysis of metals using traditional methods. **Interpreting methods** rely on enrichment indices, in comparison with a baseline background level, or by comparing measured concentrations with quality standards.

The outcome of trace metals is closely linked to the outcome of sediment; the highest concentrations are measured on fine (≤ 10 – 25 µm) and organic fractions. Resuspension of fine fractions during floods will therefore also carry trace metals. However their transfer to groundwater has been little studied, in contexts where extrapolation is difficult (groundwater recharge via wastewater). Changes in water levels, which modify sediment redox conditions, can lead to the redistribution of trace metals in geochemical fractions. However, this aspect is addressed little.

VIII.1.4.b For effects on different biological compartments

Plants can affect trace metals in two ways: some induce a higher concentration in the interstitial water of sediment, which favours their mobility into the water column; some are hyperaccumulators, while others (some macrophytes) have a stabilising effect on trace metals in sediment. High concentrations of trace metals in algal blooms have been detected in zones where sediment was highly contaminated. **Invertebrates** accumulate higher concentrations than **fish**, likely as a result of increased excretion for higher trophic levels. For the latter, the accumulation correlates with the sum of fractions F1 and F2. Other than for organic forms of mercury, trace metals are not bioamplified.

VIII.1.5 Influence on agrochemicals

Various types of reservoirs have been studied within the context of this issue: fishponds, farm ponds, retention basins, dams for various uses, hillslope irrigation reservoirs, natural systems. Studies range from microcosm experiments in order to study sorption processes, to real site monitoring in natural conditions (mainly to study the occurrence of pesticides in aqueous and/or settling phases) and mesocosm experiments to study what happens to pesticides in different compartments in a controlled situation. In situ monitoring corresponds to sampling in the water column or sediment, either between the inlet and outlet, or to determine the spatial distribution of concentrations within a reservoir. One of the problems with studying pesticides in the environment is that there are such a wide variety. All the studies examine 97 molecules with differing physico-chemical characteristics[27], 41 of which are banned in France.

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[27] These characteristics are traditionally found in several different databases.

VIII.1.5.a Different types of processes

The **sources of pesticides** in a reservoir come mainly from inflows from the upstream basin, and is associated with land uses, agricultural practices and the potential presence of man-made structures. Except in some cases (old molecules in little anthropised basins), atmospheric inputs are much less significant than inputs via the upstream catchment area. In addition to the dissipation processes cited below, outflows are made up of flows into the downstream river, or volatilisation, which is rarely studied. Depending on the respective volume and concentration from the upstream catchment area and water in the reservoir, pesticides inflowing into the reservoir will be more or less diluted. The processes at play in reservoirs contributing to the dissipation of pesticides are of 3 types (Figure 42):

1. **Physical sorption processes in sediment.** The Koc (organic carbon-water partitioning coefficient), intrinsic to an active substance, is the parameter used to characterise the intensity of the process. The higher it is, the more the pesticide will be absorbed. For a given molecule, the factors that influence adsorption are pH, the organic matter concentration, and sediment particle size. A high OM concentration or fine particle size favours adsorption. Clay does not retain anionic compounds due to the negative charge on the surface of clay. The opposite process of desorption from sediment is also important but more difficult to study, and subject to significant hysteresis.
2. **Chemical processes.** Most pesticide compounds studied are stable in water, and hydrolysis or photolysis are rarely significant. Photolysis is stronger the closer the molecule is to the surface and accessible to sunlight (influence of turbidity).
3. **Biological processes.** Bacterial degradation is generally the main way in which pesticides are biodegraded. These processes take place at the water column-sediment or water column-biofilm interface or in sediment. The parameters for quantifying biodegradation are the half-lives (DT50) for different compartments. In the water phase, the mean and median DT50s are 45 days (standard deviation: 54 days) and 28 days. In the sediment phase, the mean is 105 days (standard deviation: 150 days) and the median, 48 days. Degradation seems slower in the sediment phase than in the water column due to anoxia. Plants can also contribute to retention by slowing down flows and favouring the development of biological activity, and even by assimilating them in rare cases. In general, metabolites resulting from the degradation of molecules are covered very little in scientific literature.

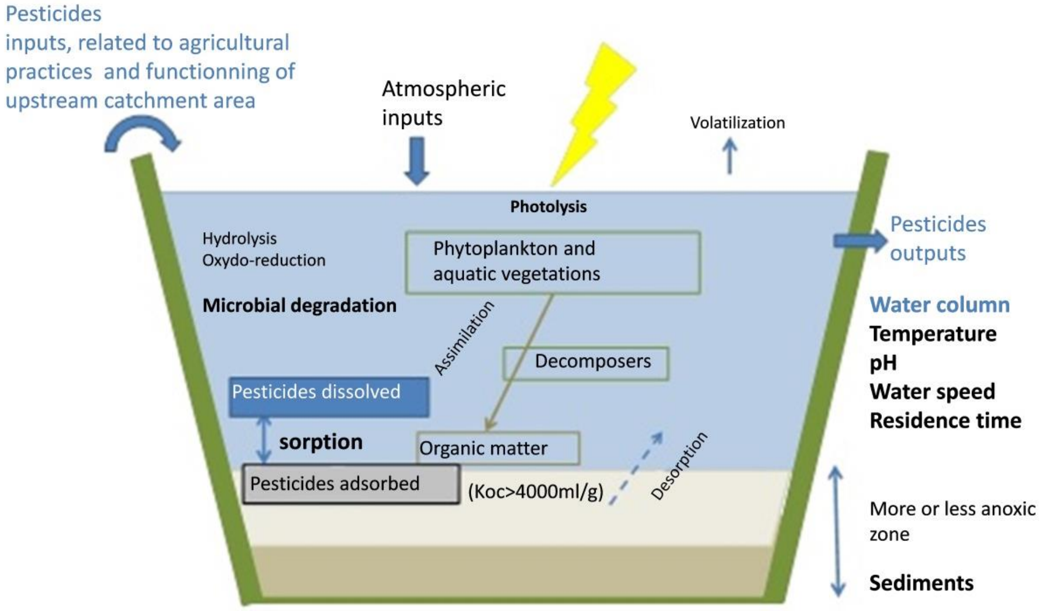


Figure 42: Process governing pesticides within a reservoir.

VIII.1.5.b For converging effects

Pesticides were detected in the water column of many of the reservoirs studied. It is closely linked to agricultural practices in the upstream catchment area and its characteristics, along with the characteristics of molecules (in particular DT50 and Koc), and shows a seasonal nature connected to uses in the catchment, which is consistent with pesticide dissipation. Some pesticides can be found in sediment although they are not detected in the water column. Some studies show a greater presence on fine fractions of sediment and assume that degradation is favoured in coarse elements, while others show bimodal distribution. Concentrations are higher on the 0-15 cm layer, except for old molecules that can be found in deeper layers. An upstream/downstream pollution gradient is also observed on sediment.

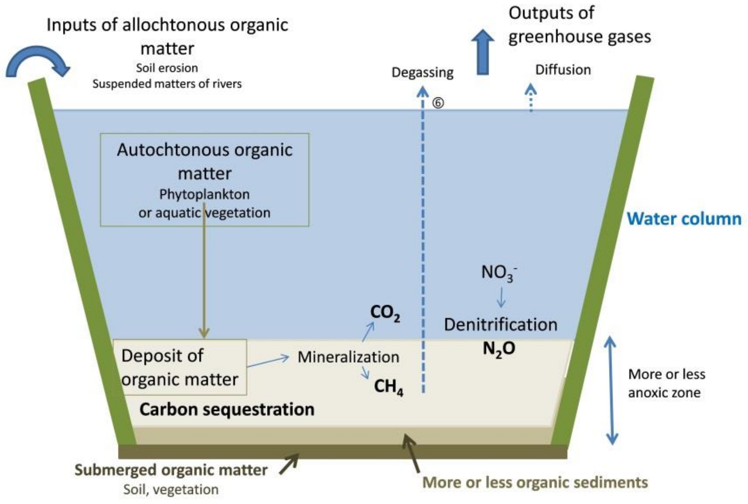
Ultimately, **reservoirs always appear as sinks for pesticides,** where the concentrations measured are the same as for concentrations upstream, and higher than in the downstream river. The long-term behaviour of pesticides absorbed in the first layer of sediment would be worth studying. The pesticide retention process depends on a number of factors, such as topography, land use, the type of soil on the contributing surface, the seasonal aspect of flows (hydrological response of the upstream catchment), the residence time in the reservoir (especially the morphology and depth of the reservoir), the concentration of organic matter and clay, pH, redox conditions, the presence of and type of vegetation, the physico-chemical properties of pesticides.

VIII.1.6 Effect of a reservoir on greenhouse gases and carbon sequestration

The greenhouse gases largely blamed for the potential impacts of reservoirs are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Carbon sequestration has been associated with this question because the associated challenge is to reduce CO_2 and CH_4 emissions. The long-term redistribution of atmospheric carbon into other compartments reduces the greenhouse gas footprint. Some studies only examine one of these elements, while others examine them together, sometimes along with carbon sequestration. The effect of an individual reservoir on greenhouse gases is likely insignificant and does not have a direct link with the quality of the aquatic environment, which is the subject of this assessment. However, given the high number of reservoirs on the global scale, it would be worth evaluating whether or not their cumulative effect is significant (see box on large-scale effects). The following paragraph first analyses the processes at play for an individual reservoir.

VIII.1.6.a Processes at play

Organic carbon (CO) is generally present in reservoirs. It comes from the organic matter (OM) from the land flooded from filling the reservoir and the decomposition of submerged biomass, from the OM generated from the senescence of the primary production in the reservoir, and from OM carried by sediment from surrounding soil erosion. Its accumulation in the reservoir is considered as relatively long-term atmospheric C sequestration. Reservoirs also counteract sources of greenhouse gases due to the fact that when reservoirs flood vegetated areas, the C stored from plant photosynthesis is eliminated, and stored OM releases carbon dioxide and methane when it mineralises (Figure 43).



- CO_2 is produced in the presence of oxygen.
- CH_4 is produced in anoxic environments.
- N_2O is emitted during the denitrification process in water with high nitrate concentrations in anoxic conditions.

Figure 43: Simplified diagram of the behaviour of carbon and greenhouse gas emissions in a reservoir.

VIII.1.6.b Observed effects, determining factors

Greenhouse gas fluxes are measured using different techniques depending on whether studies seek to measure atmospheric exchanges on the surface of the reservoir (diffusive methods), degassing from sediment at the bottom of the reservoir, or gas concentrations in the water column (multiparameter probe or chromatography analysis in the gaseous phase after sampling).

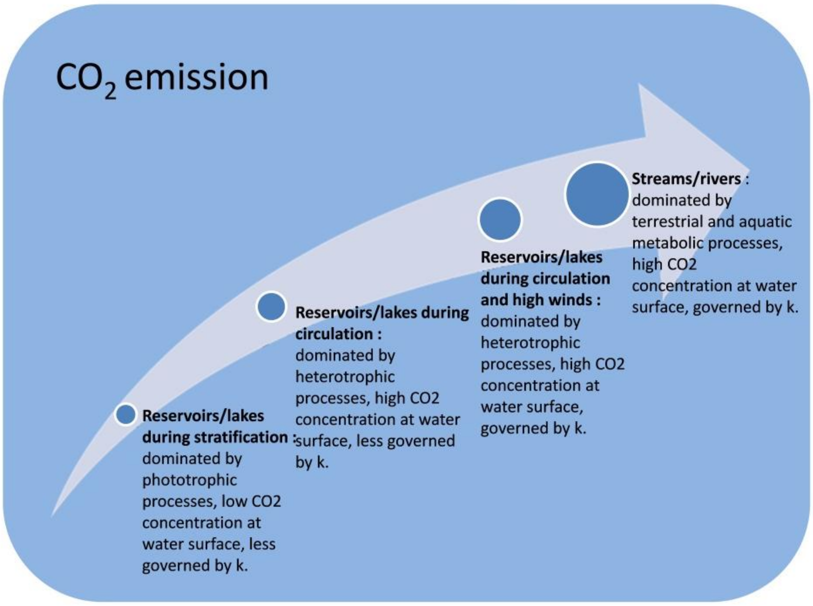


Figure 44: Schematic diagram of the effect of different regulation mechanisms on the CO_2 emissions (per area unit) of rivers and lakes with low wind. k is the gas transfer speed. The CO_2 flux is equal to the difference in CO_2 concentrations in the water and in the air, multiplied by k: $FCO_2 = (CO_2\ water - CO_2\ air) \times k$. Halbedel, 2013.

The CO_2 and CH_4 fluxes measured are extremely variable, ranging from 700 to 4500 mg/m²/day for CO_2, to 3 to 4500 mg/m²/day for CH_4. They vary depending on the quantity and quality of OM flooded, the age of the reservoir (the residual flooded OM becomes more stable), on water temperature, which accelerates decomposition reactions, and the extent of primary production. The life cycle of primary production induces a seasonal cycle of the sink and source functions. The presence of stratification, which is accompanied by lower O_2 concentrations in deep water and orients the bacterial activity that creates greenhouse gases is also an influencing factor. In a temperate environment, there is therefore a seasonal aspect involved in CO_2 emissions associated with stratification. In the summer, reservoirs are sinks of CO_2 consumed by primary production, mainly at the surface. During hydrological recovery, this surface layer mixes with the deeper layers with higher CO_2 levels from OM mineralisation. Reservoirs therefore become sources of CO_2. However, rivers create more CO_2 emissions than reservoirs due to the fact that rivers are saturated with CO_2 and flow turbulence favours emission into the atmosphere (Figure 44).

On the other hand, reservoirs systematically act as sources of CH_4 and emissions, which seem to be linked to the organic sediment accumulation rate, create more emissions than rivers. Shallow reservoirs seem to favour CH_4 emissions, probably because this gas is diffused into the atmosphere before its oxidation into CO_2. CH_4 degassing from sediment also depends on atmospheric pressure and temperature.

As for organic carbon sequestration in a reservoir, it is linked to the net annual sediment accumulation rate. For a group of small farm ponds, the rate of C sequestration is positively correlated with the area of the upstream catchment, but negatively with the area of the reservoir, the sedimentation per area unit becoming less “efficient” the greater the area of the reservoir. These fluxes vary between 148 and 17 000 g C/m²/year. Small reservoirs are more effective than large reservoirs in terms of C sequestration and also seem more effective than natural lakes (Figure 45). For fish ponds, the flux of C stored is estimated at between 28 and 333 g/m²/year, which is lower than large river dams and small eutrophic lakes in agricultural regions but higher than for natural lakes.

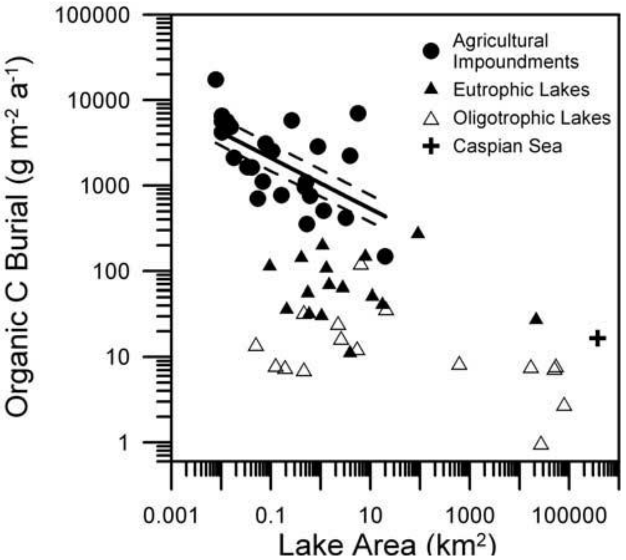


Figure 45: Quantity of sequestered carbon per area unit and per year, depending on the type of water body and its area. Downing 2008.

There are few studies that examine N_2O emissions. They point to moderate emissions, similar to those of natural lakes.

In the end, **reservoirs can sequester carbon in the form of organic matter and contribute to CO_2 and CH_4 all at the same time.** This behaviour depends on the characteristics of each reservoir (age, depth, size, climate, etc.) and their environment (nutrients for the development of primary biomass, organic sediment, etc.), and can vary considerably over time, often with an apparent seasonal effect. For reservoirs on rivers, it seems that rivers emit more CO_2 than reservoirs, and inversely for CH_4. From a methodological standpoint, the spatial variability (measurements often taken from one location in the reservoir) and temporal variability (seasonal aspect and variability from year to year) of processes would need to be taken into account in order to obtain complete assessments of the fluxes at play.

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CHAPTER III: SURVEY OF RESERVOIRS AND THEIR CHARACTERISTICS

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CHAPTER IV: CUMULATIVE EFFECTS OF RESERVOIRS ON HYDROLOGY

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CHAPTER V: CUMULATIVE EFFECTS OF RESERVOIRS ON RIVER SEDIMENT TRANSPORT AND HYDROMORPHOLOGY

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CHAPTER VI: CUMULATIVE EFFECTS OF RESERVOIRS ON RIVER PHYSICO-CHEMICAL CHARACTERISTICS

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CHAPTER VII: CUMULATIVE EFFECTS OF RESERVOIRS ON THE RIVER AND CATCHMENT AREA BIOLOGICAL COMPARTMENT

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