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Photo: Arnulf Husmo. The Alta Dam in Norway.

Forskningsrådet för miljö, areella näringar och samhällsbyggande, Formas
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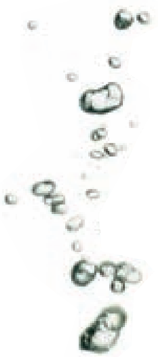
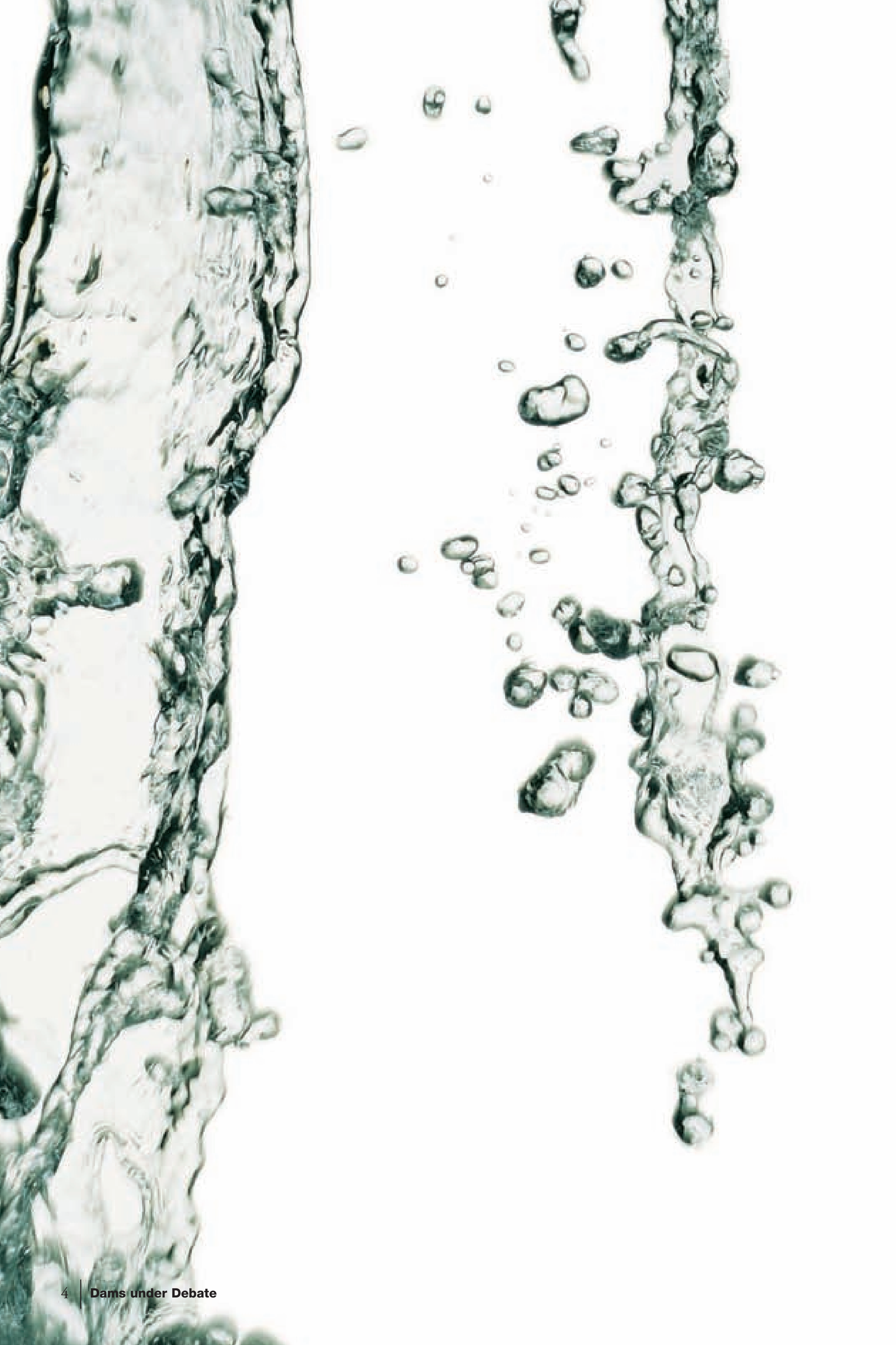
R6:2006
ISBN 91-540-5975-5
ISSN 1653-3003
Swedish Research Council Formas
Editors: Birgitta Johansson and Björn Sellberg
Planning group: Lars Bengtsson, Lars O Ericsson,
Jan Lundqvist, Britt Olofsdotter
Translation: Lewis Gruber
Design: Lupo Design
Print: august 2006. Elanders Gotab, Sweden



Dams under Debate

Contents



Dams can tame water

Dams are used for many purposes. Construction of dams proceeds at a great pace in the third world, and there is a lively debate concerning dams. They do not only provide benefits and contribute to human survival. They also cause large scale encroachment and may therefore pose hazards and give rise to negative impacts, for both nature and humans.

Sture Blomgren
Acting Director General
Formas

For thousands of years, humans have built dams to control the distribution of water in time and space. Dams tame water. They give us water on our terms. In the global water crisis of today, use of dams with several functions can be an important part of the solution. But construction of dams must be based on knowledge – and on consideration for nature and humans. In such a way, dams may be of critical importance for human survival and comfort.

Dams on rivers can supply electric power, contribute to water supply and provide water for irrigation. But they can also disrupt ecosystems both upstream and downstream. They may also cause serious social impacts. The disruptions that arise due to dams must be balanced against the positive consequences of dams. The dilemma is that the people who benefit from dams are in most cases different from those who lose by them. Dams that are used for several purposes at one and the same time may create conflicts. For example, dams that are to provide protection against flooding should have empty reservoirs, while those used for irrigation should have their reservoirs full of water. This is a technical challenge that needs to be solved.

Another type of dam can protect us from floods and waves. Some low-lying parts of the world would be scarcely habitable without dams.

This is what the third water book of Research Council Formas is about – dams to tame water, to utilise water and to protect us from water. Researchers have written the articles. Research is needed to show how dams can be designed and what the consequences are of building dams in different ways. Dams must, for instance, be safe – also in the changed climate of the future. Umeå University has collected information on dams in 292 of the large river systems of the world. This is essential basic knowledge for continued development of rivers and on the eve of future climate changes.

Sture Blomgren
Acting Director General
Swedish Research Council Formas

Further reading (www.formas.se):
- *Water research – what's next?* Formas 2004
- *Groundwater under threat*, Formas 2005

Dams in the world

Professor Christer Nilsson and PhD student Cathy A. Reidy,
Department of Ecology and Environmental Science, Umeå University.

Umeå University has compiled information on dams in the world. This work has gone on for more than fifteen years, and data have been collected regarding all rivers that are as large as, or larger than, the Torne River in Sweden. A total of 292 river systems have been investigated. Researchers now know how closely dams are placed in the rivers, and how heavily water flow is regulated. Regulated and free-flowing rivers are expected to be affected to different degrees by future changes in climate, rates of runoff and sea levels. This global overview may make it easier to make preparations for the future challenges.

The dam at Stornorrfors on the Ume River. This river is one of the large rivers comprised in the investigation described in this article. Photo: Roland Jansson.

Most of the rivers in the world were originally characterised by large variations in flow. Humans have experienced great difficulty in adapting to this natural variability. They have instead made comprehensive changes to river systems by constructing dams and diverting the water, to satisfy the human need for water, energy and transport, and other purposes. Today there are about 50,000 dams in the world with heights in excess of 15 metres. These dams can retain more than 6.5 trillion m^3 of water, which represents about 15 per cent of the annual global runoff. If this water were evenly spread over the surface of Sweden, it would create a layer 14.4 m deep.

More than 300 dams are considered to be giant dams.

More than 300 dams are considered to be giant dams. They satisfy at least one of the criteria regarding height (at least 150 m), dam volume (at least 15 million m^3) or storage capacity in the reservoir (at least 25 billion m^3). The recently constructed Three Gorges dam on the Yangtze River in China is regarded to be the largest so far – it is 181 m high and the reservoir has a capacity in excess of 39 billion m^3 of water. If we consider that the reservoir is 600 km long, it is easier to appreciate how gigantic this construction is. It is 100 km longer than the Torne River, the largest free-flowing river in Sweden. But there are even higher dams, even though they have a lower storage capacity. The two highest dams in the world, Rogun and Nurek, both on the Vakhsh River in Tajikistan, are 335 and 300 m high. They store water for irrigation and hydropower. It is possible to get an idea of the size of the Rogun Dam by comparing it to the Eiffel Tower in Paris, the height of which to the tip of the aerial is 324 m.

Impacts on nature and humans

The effects of dams on ecosystems are generally well known. These comprise both upstream and downstream effects due to impounding, flow regulation and fragmentation of the landscape. Impounding schemes completely destroy the terrestrial ecosystem. They also eradicate the rapids, which obviously affects the organisms that demand fast-flowing water. Impounding can also give rise to oxygen deficiency, the emission of greenhouse gases, sedimentation of silt and liberation of nutrients when new reservoirs are created. Resettlement of people when developed areas are flooded can create health problems, social, cultural and religious problems, and comprehensive changes in land use patterns. It is estimated that between 40 and 80 million people have been forced to move because their homes have been flooded. This is a tragic development since in most cases sustainable agricultural communities are destroyed to provide support for unsustainable cities.

Manipulation of flow may hinder development of the river channel, drain wetlands close to the river, reduce the productivity of river banks, lower the dynamics of delta regions, and eradicate communities of organisms in the water. Dams also hinder the spread and migration of many organisms, resulting in populations or entire species of fish being eradicated. One very clear example of what flow regulation can give rise to is the devastation of New Orleans in the Mississippi delta last year. Regulation of the river over many years has reduced the size of the delta and lowered its level, and necessitated the construction of extensive river walls to keep out the waters. When hurricane Katrina arrived, the protective walls did not hold, and 80 per cent of the city was flooded.

Compilation of the world's dams

At the end of the 1980s, we at Umeå University began a compilation of the world's dams. The starting point was the largest free-flowing river in Sweden – the Torne River. Information was collected concerning all rivers that were as large or larger. This means that all river systems with an annual mean flow equal to, or greater than, 350 m^3/s have been investigated. The objective was to find how closely dams are situated on these rivers, and how heavily their flow is regulated. Owing to irregular funding, work has proceeded by fits and starts, but now it may be considered finished at the scale employed. There are only a few small areas in Malaysia and Indonesia that remain, but runoff data there are so poor that it is impossible to decide whether there are rivers in these countries that are sufficiently large to come within the investigation.

292 river systems have been divided into three categories: strong impact, moderate impact and little or no impact.

A total of 292 river systems have thus been considered. They have been divided into three categories in view of the degree of impact which the dams have: strong impact, moderate impact and little or no impact. Fig. 1 shows how these three categories are spread over the world. There are about the same number of large river systems where the dams have no impact or strong impact (120 and 104 respectively). Only 68 of the large river systems have been classified as being moderately affected by dams. Of the ten river systems in the world that carry the most water, the dams on six have moderate impact and on four strong impact. Dams on both the world's two river systems which carry the most water (Amazonas-Orinoco in South America and Congo in Central Africa) have moderate impact, while dams on the third largest river in terms of water volume, the Yangtze, have a strong impact. The largest free-flowing river in the world is the Yukon in Alaska. It is in twenty-second place in terms of annual mean flow. Most of the large river systems on which the dams have no impact are in North and Central America, while Australasia has the highest proportion of systems with no impact, 74 per cent. Europe has both the smallest number (five) and the lowest proportion (12 per cent) of systems where the dams have no impact.

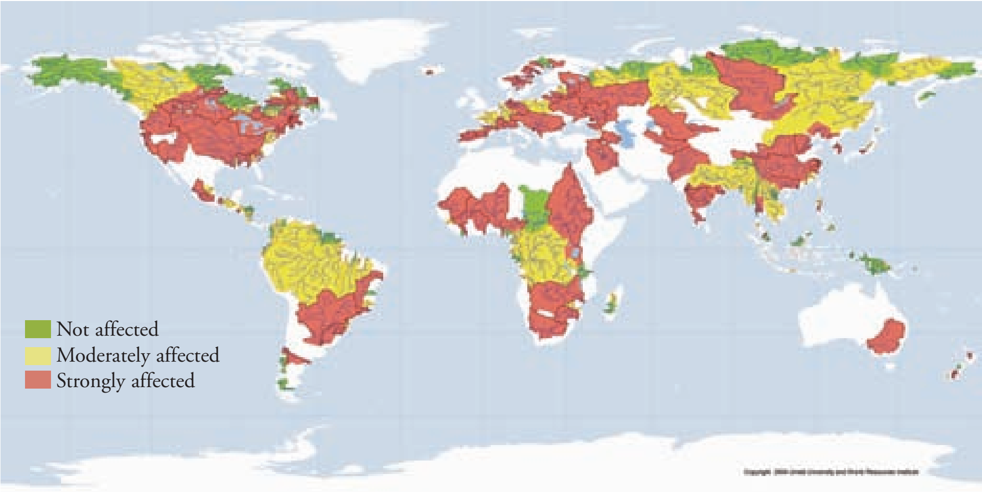


Fig. 1. Classification of the impact of dams in the form of fragmentation and flow regulation on the 292 large river systems in the world. River systems are treated as units and are represented on the map by their catchment areas. Red, yellow and green denote great, moderate and little or no impact respectively. White areas denote areas of land not encompassed by large river systems. Systems that have not been considered owing to unreliable data are shown in grey.

One third (102) of the large river systems have no dams at all. This means that there are 18 unaffected systems that have single dams on their tributaries. Europe has the lowest number of rivers without dams (only three rivers in North-West Russia – Pechora, Mezen and Onega). The continent which has the most (35) large river systems without dams is North and Central America. Twelve large river systems (nine in Europe and three in North America) have so many dams that less than one quarter of their length is free of dams.

The largest degree of regulation (428 per cent) is found on the Volta river in West Africa. This means that its reservoir can store more than four years' normal runoff without any water having to be discharged. In North and Central America, the Manicougan and Colorado rivers are both regulated more than 250 per cent, and in South America the Rio Negro is the large river system that is most heavily regulated. The most heavily regulated large rivers in Asia are the Shatt Al Arab (which is formed by the confluence of the Euphrates and Tigris) in the Middle East, and Mekong in Thailand. Europe and Australasia have no large rivers with degrees of regulation exceeding 100 per cent.

Many of the rivers in the world are subjected to extensive water abstraction, primarily for irrigation. Most of this water evaporates, which means that the rivers dwindle. The rivers that are most heavily affected do not reach the sea during the whole year or parts of the year. Changes like this have devastating consequences for plant and animal life in the delta regions and the sea. Most irrigation, in terms of the irrigated area and the water that is available, takes place on rivers that are already extensively dammed. In most countries there is also a strong coupling between population, economic activity and degree of impact. The exceptions are rivers in sparsely populated northern regions which are heavily exploited for exportation of hydropower.

Many of the rivers in the world are subjected to extensive water abstraction, primarily for irrigation.

Peak in the 1970s

The annual number of newly constructed dams reached its peak in the 1970s and has since decreased. Today, dams are being planned or constructed on 46 of the large river systems we have studied. There will be between one and 49 dams per river system, and most are located in developing countries. Almost one half of the new dams are situated on four river systems, 49 on the Yangtze, 29 on Rio de la Plata in South America, 26 on Shatt Al Arab and 25 on Ganges-Brahmaputra in south Asia. New dams are also being planned in several large river systems which are today unaffected, for instance on Jequitinhonha in South America and on Cá, Agusan, Rajang and Salween in Asia. Just as in the north of Canada and in Sweden, construction can be influenced by the fact that benefits reaped within the directly affected catchment area can be exported to other regions. This is the case, for instance, on Salween (in China, Myanmar and Thailand) where it is expected that some of the electric power produced can be exported.

One of the advantages of having a global overview of how the world's rivers are affected by dams is that it is easier to judge the effect of new dams and regulation schemes. It is also easier to judge the aggregate contribution of the regulated rivers to energy production and water management in various countries, and to evaluate the remaining river systems and to draw up nature conservancy strategies. Since it is expected that regulated and free-flowing rivers will be affected differently by future changes in climate, rates of runoff and sea levels, the global overview may make it easier to make preparations for the new challenges. One conclusion that can be drawn from the international perspective is that, owing to their small numbers, the free-flowing rivers should be valued even more highly than has been the case so far.

The free-flowing rivers should be valued even more highly than has been the case so far.

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Cooperation on international waters

Dr Anders Jägerskog, Stockholm International Water Institute (SIWI).

Traditionally, water has often been talked about as a source of conflicts and even war, not least in the Middle East. It has however been found that transboundary water resources are rather something that brings cooperation, and the fact is that even today, when relations between Israelis and Palestinians are at bottom level, there is cooperation about water.

View of the Golan Heights that are occupied by Israel.
Photo: André Maslennikov

Water is of fundamental importance for economic and social development and stability. In most processes in human society, water cannot be exchanged for something else. Because of this, a secure supply of water is even more important than if it had been an exchangeable resource. Dependence on the "nature-given water" that is in circulation in the soil and water that is located in surface water sources and the atmosphere is a basic need since for most countries in the world it is far too expensive to desalinate or to transport water in canals or in a similar way. In regions where countries compete for scarce water resources, this supply is often seen as a matter of national security.

Water conflicts are based on the fact that the country that is situated upstream in a river basin can manipulate flows to countries that lie downstream.

The fact that many countries are dependent on water resources that originate in other countries, and are therefore also controlled by other countries, turns water into a potential weapon in a political conflict. Water conflicts are based on the fact that the country that is situated upstream in a river basin can manipulate flows to countries that lie downstream, for instance by constructing dams and diverting water for irrigation. A rapid rise in population further aggravates the problem. In the years prior to the six-day war in 1967, Israel attacked Syrian dam structures that threatened to reduce Israeli water supplies. In the light of this background, it is perhaps not so strange that we increasingly hear cries that "water wars" are imminent. For example, King Hussein has said that the only reason for Jordan to make war is water. The Secretary General of the UN, Kofi Annan, said some years ago that "violent competition for freshwater may very well be a source of conflict and war in the future". Later, however, he changed this statement and pointed out that it is more often a reason for cooperation.

Many factors determine whether a conflict arises

It has been found that water cooperation is something that both parties in a conflict can benefit from.

In the 1990s it was thought that water would be a reason for armed conflict and even war. But the issue was found to be more complex than this. There are many other factors that decide whether lack of water will lead to conflict, and the kind of conflict this turns out to be. Important factors in addition to the sharing of water resources are the economic and institutional stability of the countries, population growth, political relations, underlying conflicts, treaties on the sharing of water resources, as well as the balance of power. Today there is consensus among researchers that, although shared water resources in combination with water scarcity lead to political conflicts, these conflicts tend to result in the parties taking stock and finding ways of cooperating on this common resource. It has been found that water cooperation is something that both parties in a conflict can benefit from.

Further, the concept of "virtual water" has made it possible for countries suffering from scarcity of water to compensate for this and in this way reduce the incentive to take action that makes conflict more likely. Virtual water is the water that is imported (or exported) to a region through the trade that primarily involves food. Food is namely the area that demands the most water. By importing, for instance, one kilogram of wheat, one in practice imports one thousand litres of water since this is the quantity of water necessary for the production of one kilogram of wheat.

Virtual water is the water that is imported or exported to a region through the trade that primarily involves food.

Database over shared river systems

Aaron Wolf and his research team at Oregon State University have created a comprehensive database over all the shared river systems in the world (http://www.transboundarywaters.orst.edu). He is of the opinion that water has been a source of cooperation rather than conflict, which is also shown by his examination of the world's 263 shared rivers. Today, 45 per cent of the world's population lives in river basins that are shared by one or more countries. In Africa, this figure exceeds 90 per cent. And over 50 per cent of all accessible surface water in the world (that which has not yet been allocated for other fields of use) is shared among two or more countries. In the Middle East, there is great dependence on water. Dependence on water, according to him, means that a country is dependent on water that originates in one or more other countries.

Country	Water dependence (%)
Kuwait	100
Egypt	97
Bahrain	97
Syria	80
Palestine	75
Israel	55
Iraq	53
Jordan	23
Tunisia	9
Iran	7
Lebanon	7
Algeria	4
Qatar	4
Morocco	0
Djibouti	0
Oman	0
Yemen	0
Malta	0
Saudi Arabia	0
Libya	0
United Arab Emirates	0

Water dependence in the Middle East and North Africa according to World Water Development Report 2003 and Phillips et al, 2005. The table shows, for instance, that Kuwait is one hundred per cent dependent on water that has its origin in other countries.

Because of the above, the matter of transboundary water is of great importance, both for the countries themselves and for the international community. Many international organisations such as the UNDP, the World Bank and other donors also support work on water resources in river basins that are shared by one or several countries. Even though the issue of transboundary water is important, the inputs made by the international community are limited. In addition, financial support for work on transboundary water is often not coordinated satisfactorily. In spite of these problems, important lessons have been learned from the inputs that have been made. The one great lesson is that long term perspectives and patience are needed. The focus should be placed on financing a process – and this often takes a long time.

Water and future international security

Attempts are made to find ways for countries to cooperate and to optimise the benefit that water could give.

Through building on the insight that water tends to get even political opponents to cooperate, attempts are currently underway within the international community to stimulate this cooperation in order that water should become an even more important factor for peace, stability and international security.

Attempts are made to find ways for countries to cooperate and to optimise the benefit that water could give. Instead of allocating parts of the river to the parties that are riparians, the idea is that they should cooperate on sharing the benefits that may be derived from the use of the water, such as effective energy exploitation, more effective transport and more effective farming. It may be thought, for instance, that countries that share a river will build their own dams and hydropower plants, and then build a joint dam at the place where the most energy can be derived. In the same way, cultivation is carried out where it is climatically most advantageous, and the produce is then traded. Such thinking leads to a plus-sum game where all parties can win, instead of a zero-sum game where the win of one is the loss of the other. Smarter utilisation of a common river, with the cooperation that is required among countries and parties, could also contribute to greater understanding of each other and to long term peaceful relations.

Such thinking leads to a plus-sum game where all parties can win, instead of a zero-sum game where the win of one is the loss of the other.

One example of endeavours at such work is found around the Nile. There, countries are attempting, with the assistance of the World Bank, to find ways of sharing the benefits that can be jointly derived from the river rather than focusing on sharing the water as such. It is thought that such an approach may contribute to greater security and understanding in otherwise tense political regions. In the Nile region, there are a number of simultaneous problems that the countries alongside the river must tackle. At the present time, several of the poorer countries in East Africa (Kenya, Uganda, Tanzania and Rwanda) and also Ethiopia have very limited capacity for water storage since they have no large dams. These countries are naturally interested in increasing their storage capacities, but at the same time this would reduce downstream flow to Sudan and Egypt. Obviously, this is something that neither Egypt nor Sudan views favourably. On the other hand, Egypt has large storage capacity by virtue of the Asswan Dam, which means that it can regulate water much better and alleviate the effects of droughts.

Cooperation in the Jordan basin

In Sweden, annual supply of water is 20,000 m^3 per person, and an ample supply of water is considered self evident. But this is not the case in many other parts of the world. In the Middle East and North Africa, five per cent of the world's population must share one per cent of the earth's freshwater resources. In Israel the annual supply is 300 m^3 per person, in Jordan it is less than 100 and on the West Bank 70. The situation is worst in Gaza; the annual supply there is around 50 m^3 per person.

Ever since the State of Israel was proclaimed in 1948, a number of initiatives have been taken regarding the utilisation of water resources. The issue of water is part of the peace treaty of 1994 between Israel and Jordan, and of the Declaration of Principles between Israel and PLO in 1993. In spite of the political instability in the Middle East, cooperation about water continues in different forms. Israel and Jordan had water coordination as early as the 1950s, in spite of the fact that there was no formal peace. Water experts from countries in the region have continually met to conduct a dialogue on issues connected with water – there is, among others, a group called EXACT (Executive Action Team; http://exact-me.org). This is a group where representatives from Israel, the Palestinian Authority and Jordan meet together with a number of donor countries to discuss common projects. In 2005 Israel, the Palestinians and Jordan signed an agreement to carry out a study into the feasibility of building a conveyance structure between the Red Sea and the Dead Sea to save the Dead Sea, improve the availability of water and generate hydropower.

In spite of the political instability in the Middle East, cooperation about water continues in different forms.

Even though cooperation is important, it cannot completely alleviate water scarcity. One important factor that is neglected by those who are convinced that wars about water are likely in this region is that virtual water is exported from certain regions. Through the import of virtual water to the countries around the Jordan, Israel, Jordan and the Palestinians have been able to use water in sectors such as industry and households, water that would normally be needed for agriculture. In order to manage the increasing population in the region and its need for food, greater imports of water-rich crops are required. While Israel can cope with such increased importation of food economically, the situation for the Palestinians and Jordanians is more difficult, both economically and, most importantly, socially. They would be forced to make other products for sale in an export market in order to finance the import of increasing quantities of virtual water. They would also have to find alternative employment for many of those working in the agricultural sector. In the Palestinian economy, 25-30 per cent work in agriculture.

Israel is actively engaged on desalination, and by 2010 about 20 per cent of its water use will be based on desalinated water.

Even though Israelis and Palestinians cooperate on water, this cooperation is not without problems. There are clear differences concerning the way future water needs are to be managed, the priorities in the water relations of the parties, and so on. Both parties are agreed that cooperation and coordination are essential, but in the opinion of Israel the focus in the work should now be on how "new" water resources can be developed, for instance production of freshwater through desalination of seawater. Israel is actively engaged on desalination, and by 2010 about 20 per cent of its water use will be based on desalinated water. They consider that Palestinians should also invest in desalination – preferably in cooperation with Israel. The Israelis also think that an effective way of saving water is to re-use partly treated sewage effluent. 35 per cent of Israeli agriculture is today irrigated with re-used water, and that proportion is estimated to rise to 55 per cent by 2010. This offers great opportunities for the Palestinians also, if they receive economic support. Israeli water saving technology is also very advanced and is under constant development. In 1988 Israel was able to produce one unit of crop per unit of irrigation water; today, two units of crop can be produced for the same quantity of water.

In practice, Israel today has complete control over the water sources on the West Bank and in Gaza by virtue of the fact that they must approve all new wells.

The Palestinians, on their side, consider that before the parties can be fully engaged in discussions to find "new" water, it is necessary to discuss allocation. Today it is stipulated in the interim agreement signed in 1995 that the Palestinians have water rights, but what these rights consist of has not been defined. In practice, Israel today has complete control over the water sources on the West Bank and in Gaza by virtue of the fact that they must approve all new wells. This occurs through their civil administration and through the consensus process in the joint water committee, something that, in practice, gives Israel the veto. A solution to the allocation problem will be negotiated when the final talks are commenced. Since it does not appear that this is in the immediate future, it is probably inevitable that the Palestinians must consider how "new" water can be produced. It must however be pointed out that the Palestinians realise that it is necessary to find new ways to improve the water situation.

Conclusions

Adequate supplies of water are a fundamental condition for the achievement of all the Millennium Development Goals agreed on in the UN. Since the bulk of the water that is today available globally is of transboundary character, it is essential that these issues should be accorded priority. This is of key importance from a developmental perspective. Cooperation among countries in river basins must be increased, and developing countries need support to increase their storage capacity to prevent the negative impacts of droughts.

Since the bulk of the water that is today available globally is of transboundary character, it is essential that these issues should be accorded priority.

The fact that countries often decide to cooperate in international river systems can be interpreted to mean that acceptable solutions are reached for most parties. But it often happens that the strong country in a river basin can manipulate the results into something that is in line with its own interests. This is evident when we look at the situation in the Jordan basin where Israel is in a dominant position, but also in the Nile basin where Egypt is dominant.

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Conflicts regarding dams with several functions

Professor Lars Bengtsson and Professor Ronny Berndtsson, Department of Water Resources Engineering, Lund University.

We are facing a water crisis because the world's water resources must supply a population of record size. Strategic use of water and utilisation of dams in some form will be an important part of the solution. The pressure for multi-objective utilisation of dams will increase. But if one and the same dam is to be employed for a number of purposes, conflicts of interest may arise. When dams are to provide protection against floods, the reservoir should preferably be empty, while for irrigation it should preferably be full. This is a complicated technical issue to solve.

The gigantic Three Gorges hydrolectric dam on the Yangtze was completed in 2006 after eight years of construction. The reservoir has drowned around a dozen small towns and more than 300 villages. Photo: Joelle Garrus/Scanpix.

A dam is planned and built for one or several purposes. The most common are hydropower production, flood protection, irrigation and urban water supply. Equalisation of downstream flows and levels makes for better irrigation facilities a long way downstream, improved transport, recreation or better ecological conditions for certain species or biotopes. When a lake or a reservoir upstream of a dam structure is used for several purposes, it is said to have multiobjective utilisation. These different uses may conflict to some extent, and in such a case an endeavour is made to control regulation of the reservoir so that the dam is used optimally.

Multiobjective use of the water in dams is a complex technological problem.

Multiobjective use of the water in dams is a complex technological problem. If, for instance, a dam is to be used for both flood protection and irrigation, the problem arises that these purposes are to some extent contrary. For a dam to be used as flood protection, it is necessary for the reservoir to be empty or in any case almost empty when a flood wave can be expected. On the other hand, for water supply purposes as much water as possible is to be stored so that future urban and agricultural water needs may be secured. The task is even more complicated if there are other purposes, such as improvement of ecological conditions, recreation or navigational needs.

Contrary interests

One way of solving this problem is to assess the probability of a certain water flow upstream of the dam. Floods are perhaps most common at a certain time of the year. Irrigation needs arise during dry and warm periods, and these occur during a different part of the year. Use is then made of the assessed probabilities that certain flows in the river will be exceeded, and calculations are made of the likely filling ratios to be used in the reservoir concerned at certain times. Regulation of the water level in the reservoir may be said to be subject to some risk assessment. During periods of flooding the reservoir will then be empty or almost empty so that it can accommodate masses of water in the event of downpours or snowmelt. Towards the end of the flooding period the reservoir is gradually filled, so that it is full or almost full to generate hydropower or to contribute water for towns downstream or for agricultural areas during the upcoming dry period.

But when the dam has several purposes, this method of solving conflicts becomes increasingly complicated. In practice, it may be almost impossible to balance all the functions for a certain dam. Some examples are given below of the purposes that a dam may have to serve and the way the reservoir is to function for each field of application.

Flood protection

Flood protection. The reservoir must at all times be kept at a low level, and the first waters in a flood wave are discharged. A prediction must be made of expected future flows.

Hydropower

Hydropower. The reservoir must at all times be filled when this is possible; no water is to be discharged without passing through the turbines. Compared with other uses, water utilisation is almost continuous over the year. If there are heavy rains when the reservoirs are full, the dams have no flow reducing function.

Irrigation

Irrigation. The reservoir must be full at the beginning of the growing season, and water is used during dry periods. Downstream flows are very low.

Water supply

Water supply. Water utilisation is fairly continuous over the year although it may increase during warm periods. When water is used locally, most of it is returned into the river system. During transits (moving of water to another catchment area) water is lost and this affects downstream flows. Surface sources of water must be protected from contamination.

Environmental or ecological flows

Environmental or ecological flows. Minimum flow must be guaranteed.

Recreation and navigation

Recreation and navigation. Water level must be stable and quite high.

Dam problems in Sweden

In Sweden practically all rivers have been developed for hydropower purposes. This means that high water flows are taken up in reservoirs so that discharge in the river downstream of the reservoir is equalised. One secondary effect is that the number of floods is reduced. Villages and urban areas began to be planned as though there would never be any high flows again. Extreme flows have however occurred in recent years when heavy long term rains fell during the summer and early autumn when the reservoirs were full.

The flooding of Arvika north of Lake Vänern in Sweden in the summer of 2003 is one example of this. The river Byälven is regulated for hydropower. During that summer there was a lot of rain over a two-week period, and this resulted in very high flows. The reservoir upstream of Arvika was filled up before it was realised how high the flow would be. The result was that the town of Arvika was flooded. There was widespread destruction, and several bridges and roads were swept away.

Dam problems in China

Dams are often constructed for a certain purpose, but after they have been used for varying periods, the needs for other uses may arise. At an early stage, a dam may be built for flood control. As economic development proceeds, greater needs arise for e.g. energy and irrigation water for agriculture. Especially in China there are many examples of this. Industrial development there is consuming increasing amounts of energy. An ever larger urban population demands stable supplies of drinking water. Agriculture is also demanding increasing amounts of water for irrigation. The gigantic Three Gorges Dam has been part of the solution to these problems.

The Three Gorges Dam is primarily constructed to generate hydroelectric power. But one secondary purpose is to regulate the great Yangtze River so that the annual floods should be reduced. The dam project will also facilitate navigation and transport on the river. The greatest conflicts associated with this construction are ecological, environmental and social.

The Yangtze River passes through the Three Gorges, the site of the world's largest dam.
Photo: Lars Bengtsson

Most dams on the somewhat smaller rivers in China are built for irrigation purposes. 12.5 per cent of China's population lives in Henan Province in the central part of Eastern China. Agriculture predominates. The climate allows two harvests a year, provided that there is enough water. Most of the rains fall during the late summer. To get a harvest in the spring and early summer, the fields must be irrigated, and irrigation water must therefore be stored from early autumn until the spring. In order to ensure that there will be water in the reservoir when spring arrives, the reservoir is to be filled as early as possible. Week-long periods with 300 mm of rain have occurred about fifty times during the past fifty years. The reservoir is then rapidly filled. But in some years the late summer rains almost completely fail. It may also happen that a lot of heavy rain falls in the autumn when the reservoirs are full. At such times there is a great risk of flooding downstream.

In the HongRu catchment area that is 12,380 km^2 in extent there are five dams with a total storage capacity of over 3,000 million m^3. Their principal function is for irrigation, but turbines have also been installed for hydroelectric power. The dams also function as flood protection; for the same purpose there are flood plains downstream, and attempts are made to divert the water to these when flows are very high. In August 1975, 1,600 mm of rain fell in three days. Two dams were destroyed, but without really increasing the downstream flow that was already high. The other dams were not able to hold back the water. Discharge in the Ru river increased a long way upstream from less than 10 m^3/s to almost 1000 m^3/s. The water reached villages several km from the river. Many people died.

Ru River at low flow in April. There is cultivation on all surfaces near the river. At high water the whole river ravine is filled. During the floods in 1975 and 1982 the water spread out for several kilometres over the agricultural land on the plateau above. Photo: Lars Bengtsson

In this case in 1975 the high flows could not have been held back even if the reservoirs had been quite empty when the rain began. In 1982, however, it was possible to mitigate the peak flows to some extent. In that year, over 300 mm rain fell in the middle of July, almost 200 mm in the first week in August and almost 250 mm in the middle of August. This gave rise to three peak flows to the largest but shallowest reservoir in the region, Suyahu Reservoir. If it is decided to hold back as much water as possible to guarantee water for the next year, it will not be possible to contain the subsequent flows, and the outflow from the reservoir will be as large as the inflow; the peak flow was 1,200 m^3/s. If it had been decided to use Suyahu Reservoir only for flood control and the reservoir had been empty when the rain began, the outflow in the event of optimal regulation would have been 300 m^3/s.

Special houses in a region prone to flooding near the HongRu river. People will be able to escape to the top floors in the case of flooding.
Photo: Ronny Berndtsson

The floods in the HongRu river in 1975 and 1982 show that in low lying areas protection cannot be provided by dams. In the HongRu region attempts have been made to resettle some of the population, but people want to live near their farming areas which are situated right up to the river. To enable the population to live reasonably near the river and yet have some safety, special houses have been built in which people can escape to the top floor in case of flooding.

Dam problems in Mozambique

Mozambique in Africa is a country that is of special interest as regards dam problems. The Umbezi River is important, among others, for the capital Maputo. Along the Umbezi there are three dams. The smallest of these, Hawane, is far upstream in Swaziland and is used for water supply for the town Mbabane. The lowest and largest dam, Pequenos Limbombos dam, is 30 km upstream of the capital Maputo. Its duty is to secure water supply for Maputo and provide irrigation water for large sugar cane plantations. The mean discharge at Maputo is 16 m^3/s, but there is great variation. Water extraction for the city is 2.5 m^3/s, and about half this for irrigation. The lake that has been created upstream of the dam is now also a popular excursion area with good recreational facilities. The dam also functions as protection against flooding. The reservoir holds 400 million m^3. The other large dam, Mnjolidamme, is upstream in the river inside Swaziland. It is primarily for irrigation of sugar cane plantations; average annual extraction is 7.5 m^3/s. Climate variations are extensive and there may be long dry periods. In that case water is scarce since the reservoir is not large enough to store sufficient water and also because there are large evaporation losses from the reservoir.

Use of water from both these dams causes problems downstream. Irrigation of sugar cane plantations creates water quality problems due to salination, nutrients, pesticides and herbicides in the reservoirs. It also affects water supplies to the capital Maputo.

There are also problems downstream of the dams in the form of sewage effluent discharge and decreasing ecological flows. Necessary minimum flows for animals and plants cannot be maintained. The Pequenos Limbombos dam exhibits the whole range of conflicts associated with the use of dams. To provide protection against flooding, levels in the dam have to be low, but to guarantee water for irrigation and supplies for Maputo the level in the dam must be the highest possible. From the standpoint of recreation there must be a stable high water level, but for irrigation and water supply water must be extracted continuously.

Future dam problems

We are facing a water crisis because the finite water resources of the world must be sufficient to supply a world population of record size. Strategic use of water and utilisation of dams in some form will be an important part of the solution. There will be mounting pressure for multiobjective utilisation of existing dams. This will place great demands on effective management of the dams, and at the same time conflicts will increase.

Strategic use of water and utilisation of dams in some form will be an important part of the solution.

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Dam safety and climate change – the hydraulic engineering perspective

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Failure of a dam may result in the release of very large volumes of water which then propagate as a destructive dam-break wave down through the river. The ability to design, build and operate large dam installations with safety in focus is a good example of the development of Sustainable Engineering. A dam project must be not only technically and economically safe and well functioning, but also socially and environmentally sustainable.

Multiple gated spillway under construction in USA Photo: Klas Cederwall

Large hydropower and water regulation dams have an almost geological dimension.

Management of water resources and dam safety are closely connected, since the damping of high flows generally requires an effective water regulation input, while at the same time failure of a dam caused by large natural flows in the system may augment, with devastating consequences, flow conditions that are already highly stressed. Dam construction has a long term perspective coupled to climate and climate changes, and also to the fact that a large dam causes such a large change in nature that, for economic and practical reasons, it is generally impossible to "remove" or decommission a dam after its functional life is over. Dams are special structures that are clearly different from other constructions built by man. Large hydropower and water regulation dams have an almost geological dimension.

Dam risk management

Management of dam safety is based on the experiences of risks in technical systems. Of special importance are fundamental elements such as monitoring and performance control, periodical assessment of the status of dam safety, and strategic training that enhances the preparedness to handle critical situations. Development of operating and maintenance procedures is particularly important. Great emphasis must be placed on maintaining a high level of safety for dams that are already in existence, and at the same time safety issues are of fundamental importance when new dams are designed. One key issue is how the knowledge base that is needed can be established effectively and in broad cooperation. As part of this process, safety procedures must be documented in reports that illustrate:

- how risks and uncertainties can be identified and how they can be analysed and evaluated
- what measures have been taken to reduce these risks to acceptably low levels
- what systems are applied to provide a reliable understanding and control of various risks

A risk analysis that focuses on dam safety must therefore deal with all relevant issues concerning factors that may lead to dam failure or damage, and also comprise an assessment of the probability of various conceivable damage and failure processes.

Primary technical dam functions

A dam has several functions that are associated with its fundamental task of storing water in the dam reservoir in a way that is safe for the dam. In its structural and loadcarrying function, a dam is special inasmuch as it must often accommodate very large horizontal water loads which it then transmits, in different ways depending on the type of dam, down to the foundations or into steep rock faces, as at sites for e.g. arch dams. A dam must also be able to withstand all other environmental loads that affect the stability of the dam. These may be extreme floods in the water system, seismic action on the dam structure and reservoir, or wind waves attacking dam structures in the reservoir. In winter in cold climates, there may also arise ice forces which attack the upstream slope of the dam in particular.

Effective interaction between the dam structure itself and its foundations is critical for the stability and functioning of the dam. Very high dams may be more than 300 m in height and several kilometres in length. In the case of embankment dams the width of the base of the dam is at least three times the height. Embankment dams are usually constructed of zones of gravel and earth of different fractions which interact to form an internally stable and relatively watertight dam structure. This means that there is a slow, uniformly distributed and controlled leakage when the reservoir has filled up, a limited seepage that does not cause internal erosion and does not jeopardise dam stability.

Effective interaction between the dam structure itself and its foundations is critical for the stability and functioning of the dam.

Discharge function

The dam must also be able to discharge incoming flows which, for various reasons, cannot be stored in the reservoir. The design capacity of the spillway system of the dam should therefore also be able to cope with extremely high inflows to the dam. This is of particular importance in the case of dams that do not withstand overtopping of the crest, such as embankment dams. This situation may arise if the inflow to the dam over a certain period exceeds the discharge capacity of the dam. A climate change may give rise to more extreme floods and may require preventive measures.

Water retention dams and tailings dams

There are dams that are built for purposes other than storing and regulating water. Water retention dams are low dams that protect areas of land from the risk of flooding that may come from the sea or a river, or a combination of the two.

There are almost as many tailings dams as water regulation dams in the world. Tailings dams are built of mining waste and are a component in the management of water that is used and recirculated in mining. These dams are generally built up continuously in different ways during the active period of the mine and are decommissioned in a suitable manner after the active mining period. Mining as such is a risky operation. In the case of tailings dams there is the risk of large dam-break flood waves, but also a potentially great environmental hazard since toxic products in the dam structure and out in the impoundment may be dispersed into nature in the event of a dam failure.

Dams age

As all other structures, dams are subject to ageing effects that are associated with external and internal stresses and other impacts. Embankment dams are normally built up of natural materials – gravel and sand – which have been tested over thousands of years and found stable. However, leakage and internal erosion in the dam structure may give rise to local instabilities which jeopardise the existence of the entire dam.

The "dam doctor" who is responsible for dam safety must understand the specific problems and aches and pains of a large number of "dam patients" of various ages.

Problems in the case of a concrete dam may be detected more easily since the effects in the form of cracks and leaks are generally apparent during daily inspections, while internal problems in an earth or rock fill dam are more difficult to discover, especially if the dam is not strategically instrumented to monitor and evaluate its overall performance. Acquiring adequate knowledge of the state of existing dams is in practice more demanding than similar engineering assessments related to the design and construction of new dams. The "dam doctor" who is responsible for dam safety must understand the specific problems and aches and pains of a large number of "dam patients" of various ages.

Sustainable dam engineering

The Brundtland report "Our Common Future" to the World Commission on Environment and Development (1987) lays down a guiding principle for the sustainable society: "Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs". To be able to create such societies we need a process in which human activities are developed and adapted to patterns which are robust in the long term. This implies restrictions which take account of the three fundamental dimensions of the sustainability concept – ecological sustainability, social sustainability and economic sustainability through well functioning technical systems. As regards dam construction and dam safety, we can identify three possible causes that a dam project cannot be implemented or it does not function sustainably:

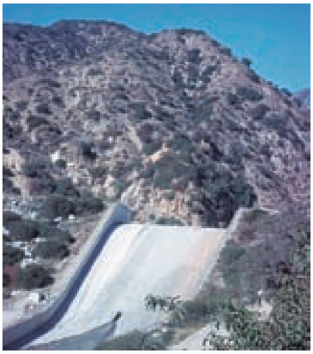
Seismic action

1. Seismic action. Dams in seismically active regions are beset by problems for several reasons. An earthquake has an impact

Highlighting some aspects of dam engineering and dam safety

Erosion protection structure upstream of dam (USA).

Natural dam spillway for flow diversion into the landscape (Ethiopia).



Flood chanelling structure upstream of dam (USA).

Van Norman Dam in USA close to collapse after earthquake.

Excavation of sediment trap upstream of dam (India).

Photos: Klas Cederwall

on both the reservoir and the dam structure, and interaction between the reservoir and the structure is complicated. Because of their weight, large reservoirs can also trigger induced seismicity. It is possible through design and construction to create dams that are relatively resistant to this type of stress and also to ensure that a damaged dam can retain an important residual stability so that the entire water volumes of the reservoir are not discharged in the case of serious damage. Nevertheless, an earthquake that also causes a large dam to collapse is a disaster that may cause destruction on a vast scale.

Siltation of the reservoir

2. Siltation of the reservoir. The practical service life of a dam may be determined by sedimentation within the reservoir which occurs in a water system that carries sediment. When the reservoir is full of sediment, the water storage function of the dam ceases. Catchment management which also comprises extensive soil conservation is therefore very important in regions with erosive soils.

Resettlement when large dam reservoirs are created

3. Resettlement when large dam reservoirs are created. Large dam projects often involve the creation of reservoirs in populated areas. This causes almost incomprehensible suffering to the local population unless resettlement of communities takes place according to a well prepared plan which ensures the participation of the people affected by the project. There are good models for creating well functioning and sustainable water resources projects in this way, but, unfortunately, there are many examples of the opposite.

All the dimensions of dam safety

The important concept of dam safety therefore has several dimensions. Safe management of dams implies that the stability of the dam installation must withstand all the loads and stresses it is designed for. Hydrological dam safety focuses on the ability of the dam installation to discharge safely the design floods. This implies, in particular, the ability to overview and analyse risk exposure, uncertainties and various forms of vulnerability. To this must be added the non-technical components of the dam safety function which are just as important to develop. There is a need, for example, for broad and advanced training in dam construction and risk management and for setting up effective maintenance and performance control systems. All these parts of the dam safety function interact in various ways and form an integrated system of safety management.

The design, construction and operation of a dam installation must therefore take place in such a way that safety during the entire life of the dam complies with stringent performance specifications. Climate changes and other changes in environmental impacts must be predicted, and adequate consideration must be given to these in an advanced dam safety function. An individual dam is normally a component in a major water system, represented by the entire connected catchment area with, inter alia, the water infrastructure and other buldings that are established there. Management of the complex problems in the catchment area demands a system approach. It is essential that planning of a water resources project should take place in close cooperation among the decision makers, the public and those who benefit – and those who do not benefit – from the project. It is necessary to have clear communication between those responsible and the public so that the necessary trust may be created among all those who are affected.

Knowledge base

Perhaps the most important aspect of dam safety is a scientifically embedded and well balanced knowledge base. Knowledge comprises both theory and practice. Dam construction, in all its elements and applications, in which climatic issues and environmental impact are key concepts, must be based on a scientifically sound knowledge base and make use of all the experience that may be documented in the form of best management practice.

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Safety of dams in our future climate – as seen by the hydrologist

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In recent years a number of spectacular events have occurred in the world which have put into focus the issues of flooding and dam safety. Experience has shown that we almost always underestimate the climate extremes and base far too many decisions on insufficient data. We must first of all analyse how we can best protect ourselves from today's climate variations, and then determine what margins we must add because we can no longer rely on the stability of the climate.

The failure of the Noppikoski dam in September 1985 rang the alarm and had great symbolic value for Swedish dam safety work. Photo: Lantmäteriet.

On Saturday the 7th of September 1985 the dam at Noppikoski in Central Sweden failed. It had rained all Friday when a low pressure deepened and moved over the North Sea from the British Isles into Sweden. It had also been raining heavily all the week. High waters were expected. It was at 5.25 in the morning when the staff at the dam impotently watched as the water overtopped the crest. Then one of the two gates of the dam was jammed, and 45 minutes later the dam had collapsed.

Luckily, the reservoir at Noppikoski was quite small and there were no injuries. But the failure attracted great attention. It confirmed fears that had been aroused some years earlier. There were problems at that time with the dams on the upper reaches of the rivers Indalsälven and Ångermanälven. It began to be suspected that there was a fundamental error in the methods used to calculate the design floods in Sweden. The Swedish Committee on Design Flood Determination for Dams was set up with the task to investigate how design floods ought to be calculated to guarantee dam safety.

About one per cent of all large dams built in the world have failed, and one of the most common causes is underestimation of extreme floods.

The Committee had been at work for less than six months when the Noppikoski dam failed. The failure was the warning shot that was needed to make everybody realise at last that there was a Swedish dam safety problem associated with design floods. And this Swedish experience is not unique. About one per cent of all large dams built in the world have failed, and one of the most common causes is underestimation of extreme floods, often in combination with technical problems. It is not unusual for these accidents to cause disasters with hundreds or perhaps thousands of fatalities.

How extreme can a flood become?

One fundamental issue in dam safety work is to determine the design flood. If this flood is underestimated, there is a risk of failure. This is also one of the most important scientific hydrological issues. Traditionally, the concepts Probable Maximum Precipitation (PMP) and Probable Maximum Flood (PMF) have often been used. PMF is a very extreme flood that cannot, in principle, be exceeded. Unfortunately, however, the scientific foundations of PMP and PMF are quite shaky. And the situation has been made worse by fears that global warming may influence the risks in future.

The Swedish Committee for Design Flood Determination for Dams developed a new hydrological simulation technique for calculating design floods. This technique is geared to Nordic conditions where extreme floods are often created by a combination of snowmelt and rain. The new guidelines were adopted in 1990, and are considerably stricter than previous practice. A systematic evaluation of the safety of all the more important dams in Sweden was then begun, a process that is still in progress. It has been found that improvements are needed in many places. Several dams have been modified, and comprehensive design work is in progress in many places.

The most extreme floods in Swedish rivers usually occur through an unlucky combination of snowmelt and extreme rainfall. The Swedish calculation method is based on simulation techniques to identify the most serious possible hydrological situation. The main difference between this method and traditional PMF calculations is that the combined effect of several factors is judged to be more important than maximisation of one single factor. It is the extreme precipitation that is most in focus in a traditional PMP/PMF calculation.

In actual fact, it is not possible reliably to assign a probability to either PMP, PMF or the design floods calculated according to the Swedish method. In spite of this, the usual ambition in the case of the very largest dams is to achieve a probability that is 1 in 10,000 per year, and preferably lower. This is not as unreasonable as it may sound. Since dams must stand for many years, the hazard gradually accumulates and reaches perhaps 1 per cent after one hundred years. In view of the disastrous consequences of a large dam failure, exposure to a hazard greater than this is not to be allowed. A large dam failure may develop into a national disaster.

A large dam failure may develop into a national disaster.

Global warming raises new questions

In the middle of the work on upgrading Swedish dams, the issue of the climate has arisen. In 1990, when the new guidelines for flood calculation were adopted in Sweden, there was awareness that this issue may alter assumptions, but a wait-and-see attitude was nevertheless adopted. It was considered that there were such great uncertainties that it was impossible to give any concrete recommendations on adaptation to climate changes. Today, we have much more knowledge and greater awareness of the hazards posed by global warming.

For the hydroelectric industry, a new situation has arisen. There is extensive activity, and large investments are made to upgrade dams to comply with the current safety requirements. At the same time, it is realised that the hazards of global warming

For the hydroelectric industry, a new situation has arisen.

cannot be ignored. However, existing climate scenarios continue to vary over a wide range, especially in the case of extreme precipitation within areas as small as a catchment area. In other words, precisely what is of the greatest interest from a dam safety standpoint! On top of that, new climate calculations will appear as research advances. A new attitude must be developed to deal with all this. A new dimension has arrived in dam safety work.

But new demands are also placed on researchers. They must put themselves into the situation of decision makers and, in a clear and educational manner, impart the knowledge that is available and the assumptions it is based on. This demands both changed attitudes and a new way of speaking.

The issue of climate change has posed new questions which force all of us to adopt new ways of thinking.

Questions concerning the future climate are asked all over the world, in the same way as in Sweden. The risks associated with water resources are particularly worrying. In Sweden we think a lot of storms and floods, but we must realise that our problems are quite small when seen in a global perspective. Lack of water and rising levels in the oceans may have disastrous consequences in many places on earth, often in countries without the technical and economic resources to deal with this threat. The issue of climate change has posed new questions which force all of us to adopt new ways of thinking.

Nature makes its presence known

The fears aroused in Sweden at the beginning of the 1980s have been confirmed many times. Problems with flooding have occurred almost every year, and the calculation method suggested by the Swedish Committee on Design Flood Determination for Dams has been found broadly reasonable. This applies in particular to problems with flow in the lower reaches of a major river with a complex system of dams and reservoirs, something that is typical of developed Swedish rivers. Without computer simulations and modern hydrological models it is difficult to predict how water flows in a river as a whole will develop when, at the same time, it is deep winter high up in the catchment area, spring in the central reaches and early summer down near the sea.

The most dramatic warning signals in Sweden in recent times were the floods in the summer, autumn and winter of 2000, and the devastating storm in the south of Sweden in January 2005. The rest of Europe suffered a lot more. In the river Oder in Poland and Germany there was a disastrous flood in the warm summer of 1997, and the greatest disaster since the second world war hit Dresden when the Elbe overtopped its banks in August 2002. We can see this pattern all over the world. One of the most recent and most drastic examples occurred in the US in the summer of 2005 when hurricane Katrina caused the protective walls at New Orleans to be breached. In terms of human suffering and fatalities, there are examples of considerably greater flood disasters in Asia and Africa, but they have not received the same degree of intensive media attention from the western world.

In spite of all the examples of disastrous floods, there is reason to be cautious in coming to conclusions. The scope of the disasters obviously depends to some extent on the weather, but also on imprudent physical planning. We have made ourselves increasingly exposed to events like these. In some cases, as in New Orleans, the extent of the disaster could also have been mitigated by better maintenance of the existing protective walls. It is easy to demonstrate that the costs of floods have dramatically increased in recent years, but it is much more difficult to determine whether it is the weather that has really turned more extreme or whether we have become more vulnerable to extreme hydrological conditions.

The scope of the disasters obviously depends to some extent on the weather, but also on imprudent physical planning.

Ongoing research

Research on how a changed climate may influence the risk of floods and dam safety is carried on in many places in the world. In Sweden there are two research projects that are of particular interest. The insurance industry has supported the project "Future flood risks" and the Research Organisation of Swedish Electrical Utilities, Elforsk, has financed the project "Sensitivity analysis of Swedish guidelines for design floods for dams in a future changing climate". Further studies of the impact of climate on hydropower systems and dam safety are made within the Nordic Climate and Energy project with funding by Nordic Energy Research, the power industry in the Nordic countries and the national hydrological services. In these projects, new techniques have been developed for analysing how the most extreme hydrological conditions in Sweden and the other Nordic countries may be affected by a changed climate.

It is not easy to predict how a global warming will affect the risk of floods and high flows in the Nordic climate. What is most evident is that a warmer climate will result in shorter and less stable winters, with smaller spring floods. At the same time, climate scenarios show that there is a risk of an increase in the most extreme rainfalls. But a higher temperature is also expected to cause increased evaporation. The total picture is therefore a complex one. In regions in the north, with long winters and a lot of snow, a decrease in the problems in conjunction with spring floods may be expected unless there is an appreciable rise in winter precipitation. In the south, where rainflows dominate, flooding problems may increase unless the increase in evaporation is sufficient to counterbalance the rise in precipitation.

Understanding of the overall picture needs computer simulations. These have been made for a selection of rivers in the Nordic Region. As far as Sweden is concerned, it is mainly a matter of the rivers that are important for the hydropower industry, but the situation regarding some of the largest lakes in the country has also been analysed. Lake Vänern, the third largest lake in Europe, is surrounded by several communities which are at risk of flooding. Changes in Vänern also have a key role for the safety of its outlet, Göta River. Water levels in Lake Mälaren are important for the safety of Stockholm against flooding and for other communities along its shores.

Some of the most important questions faced by Nordic researchers with regard to extreme flows in the climate of the future are as follows:

- How is the best use to be made of future scenarios from meteorological climate models in order to calculate the effects on extreme floods?
- What is the size of uncertainty?
- What will be the combined effect of more irregular winters, altered snow conditions, altered precipitation and altered evaporation?
- How much of the expected change in hydrological conditions can we already observe today?

Results so far show that global warming may have great significance for dam safety, flood risks and the production of hydro-electric power in the Nordic countries.

Results so far show that global warming may have great significance for dam safety, flood risks and the production of hydro-electric power in the Nordic countries. They also show that there is great uncertainty. Research has demonstrated that it is important to use more than one climate scenario, and not to believe that there is only one solution to the climate issue.

During 2006 we can expect a lot of new information from the Nordic researchers. But we cannot expect to have the final answers. However, we can already say that it is not obvious that conditions are deteriorating everywhere. It is likely that conditions will be worse where we are already having problems with large rainfloods, while flows in the rivers caused by snowmelt may in many cases be reduced. It is however a common feature that winters will be less stable. This means that water will be released more often into rivers where we are used to long calm periods in a long cold winter. This affects both dam safety and the lives of those who live along the the rivers, but higher winter flows are at the same time beneficial to the production of hydroelectric power.

This means that water will be released more often into rivers where we are used to long calm periods in a long cold winter.

Adaptation to climate changes or to today's climate?

Almost every time that there is a serious flood, the media sound the alarm about climate change. This is usually followed by careful and perhaps slightly humdrum explanations by meteorologists and hydrologists: "This has in actual fact happened before". But, in spite of this, we can discern a clear trend towards increasing damage all over the world. The reason in most cases is a combination of imprudent physical planning, pressure on those living near the rivers, variations in the climate, technical problems and, sometimes, even lack of maintenance. To all this must be added the threat of a global warming that poses the risk that all our planning data will become out of date. We are thus facing a very complex set of problems. There is a need for long term decisions and large investments based on data that are recognised to be increasingly unreliable.

In spite of all the uncertainties, the events of the last few years have confirmed that the climate issue must be taken very seriously and that action must be taken now. It has been found that we almost always underestimate the extremes of the climate and base far too many decisions on insufficient data. A necessary first step is to carefully analyse how we can best protect ourselves from today's climate. We must then ask ourselves what further margins are needed because of the threat of a climate change. So, to protect ourselves from the stresses that may arise because of changes in the climate, we must begin to take measures to ensure that we can deal with today's climate. There is already a lot to do in this respect!

In spite of all the uncertainties, the events of the last few years have confirmed that the climate issue must be taken very seriously and that action must be taken now.

Further reading

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Flood mitigation – flood protection

Associate Professor Torbjörn Svensson, Karlstad University.

Floods have affected many European countries in recent years, causing heavy economic damage and forcing tens of thousands of people to leave their homes. Globally the problems connected to floods are on an even larger scale. In this paper the hydrological background to floods is described along with methods for flood protection and management. Information to the public, restoration of flood plains, withdrawal from flood prone areas, and risk based land use planning and insurance policies are elements in a modern management of floods.

Levee break in Elbe during 2002 flood. Photo: M. Zebisch, TUB/PIK

Large resources have been assigned to flood protective measures since historic times. Dams have been a major component as protective levees along the rivers and to create reservoirs to store flood water and decrease flood peaks. This has, however, proved insufficient in many cases. Flood management today acknowledges that the river needs space to accomodate flood peaks and that the whole river basin must be considered.

Flooding of rivers is one of the worst natural disasters. It occurs in all parts of the world but with most damage to health and life in the tropics. When it comes to the number of people affected, floods account for half the total number. Dartmouth database for floods shows 28,400 (12,400 without tsunami) killed and 32 million (31.5 without tsunami) displaced per year during the last decade. Severe flooding has occured in Europe in the last decade e.g. in the Danube, Rhine, Elbe and Oder. These river basins cover almost the entire European mainland.

DFO Event # 2006-063 - Romania and Bulgaria - Lower Danube River - Rapid Response Inundation Map 1

MODIS flood inundation limit
- April 24, 2006:
- April 17, 2006:
- April 15, 2006:

MODIS reference water:
DOW Rivers: – Urban Areas:
Maximum Obeserved
inundation Limit 2000-2006:

Universal Transverse Mercator
UTM Zone 35 North - WGS 84 - Graticule: 2 degrees
Shared relief from SRTM data

Fig. 1. Satellite photo of lower Danube showing the extent of flooding in April 2006. Källa: Dartmouth Flood Observatory.

Severe flooding is not a new feature. Going back to the Flood in the Bible it is obvious that devastating floods were known since prehistoric times. From a variety of written sources it has been shown that floods have been a recurring feature in central European rivers during the last 1000 years. During this period the rivers have been largely modified by dams, river training works and flood walls. There is a general belief among planners that flooding will increase in the future, but the situation may very well differ from region to region and from one river to another.

River characteristics

Inundations caused by extreme flows are part of the natural variability of a river, as well as drought periods. The river landscape has been formed in accordance with this variability. River plains have developed along the rivers, where the river can overflow. These plains make up fertile agricultural soils, which are further fertilized by regular flooding. Farms, transport infrastructure and settlements are naturally located in river plains and this makes them vulnerable to flooding. Flood damage is thus a combined effect of the natural variability of river flow and the accumulation of people, infrastructure and valuable crops and goods in areas at risk of flooding.

Rainfall and snowmelt in the river basin provide the ultimate sources of river flow. The response to this input is heavily modified by landforms, infiltration capacity, soil properties, and vegetation cover. Steep areas and areas with low infiltration and storage capacity (e.g. urban areas) favour rapid discharge of the water whereas flat areas with ample storage capacity in soil, wetland and depressions slow down the flow and smooth out the flow peaks.

In general, river basins start in steep upland areas, then flow through intermediate regions of smaller slope and variable landscape to end in flat, lowland coastal regions. Sub basins empty their water through tributaries at different spots along the main river channel, thus increasing the flow successively along the river. Lakes, reservoirs and wetlands retain water for longer or shorter periods thus slowing down the flow and smoothing out flow peaks. Natural lakes are common in formerly glaciated areas, as in Sweden and Finland, and in intermediate regions of the main European river basins. In these regions also a great number of artificial reservoirs have been built with large dams crossing over the river valley or raising the outlet level of a natural lake. These reservoirs may serve several purposes, of which an important one is to reduce downstream flooding.

Wetlands once covered large parts of the lowland areas and the river plains. Much of this has, however, been drained to gain new land for agriculture. In Poland, for example, it is estimated that 75% of former floodplains along the Odra river has been lost.

Today there is a strong movement to restore wetlands, primarily for environmental reasons, but also to retain some of the former "natural" flood protection.

Hydrology of flooding

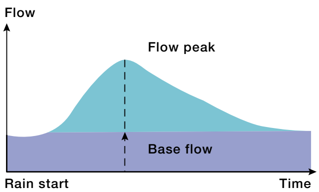


Fig. 2. Rain hydrograph showing the flow peak following a rain event.

A rain passage over a small catchment results in an outflow hydrograph as illustrated in Fig 2. The time from start of the rain to start of the /excess/ outflow reflects the retention in vegetation, infiltration in the ground, and in surface depressions. The length of time from the start to the top of the hydrograph or the time when the discharge curve is levelled out is the concentration time. This depends on the distance from the nearest part of the area to the most distant part, and on the velocity of the flow, which strongly depends on the inclination of the ground.

The maximum discharge, i.e. the top of the hydrograph, is crucial for the risk of river flooding. It depends on the rain intensity, the discharge area and the duration of the rain. Thus small catchments in steep terrain with little vegetation and infiltration capacity are at risk of rapidly growing and intense "flash floods". They occur frequently in the Alp region and may be devastating when they carry large amount of stone and mud into populated areas.

The outflow from a larger area is composed of hydrographs from the different sub basins, each with its own characteristics with regard to maximum flow, lag time to the maximum and length of the hydrograph. The situation is illustrated in Fig 3. If the different flow peaks coincide, flooding is likely to occur in the main river downstreams. It is obvious that the pattern of sub basins which contribute to river flow is very complex and widely varying. Thus each river has its own characteristic response to the input from rain and snow melt and should be regarded as unique in this respect. When it comes to flood management or flood protection a thorough understanding of the hydrological features is thus extremely important. For this purpose so called rainfall-runoff models are very efficient and in fact used as a standard tool for analyzing different flow situations.

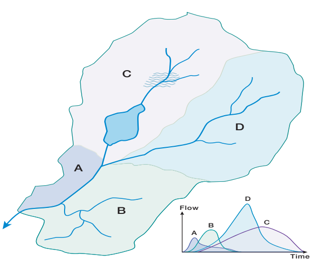


Fig. 3. Complex river basin with several sub basins. The downstream flow is the sum of the hydrographs of the sub basins.

In the main river both the flow depth and the velocity will increase with increasing flow rate as long as the water is kept within the normal cross section. If the flow continues to increase the water will eventually spill over the river banks into the flood plain. This will slow down the rate of increase of the water level as well as the flow rate downstream. Large volumes of water will be temporarily stored on the flood plain and returned to the main river later when the river flow has decreased. A similar situation occurs when the flood water enters a big lake. In this case, however, the surface area is not increased as much as in the case of flood plain inundation.

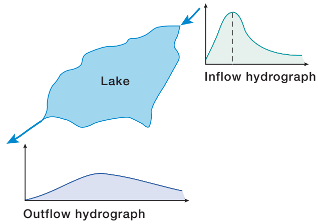


Fig. 4. Retention of a flow peak when it passes a lake.

The retention of water in the flood plain or a lake is illustrated in Fig 4. It helps to relieve the areas along the river downstream from the highest flow peaks and slows down the flow which will give the inhabitants more time to prepare for the coming flood situation. At the same time the flooding of the flood plains and lake shores will inundate crops, infrastructure and buildings in this area causing potentially large damage if not properly planned for.

The water stage in a river depends on the flow rate and on the resistance to flow from friction along the bottom and sides and from extra resistance elements like bridge piers, groynes, piers, vegetation and rocks or stones protruding into the flow. The damming effect of such obstacles to flow will extend upstream a fairly long distance. By decreasing the resistance to flow the water stage can thus be lowered for some distance upstream. Measures like widening or deepening at narrow sections, streamlining bridge piers and other obstacles, or removing vegetation, may be effective in this respect. Another possibility, which may be effective, especially in urban areas with little room to widen the river, is to construct relief channels parallel to the main river. The channel can be dry for most of the time and opened when there is risk of a flood situation.

Modelling river flow

Decreasing the flow resistance may reduce the risk of flooding locally but can be detrimental downstream. The height of the flow peak may increase somewhat as well as its velocity, which gives less time to react. In the lower reaches of a river, near the outlet to the sea or a large lake, these negative effects may be of less importance. In any case interventions in the river channel should be carefully analyzed to evaluate both the positive and negative effects. Hydraulic computer models are useful tools to study the effects of different actions or modifications in a river channel. Given the input of water from upstream and from local tributaries the models can calculate the flow and river stage at different times and locations. As in the case of rainfall-runoff modelling the availability of extensive, good-quality data is essential for the quality of model outcome.

Besides the evaluation of different proposed measures the hydraulic model has two other important applications. One is for making inundation maps, or flood risk maps, which are used for land use planning and emergency response planning. These maps show the land areas which will be covered by water at certain return periods. The other use is for flood forecasting using weather forecasts for the nearest days to come as input. Such forecasts are crucial for the planning and carrying through of emergency operations, evacuations, information to the public etc.

Flood protection

Flood protective measures have been applied along the rivers all over the world for a long time, hundreds or even thousands of years. The most common approach is to erect earth walls along the river, levees, to stop water from reaching farmland or buildings. The levees must be combined with a drainage system in the protected area, often including pumping stations, to get rid of leakage water and local rain water. The walls are built as low dams and should be designed to withstand the water pressure, prevent leakage, and be reasonably resistant to stream or wave erosion. The construction is based on locally available material such as sand, gravel or clay. Larger walls may have a dense core of clay or other dense material. Protection against erosion is provided by vegetation cover, gravel or stone coverage.

It is also important to design the flood barrier to fit into the aesthetics of the city.

In urban areas protective walls are often built from brick or concrete rather than from earth and clay to save valuable space. It is also important to design the flood barrier to fit into the aesthetics of the city. For that purpose a number of products are available, including dam planks to heighten existing walls, movable gates, and even methods to integrate the barrier into existing buildings.

The first flood protection works aimed to protect local settlements and fields. In the course of time the length of the protected river reaches increased until the river in entire valleys or plain areas was confined between two parallel levees. This in turn has led to higher water stages and flood levels, so that the heights of the walls may have had to be raised even further to achieve the same standard of protection as before.

Flood mitigation

Whereas levees and flood walls aim at protection against flood water without changing the natural river flow, flood mitigation schemes using large reservoirs for reducing the peak of the flood wave, or river training works to facilitate water flow, will have a profound influence on the hydraulic regime. This will to some extent reduce the need for local protection. In general, the best effect of retention measures is obtained if water is temporarily stored in the upper parts of the river basin and the flow resistance is reduced in the lower parts. The individual properties of the basin and sub basins must, however, be carefully considered and analyzed as discussed above.

The retention of rain and snowmelt water in large dam reservoirs to avoid flooding requires very large storage volumes. This is especially true in the middle and lower parts of river basins. Even if it is possible to find effective solutions for low and moderate flood situations it is virtually impossible to assign enough storage capacity to single large facilities to deal with extreme situations. In the case of a dam reservoir being filled it is a strict requirement to pass on any further water flow to secure the dam. In contrast to storage in a natural lake there is no "extra" storage capacity available in a dam reservoir and thus the full amount of the flood water flow will reach downstream locations.

The damage potential of flooding has increased considerably in the latest decades. According to the International Flood Network there has been a tenfold increase in flood damage from the 1960s to the 90s. This is in spite of continuous efforts to improve the flood defence. One obvious reason is the pressure of development in the flood risk zone, which has led to an accumulation of people, infrastructure and valuable goods in areas at risk of flooding. There is a trend in western countries of wanting to live close to water, which increases the vulnerability.

The damage potential of flooding has increased considerably in the latest decades.

The other possible reason, whether floods have become more frequent and more severe, is more difficult to answer. It is true that many of the major river systems in Europe have been severely flooded recently. In a longer perspective this is, however, nothing new. A study of historical records of flooding in central European rivers dating back to the 16th century has revealed no significant change in either the frequency or the magnitude of floods. Still there are reasons to believe that the ongoing climate change will lead to (or has already led to) more flood problems, at least in some regions. As an example may be taken the Danube and its tributaries, which have inundated large areas in Romania both in 2006 and the year before. Tens of thousands of people were forced to evacuate their homes, not to mention destroyed buildings, roads and crops. The full extent of the flood damage has still to be evaluated. Similar problems in this area have occurred several times before (see table 1), but a

There has been no significant change since the 16th century in either the frequency or the magnitude of floods.

Table 1. Flood damage in Romania 1969–95. Source: The World Bank

Years of historic floods	Main hydro-graphic basins affected	Affected area (km^2)	Houses (number)	People affected (number)	Industrial units (number)	Railroads (km)	Roads (km)	Bridges (number)
1969	Mures, Olt,	3650	28890	115560	160	42	460	340
1970	Somes, Crisuri, Mures, Olt, Siret, Prut, Danube	10000	84680	338720	290	330	2800	1980
1975	Olt, Arges, Ialomita, Prut	3300	33240	132960	250	137	1900	1360
1981	Crisuri, Mures, Olt	900	22160	88640	100	30	300	220
1991	Jiu, Banat, Olt, Ialomita, Siret, Prut	1400	14450	42800	140	35	400	290
1995	Somes, Mures, Jiu, Olt	300	5140	15560	10	24	250	170

situation with recurring inundation damage would put strong pressure on society as a whole.

Flood management principles

In the light of recent and foreseen flooding it has become clear that traditional flood protection methods alone are not able to provide reasonable safety against flood damage. The present trend is thus to turn to a principle of flood management where the traditional methods are but an integrated part. It is recognised that flooding is a natural process and that society should learn to live with floods. Giving back space for the river water is one guiding principle for retaining water and smoothing out flow peaks. This means in practice e.g. to move flood walls away from the river banks, to open up for deliberate flooding of assigned rural areas, and to create many new retention basins spread out in the terrain in the upper parts of the drainage area.

Flood zoning with respect to the probability of flooding could be used as a means to direct the development according to its vulnerability.

Other important actions involve the social dimension. That is to help people to cope with the flood situation. Raising awareness, information and education are key factors, which must be backed up by the development of accurate flood forecasting and warning systems. The latter is of special importance for transnational rivers where the information must follow (precede) the flood wave from one country to another. Information on water levels and extent of water covered areas, evacuation plans, and actions to protect properties should be easily accessible to the public. Land use (municipal) planning has also an important role. By setting limits for the lowest elevation of building basements and pointing out areas where development is improper or forbidden, an adaptation to the flood risk is possible in the long run. Flood zoning with respect to the probability of flooding could be used as a means to direct the development according to its vulnerability. In some cases even withdrawal from existing settlements has been discussed. Good inundation maps or flood risk maps are essential for the planning.

For the major, transnational European rivers, e.g. the Rhine and the Danube, international commissions have been set up to develop and implement common flood management programmes. Strategies are formulated that form the basis for the work within each country sharing the river basin.

As an example the "Action Programme for Sustainable Flood Protection in the Danube River Basin" considers the following three scopes of action for reduction of flood risk:

Natural Retention
Including restoring natural floodplains; considering the storage effect of vegetation, soil and wetlands.

Natural Retention

Structural Flood Protection
Focusing on the protection of human health and safety; giving special attention to urban areas; combining with other water management purposes.

Structural Flood Protection

Reduction of hazard
Adapting human uses of floodplains to existing hazard; applying risk management methods, emergency and disaster planning; developing systems of flood forecasting and warning; pointing at the role of insurance policies for increasing the awareness and reducing the financial risk.

Reduction of hazard

These general strategies are further developed in Targets and Measures on a basin-wide as well as a sub basin-wide scale.

Further reading

Data bases

- http:// www.dartmouth.edu/%7Efloods/index.html

Position papers

- UN Guidelines for Reducing Flood Losses (available at www.unisdr.org)

- EU flood management policy (http://europa.eu.int/comm /environment/water/flood_risk/)

- Water in Rivers: Flooding. A contribution to the World Water Vision. Prof. dr. W Rodney White, Wallingford, UK.

River programs

- Action Programme for Sustainable Flood Protection in the Danube River Basin (available at www.icpdr.org)

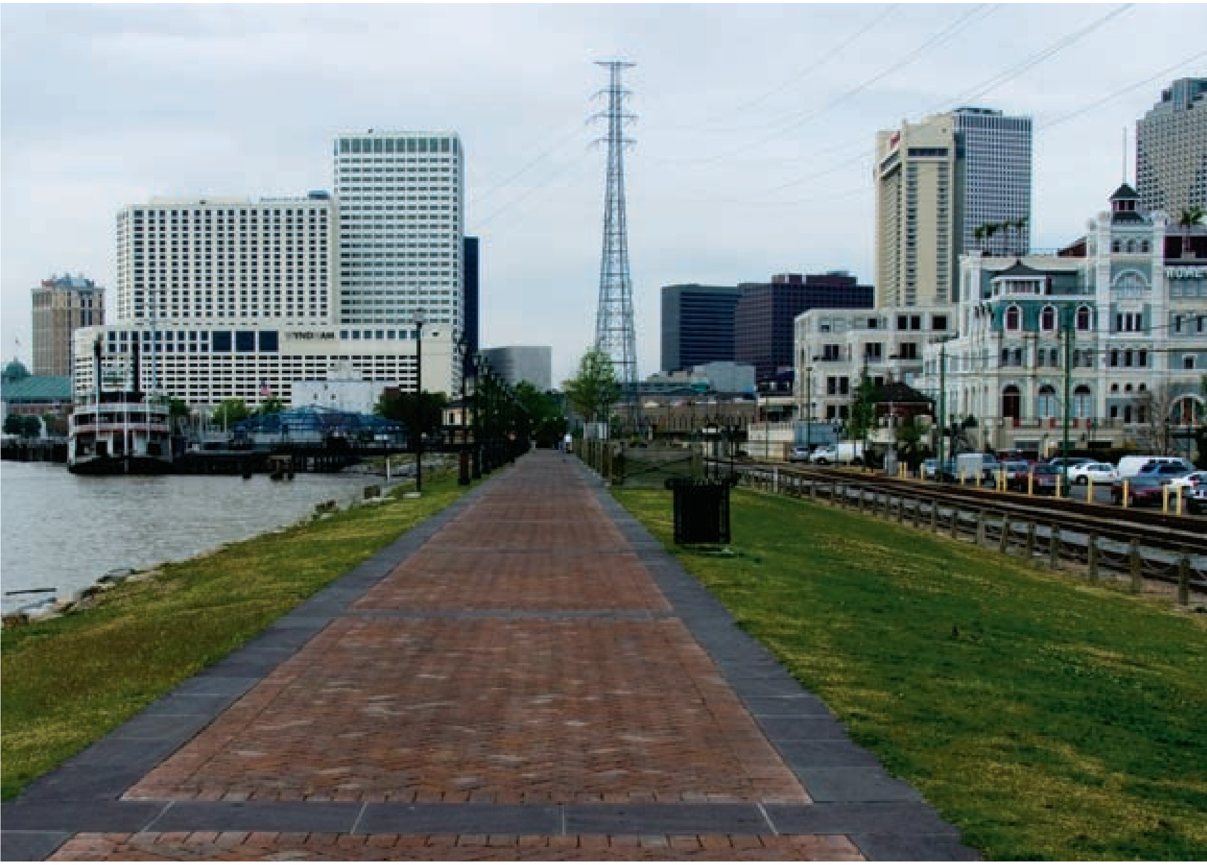
Research programs

- http://levis.sggw.waw.pl/ecoflood/

Levees at Mississippi too weak for Katrina

Associate Professor Karin Eriksson, Naturform i Garpenberg AB.

It was a harrowing experience to come back to New Orleans in the spring of 2006, seven months after hurricane Katrina, writes Karin Eriksson. All the earlier fears about the effects of a powerful hurricane have been proved right. The levees that should provide protection against flooding were breached by the waters at several critical points, both in New Orleans and out in the more sparsely populated areas. Ever since New Orleans was founded, its residents have had to fight to keep the city above water level. As the land around the Mississippi outlet is sinking, this fight is becoming harder.



In New Orleans there is a levee between the Mississippi and the city. Photo: Karin Eriksson.

Mississippi is one of the most important rivers in the world. With its many and large tributaries, it drains about 40 per cent of the area of the United States and the southern parts of Canada. From the source of the river in North Minnesota, Lake Itasca, runs a small stream that gradually, with the help of all its tributaries, forms one of the largest river systems in the world: Mississippi River. The river serves as a communications route from the Gulf of Mexico to the city of Minneapolis.

The river shapes the landscape

Like all other rivers, the Mississippi has the capacity to greatly influence and change the landscape.

Like all other rivers, the Mississippi has the capacity to greatly influence and change the landscape. Rivers erode their banks, and the material removed is carried downstream with the water. Through the years, Mississippi has created a wide flood plain, i.e. the low lying land around the river.

During the year, and from year to year, the flow in the river varies. When it floods, large amounts of sediment are deposited and these are left behind on the ground when the waters recede. The coarsest material is deposited next to the river and builds up a ridge of sand, a levee. Mississippi is therefore surrounded by naturally formed levees that can protect the surrounding areas from moderate floods. The levees have also often been used as natural foundations for roads along the river. On the flood plains outside, fine grained sediment such as silt and clay is deposited.

During periods with heavy rains, there is a risk of devastating floods. Already in the 18th century, individual land owners realised that they could protect their lands by building floodwalls. They began to strengthen the natural levees, but also constructed new floodwalls to save exposed areas.

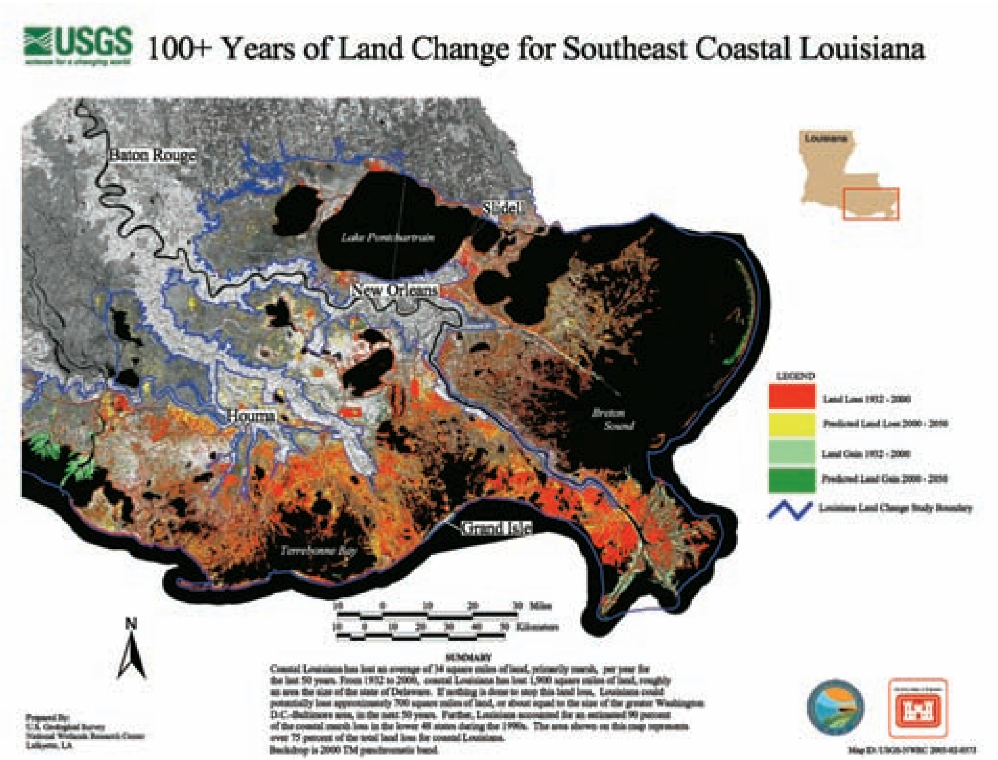
In the 19th century, construction was made more systematic. In addition to the work on the levees, dams and canals were built and pumps were installed to drain water in dangerous situations. Construction continued in the 20th century, but many of the measures taken to avoid flooding were found to have created new problems. Today it is the US Army Corps of Engineers which administers and manages channels, locks, dams and levees. This shows how important the river is for the US.

The river finds new routes to the sea

In South Louisiana, where the Mississippi has its richly branched lower reaches, there are extensive wetlands. It is here that the Mississippi has formed its deltas, one after another. During the past 5-6,000 years, the river has shifted its course about once every thousand years. Each time it finds new routes to the Gulf of Mexico. During the past 7,500 years, the sea level has remained largely the same. Both the new and old deltas from this time are therefore at the same level. A new delta is now being rapidly formed at the river Atchafalaya, a distributary of the Mississippi. If dams and floodwalls had not curtailed the natural process, the river would long ago have taken the shortest route to the sea through Atchafalaya.

The delta at the present main outlet of the river is dwindling, while four old deltas have largely disappeared. So long as the river continues to deposit sediment in the delta area, this can continue to grow. The more material that is deposited in the delta, the heavier it becomes. If the river shifts its course or if sediment transport diminishes for some other reason, the area slowly begins to sink below the water under its own weight.

When the river last changed its course about 800 years ago, the present delta began to be built up. Its outermost parts can only be reached by boat, and most of the areas are designated as nature



The lower Mississippi with surrounding wetlands. The map shows the areas Land Loss 1932-2000 (red), Predicted Land Loss 2000-2050 (yellow), Land Gain 1932-2000 (green) and Predicted Land Gain 2000-2050 (dark green). The blue line marks the boundary of the investigated area. Prepared by: U.S. Geological Survey.

reserves. The community furthest to the south is, fittingly, called Venice. One is constantly reminded here of the exposed situation. The whole community is only a few hundred metres wide, more land is not available. It is enclosed by two floodwalls. One is a natural but reinforced levee which runs along the river to the east of the road, the other is an artificial wall that abuts on the delta to the west of the road. Hurricanes and a breach of one of the levees present a constant threat.

In the wetlands to the west of Grand Isle large areas have sunk below water level, which meant that the forest was drowned. Areas of open water increase the risk of huge waves during hurricanes. Photo: Karin Eriksson.

Hurricanes also threaten plants and animals

Fishes and crustaceans that live in the sea are dependent on the shallow areas around the Mississippi outlet during their juvenile stages. A large proportion of the migrating seabirds of North America fly to these wetlands in the winter. In other respects also, the area is very rich biologically. About 40 per cent of the coastal wetlands area of the US is in Louisiana. But around 100 square kilometres of land disappear every year, a process that has gone on for the past forty years. The deltas sink because the sediment transport has diminished, and land in the coastal areas also disappears through various coastal processes.

The hurricanes that yearly hit the US Atlantic coasts are a serious threat. They can destroy the outermost islands in the delta which act as barriers against the waves. This increases wave erosion in the coastal areas of the wetlands. The hurricane is also accompanied by extremely high waves which easily penetrate long into the wetlands and increase the salt content in fragile brackish environments. The ongoing land loss and changes in the salinity of the water are disastrous for birds, fishes and other animals, and also for many plants.

In recent years these problems have attracted increased attention. Even though a large proportion of land loss can be attributed to natural geological processes, human activities have accelerated the process. Whether a delta with its wetlands is to sink below sea level or continue to be extended depends on the balance between sedimentation and compression of the sediment. In today's Mississippi delta which has been built up during the past centuries, deposition of new material has caused the sediments previously laid down to shrink. But since new material has at the same time been deposited, the delta has grown and new land has been created.

Measures that have both beneficial and detrimental effects

There are many important reasons for the loss of land. Levees have been raised and strengthened, right from the capital of

Louisiana, Baton Rouge, to the outlet near Venice. These levees prevent flooding, but also the essential supply of sediment which is needed to keep the wetlands above water level. All sediment is now transported with the river right down to the outlet where much of the material is carried further into the sea, with no benefit to the delta.

Several dams have also been built upstream in the river, both to prevent flooding and to generate electric power, and also to serve as freshwater reservoirs and recreational areas. The dams catch the sediment so that material transport to the delta is reduced. During the latest half century alone, transport of sediment has diminished by around 50 per cent.

Some of the water in the Mississippi is also diverted through Atchafalaya, and a lot of material is therefore deposited in the new Atchafalaya delta. This further impoverishes the Mississippi delta. Finally, when there is a threat of flooding, large volumes of water can be diverted via an installation upstream from New Orleans to Lake Pontchartrain and further out into the Gulf of Mexico. They never reach the delta area.

The primary purpose of these measures is to reduce the risk of flooding, but they also cut the risk that shipping channels in the river are silted up and must be dredged at great cost. However, at the same time as the supply of sediment is cut off, the problem caused by sinking of the land is aggravated.

Greenhouse effects naturally also figure in the discussions about land losses in Louisiana. But there are no such connections. Here, it is not the sea level that is rising but the land that is sinking. The hurricanes and storms which yearly hit the coasts in south-east USA and which contribute to these losses are neither more common nor more violent than before, as is asserted by the advocates of the greenhouse effect.

New Orleans is situated below river level

Geographically, the position of New Orleans is magnificent. Nevertheless, it would be difficult to find a more unsuitable location on earth on which to found a large city! Ever since the town of New Orleans was founded as a French colony in 1718 on the natural levee next the Mississippi, its inhabitants have had to fight to keep the town above water level. Without constant pumping and a lot of other measures, the city would be uninhabitable today. The levee is seven metres above sea level, while large areas of the city are below water level in the river and 1.6 m below sea level.

In the wetlands to the south of New Orleans there are many canals where the houses are built on piles a few metres above water level. This house was outside the devastated area, and escaped.

If one walks in the evening in the French Quarter, famed for its jazz history, one can see how shop owners lay sandbags outside their doors as protection against the water. If one then continues towards the river, one can see clear proof that the level of the Mississippi is above the city. The last stretch of the walk towards the river is not, as expected, a downward slope but an upward climb to the levee! Once up on the coastal promenade, one can see that the water level is much higher than the nearby streets.

Detached houses in the north-western part of New Orleans are protected by a levee. Outside the levee stretch vast wetlands. The road in the background is built on piles. Photo: Karin Eriksson.

The city is built on soil that mostly consists of soft saturated silty sediment mixed with peat and gyttja. Next to the river, on the levees, geotechnical conditions are a little better. The sediment here is a little coarser in the form of sand. But buildings must nevertheless be founded on piles to a considerable depth to stay in place. The large bridge across the Mississippi is built on piles that are 40-50 metres long. At that depth, the piles have reached glacial clay which is here regarded as solid rock!

Parts of the city are built on drained wetlands that mostly consist of peat. When the ground dries, it shrinks, and when it is loaded with buildings, it sinks, which further increases the differences in level between the river and the ground, and therefore the risk of flooding.

The authorities try to prevent future disasters by a number of measures, one of which is to build new protection against hurricanes. But the question is whether the geological processes can be stopped in the long run. On my previous journeys in the area, I talked with many people who can remember previous disasters, and many seemed worried about what might happen in the future. Many were also aware that the authorities were not taking the threat seriously, and did not put in adequate resources. In Venice, a woman showed us how high the water came up during the ravages of hurricane Camille in August 1969, but Katrina's effects were much worse. Her house was one of those that were completely destroyed. Katrina was yet another example lately of how hard it is to prevent natural disasters of this kind. The only way of doing this would be to leave exposed areas undeveloped, which is hardly an option in the Mississippi region.

Hurricane Katrina

It was a harrowing experience to come back to New Orleans in the spring of 2006, five years since my latest visit, and seven months after hurricane Katrina. All the earlier fears about the effects of a powerful hurricane have been proved right. The levees that should provide protection against flooding were breached by the waters at several critical points, both in New Orleans and out in the more sparsely populated areas, and the vast wetlands outside the city itself were drowned by tsunami-like waves up to eight metres high.

Here, the levee is raised with a concrete wall, but the question is whether the soft sediment that consists of a mixture of organic material and silty soil will remain watertight.
Photo: Karin Eriksson.

After the disaster, there were many views on why it happened the way it did. It is quite clear that there were several defects in the levees' construction. Many were built on easily eroded soils that could not withstand the stresses. In other places the levees had been reinforced with concrete at the top. When the saturated clayey material in the levee let the water through because of the water pressure, the concrete fell down. In some sections the levees had been strengthened with metal sheet piling which were not driven deep enough. The emergency measures to seal the breached levees were carried out rapidly, and pumps that had been put out of action were repaired so that the city could be drained. In the worst hit areas, the water was up to eight metres deep. Comprehensive long term action is needed so that all the areas that had been destroyed can be made habitable again. The question is whether it is at all possible to rebuild all the destroyed areas.

Venice is one of the communities along the southernmost part of the Mississippi that was practically completely wiped out, exactly in the way it had been feared. Communities further to the east in the wetlands are a long way from the river itself, but destruction was total. In Delacroix which is, or rather was, a fishing village where the houses were built on piles a metre or two above sea level, there is nothing left. On one side, the village was bounded by open water in a canal and on the other side by a hurricane protection wall about two metres high which gave no protection at all. Outside the wall, the sinking wetlands stretch out without any protection at all against the eight metre high tsunami-like waves that swept in from the sea with tremendous force, over the wall and over the village. The hurricane winds aggravated destruction.

What happens in the future?

One of the great questions is how these extensive areas, with small fishing villages and with very few inhabitants compared with New Orleans, can be protected in the future. If nothing is done, these areas will sooner or later sink down below the water level, and no floodwalls in the world can stop this process.

In preparation for the next hurricane season that usually begins in June, intensive work was carried out during the winter months to strengthen and raise the levees in exposed areas along the Mississippi to the south of New Orleans, as here to the west of Breton Sound. Photo: Karin Eriksson.

One proposal that was recently made is that the sediment brought down by the Mississippi should be collected in gigantic sedimentation basins instead of being allowed, as now, to be deposited at the bottom of the Gulf of Mexico. From the sedimentation basin the material would be pumped through pipelines to the areas where sedimentation is to be increased. This proposal is one of many that might help the situation in the worst hit areas, but its implementation would be enormously expensive.

The investigation has confirmed what everybody already knew, that all who live in New Orleans and the surrounding wetlands have nothing except symbolic protection against either floods in the Mississippi or hurricanes. One proposal for improving the levees that has been presented would involve strengthening of the levees and raising them up to eight feet above present levels. The cost of this work has been estimated at about six billion dollars, but there is no guarantee that they would provide the desired protection.

All the increasingly resigned people who are left in temporary accommodation in the area and all those who have been evacuated to other parts of the US are now waiting to see what the next hurricane season will bring.

Further reading

- Parts of Karin Eriksson's article can be read in the Swedish journal Forskning och Framsteg, No 7/2001 (www.fof.se/?id=01744).

- Preliminary Report on the Performance of the New Orleans Levee Systems in Hurricane Katrina on August 29, 2005 (www.asce.org/files/pdf/katrina/teamdatareport1121.pdf).

- NPR (National Public Radio) has several articles on Katrina, among them Q&A: Repairing New Orleans' Levees (www.npr.org/templates/story/story.php?storyId=5235774)

- US Geological Survey has a website with the title "Hurricanes Katrina and Rita" (www.nwrc.usgs.gov/hurricane/katrina.htm).

- The newspaper The Times-Picayune has a large number of articles on Katrina, such as "Coastal losses greater than thought" (www.nola.com/news/t-p/index.ssf?/base/news-3/113998708880320.xml)

- Website "Hurricane" of The Times-Picayune (www.nola.com/hurricane/).

Dams for flood and storm surge protection

K. Rainer Massarsch, Dr. Tech, Geo Engineering AB, Stockholm, Sweden.

Three main types of flooding occur: storm surges, river floods, and flash floods. This contribution mainly addresses protection measures against storm surges and river floods. According to a study by the European Spatial Planning Observation Network (ESPON), the highest number of large flood events in Europe between 1987 and 2002 occurred in North-Western Romania, South-Eastern France, Central and Southern Germany and in the east of England.

The Eastern Scheldt storm surge barrier, between the islands Schouwen-Duiveland and Noord-Beveland, is the largest of 13 ambitious Delta works series of dams, designed to protect a large part of the Netherlands from flooding.
Photo: D. Reiskoffer

Storm surges can occur along the coast or the banks of large lakes. They have extreme loss potential and may cause hundreds of thousands of fatalities. The Bangladesh storm surges with death tolls of 300,000 (1970) and 140,000 (1991) are the best known of the recent past but not the only ones. Even in Europe, storm surge events have claimed the lives of thousands of people in the second half of the twentieth century (North Sea storm surge in 1953: 2,000 dead). Major improvements in sea defences and, in particular, the enhancement of forecasting and early-warning facilities in recent years have led to great storm surge catastrophes becoming less common. However, an accelerating rise in sea levels will aggravate the risk of storm surge and coastal erosion in many coastal regions – and this will be one of the most detrimental effects of global warming. Figure 1 shows areas prone to storm surge within the EU, most of which are located in the northern part of Europe.

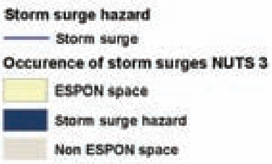


Fig. 1. This map presents the approximate probability of storm surges in the European Union. From ESPON Project Report 1.3.1, 2005.

River floods do not occur abruptly but build up gradually – although in some circumstances over a short period. They last typically from a few days to a few weeks. The destruction of the affected area may be very extensive if the river valley is flat and broad and the river carries a large volume of water. River flooding emerged as an increasing problem as a result of human intervention, by straightening and even relocating rivers, and at the same time developing low-lying areas close to rivers. Increased areas of impermeable soil also resulted in higher flood levels and the water inflow to rivers is no longer delayed by natural soil retention.

Historic Perspective

Already early human civilizations protected their settlements, farmland and religious sites by earth fill embankments and walls. Several thousand years ago, these earth structures were used to change and adapt the terrain in order to facilitate land use. Dams were also needed as reservoirs to store water for irrigation of farmland or as military defence against invasions. However, most of these early structures have been destroyed due to human impact and natural forces.

Human civilizations developed in four main regions: Egypt, Mesopotamia, China and India, all of which were located along large rivers where fertile soil deposits facilitated agriculture (table 1).

Table 1. Hydraulic characteristics of rivers in the four large civilisations. From Kerisel (1985).

	Egypt	**Mesopotamia**	**China**	**India**
River	Nile	Tigris and Euphrates	Yellow river (Huang Ho)	Indus
Annual precipitation (mm)	250	200	500	250
Origin	African lakes and Abyssinia	Mountain ranges of Armenia	Kulum mountains	Hindu Kush and Himalaya
Water level rise (m)	5–7	5	4–7	4–5
Amount of silt	0.17	0.75	1–2	0.43
Inclination	1:13 000	1:26 000	1:35 000	1:7 000

Probably the oldest known earth dam was built in 3200 BC near the city of Java in Jordan and consisted of an earth embankment protected by a layer of masonry. Its main purpose was to secure the water supply of the city. The dam was 4.5 m high and had a length of 80 m. Similar embankments were built along the river Tigris, where king Adad Nirari about 1300 BC had a 1,500 m long protection wall built outside the city of Ashur.

Similar structures were found along the Indus river, dating back to 2000 BC, where one of the capital cities of that period, Mohenjo Dara, needed protection against flooding. The dam was 1,500 m long and constructed of compacted earth fill.

Also in China many earth dams were built to protect populated areas against flooding but most of these have vanished. One of the oldest preserved dams is located near the city of Shiouxian in Central China where Emperor Sun Shu'ao built a 30 km long earth dam. This structure which dates back more than 3,000 years is still in use and fully functional.

Egypt is one of the foremost examples where hydraulic engineering has played an important role in the development of human civilisation. The Nile is one of the longest rivers in the world and irrigates in Egypt a small but fertile valley. Prior to the regulation of the Nile during the 1960s the water level varied annually by an average 6 m. These regular floods were important as the river carried along fertile sediments and cleared the ground of salts and human waste.

Nile valley at Luxor showing the fertile land in the narrow river valley. Photo: Rainer Massarsch.

Pharaoh Cheops (also known as Khufu) was probably one of the greatest civil engineers of all times. During 2589–2566 BC he initiated the construction of the great pyramid at Giza. In addition, Cheops also planned and implemented extensive irrigation and flood protection schemes.

During the Middle Kingdom (2055–1650 BC) the capital of Egypt was moved from Thebes (now Luxor) to the north near Memphis, which was then located close by the river Nile. In order to protect the city a 450 m long and 15 m high earth dam was constructed. At the base the embankment had a width of 60 m. This is probably the oldest dam in history which was built specially for flood protection purposes.

The Need of Flood Protection

Flooding can have devastating consequences in many developing countries where low-lying coastal regions face the threat of flooding. For instance in Bangladesh flooding affects at least twenty per cent of its area in a normal year because of the vulnerable topography. In extreme cases, the flood-affected area could be as high as 67 per cent. Flood control and drainage are used to reduce the depth of flooding or eliminate it through "controlled flooding", so as to provide greater security for crop production.

Flood protection is also important in industrialized countries. Extreme floods occur also along major German rivers and at the coast, predominantly in the winter and spring months. Flood control structures and reservoirs, created by concrete or earth fill dams, not only store the flood water but also reduce the peak flow and considerably slow down the discharge in the river reaches downstream of the dam.

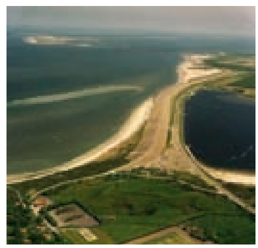
Prior to their implementation, not only the locally achievable flood protection but also their impacts as a whole on the discharge behaviour of the river system, the ecology and the appearance of the landscape are to be taken into account. Due to their economic efficiency, earth fill dams are mostly preferred. The heights of these reach from a few metres to 30 m, in particular in the case of the above mentioned flood control reservoirs.

Oosterschelde barrier. Copyright Rijkswaterstaat - Adviesdienst Geo-Informatie en ICT (AGI).

Delta Works Project, the Netherlands

In the Netherlands, more than one third of the land is located below sea level. The devastating North Sea Flood of 1953 breached many dikes and seawalls in the Netherlands, killing 1,835 people and forcing the evacuation of many more. Over 150,000 hectares of land were flooded. The Delta Works project was implemented to prevent the recurrence of similar disasters. The islands in Zeeland province were joined together by dams and other large scale constructions to shorten the coastline.

The nine kilometre long barrier was initially designed, and partly built, as a closed dam, but after public protest, huge sluice gate type doors were installed in the remaining four kilometres. These doors are normally open, but can be closed under adverse weather conditions while preserving the saltwater river delta for wildlife and the fishing industry. The construction started in 1978 and was finished in 1986. The costs of the Oosterschelde barrier are estimated at 2.5 billion Euros.



Aerial view of the Oosterschelde storm surge barrier. Embankment dam near the Veerse gat. Copyright Rijkswaterstaat – Adviesdienst Geo-Informatie en ICT (AGI).

Less known, but not less impressive, is the Maeslantkering storm surge barrier near the port of Rotterdam. A year after the opening of the Oosterschelde barrier, the Ministry of Waterways and Public Works held a competition for the construction of another storm surge barrier. The most important demand for the design was that the barrier should not hinder shipping. The barrier should only be closed under exceptional circumstances - no more than once or twice every ten years. In 1991, four years after the competition was held, construction started. The Maeslant barrier would consist of two floating steel gates which could be sunk down and could be stored in the dry docks on shore. In 1997, the storm surge barrier New Waterway near the Hoek of Holland was officially opened.

Oosterscheldekering is the largest of 13 Delta Works' dams. The sluice gates of the Eastern Scheldt storm surge barrier can be closed under adverse weather conditions to prevent flooding of low-lying areas. Photo: R. Spekking.

When the sea level rises, the arms of the barrier are activated. The waterway, with a width of 360 metres, can then be closed completely. It is the only storm surge barrier in the world with such large moveable parts. The storm surge gates have a length

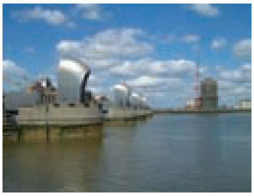
Closed Maeslantkering storm surge barrier near the port of Rotterdam, photographed from the sky. Copyright: Rijkswaterstaat – Adviesdienst Geo-Informatie en ICT (AGI).

of 240 metres each. Normally, these gates are fully opened, to allow ships access to the port of Rotterdam. The gates are stored in docks with a length of 210 metres, which lie along both shores. During storm tide the docks are flooded and the hollow gates begin to float. They are driven into the water by means of a small train. This lasts for about half an hour. When the doors are situated in the middle of the river, valves are opened and as a result the gates are flooded. Consequently, the gates sink to the bottom because of their weight. The water level on the seaside is then higher than the water on the riverside. The force against the surge wall during a storm is about 350 MN.

Thames Barrier, England

The earliest recorded flood on the River Thames was in AD 9. Some 29 years later another flood occurred that reportedly drowned 10,000 people. In 1774 another great flood on the Thames washed away Henley Bridge. Other floods occurred in 1848, 1852 and 1875. One of the worst floods on the non-tidal Thames in recent history occurred in 1894 and was due to exceptionally heavy rainfall. In 1953, the combination of a north westerly gale, a very deep area of low pressure, a high spring tide and the topography of the North Sea caused a massive storm at the southern end of the North Sea. The sea level rose nearly nine feet above normal high spring tide levels causing exceptional flooding along the East Coast and the Thames Estuary, during which 307 people died, 24,000 homes were damaged or destroyed and 46,000 of livestock were lost.

This disaster prompted the construction of the Thames Barrier at Woolwich at a cost of around £535 million. The main problem with building the barrier was that any barrier would require an opening of around 500 m. The Thames Barrier consists of 10 gates weighing 1500 tonnes, each operated by hydraulic beams. The roof is made of stainless steel. All the gates are made of steel and can be raised at high or low tide and when in the open position rest level with the river bed, so navigation is not impeded.



Thames Barrier – built in 1983 to prevent London flooding. Copyright: Colin Green, Flood Hazard Research Centre (FHRC)

Since it became operational in 1982 and until the end of 2004, the Thames Barrier has been closed on 88 occasions to protect London from flooding (54 times against surge tides and 34 times to stop high tides meeting heavy rainfall) but in the 6 month period from November 2000 to March 2001 the emergency closures happened 23 times. During the extensive flooding in the first week of January 2003, the Barrier was closed on 13 consecutive tides - a record breaking sequence, preventing the flooding of a number of properties at the top end of the tidal reach. Nearly all these closures were the result of a combination of factors including high spring tides, depressions in the North Sea, wind effects in the English Channel and high River flows.

St Petersburg, Russia

The City of St. Petersburg is located in the shallow and narrow Neva Bay at the eastern extremity of the Gulf of Finland of the Baltic Sea. Due to this location, long waves generated by storm winds accompanying deep cyclones passing over the Baltic Sea region are increased several times and this may lead to floods in the City. Floods of height above 210 cm are referred to as very dangerous and above 300 cm as catastrophic ones. Since its founding in 1703 there were about 300 floods in St. Petersburg, three of which were catastrophic ones. Very close to catastrophic was the 1955 flood of 293 cm. As floods lead to significant damage and loss of human life, St. Petersburg is in need of flood protection.

The construction of the first local dams was started in the harbour after the flood of 1924. The project was revised only in the early 1960s, after the flood in October 1955. After 20 years of design studies, the construction was started in 1979. However, construction of the Barrier was suspended in 1987 as a result of concerns about the perceived negative environmental impacts of the barrier on the Neva Bay. An International Commission determined in 1990 that the impact of the Barrier on the environment was negligible and recommended prompt completion. The Barrier comprises eleven rock and earth embankment dams, six water discharge sluices to accommodate outflow from the river Neva and two navigation channels equipped with closing gates. The overall length of the Barrier is 25.4 km. In 2002, the European Bank for Reconstruction and Development (EBRD) funded a complex feasibility study, which led to the EBRD granting a $240 million loan to the Government of Russia. The works to construct the Barrier were restarted in 2004.

Venice, Italy

High flood waters have become a serious problem for the city of Venice. The risk of flooding has increased strongly since the beginning of the century. Severe inundations, when more than 90 per cent of the city's surface is under water, are becoming more frequent. Besides the inconvenience this brings to Venetians and tourists, salty water lapping above Venice's foundations is eating away at the fabric and treasures of this unique and historic city. The city's total movement with regard to sea level is about 2.3 mm a year.

Another disastrous flood, such as the one the city suffered in 1966, may occur again in the near future. To reduce the hazard to the city and the negative impact on the activities in the lagoon, a flood warning system composed of statistical and hydrodynamic models has been developed. In the future this warning system will also be fundamental during the construction and for the efficient operation of storm surge barriers covering the three existing inlets of the lagoon.

The flood barrier gates are often referred to as MOSE, or the Moses gates, a name that comes from an experimental prototype called the modulo sperimentale elettromeccanico. The nearly Euro 3 billion ($3.4 billion) scheme will comprise about 80 hollow gates embedded in the seabed at the three inlets to Venice's lagoon. When not needed, the gates will rest on the seabed, full of water. But when high tides threaten the city, compressed air will force water out of the gates. This will cause them to rise and act as a barrier to water trying to enter the lagoon. Despite lingering doubts about the gates, construction has begun with a breakwater at the Malamocco inlet into the lagoon.

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Dams for power generation – technology and environmental considerations

Professor Håkan Stille, Division of Soil and Rock Mechanics, Department of Civil and Architectural Engineering, Associate Professor Berit Balfors and Associate Professor Hans Bergh, Department of Land and Water Resources Engineering, Royal Institute of Technology, Stockholm.

Seen from a global perspective, there is great potential for developing hydropower. But the dams that are needed to collect the water and to regulate flow encroach on the environment. Today's technology enables us to reduce the environmental impact of development. It is important that development should take place in a socially, economically, aesthetically and environmentally sustainable way. Striking a balance between impact on the local environment and access to renewable energy is an important and difficult matter.

The Höljes Dam is an 80 m high dam on the river Klarälven in Central Sweden. Photo: Fortum

Chiriqui dam, constructed as a part of Rio Esti Hydropower project in Panama, is an example of dam construction where special attention has been to reduce the environmental disturbance to an acceptable level.
Photo: Lars Hässler

Hydroelectric power is one way of utilising that part of solar energy which causes the natural cycling of water consisting of evaporation, precipitation and surface runoff. Hydropower is therefore a renewable energy source. Mankind has for a long time used energy from water power by making the water in rapids and waterfalls drive mills, saws and pumps. Since the turn of the previous century, water power has been used for large scale production of electricity in hydropower plants. This applies mainly to some countries in Europe and to the US.

In Sweden, development of hydropower was most extensive in the 1950s and 1960s, and was mainly completed by the middle of the 1970s. At present, only a few single dams are built each year. During a normal year, about 65 TWh is produced in Swedish hydroelectric plants. This is just under half of electricity production. The water resources that can be economically developed but are not yet exploited amount to about 30 TWh per year.

Porsi power station on the river Luleälven in the north of Sweden. Intake, power station and outflow are combined into one unit. Photo: Vattenfall

Seen from a global perspective, there is great potential for developing hydropower. In many developing countries, only a very small proportion of the potential hydropower has been developed. Hydropower is therefore an interesting renewable energy source, provided that the inescapable environmental disturbances can be kept at an acceptable level. In some countries, hydroelectric power is practically the only primary source for the production of electricity. Norway, Iceland, Brazil and some countries in Africa are examples of countries with large or dominant hydropower production.

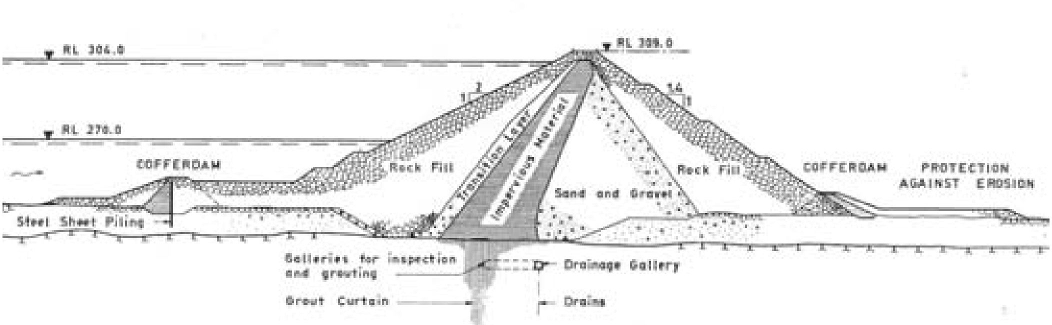
In a hydropower plant, the difference in potential energy between an upper and a lower water level, the head, is utilised for the production of electrical energy. The principal components of a hydropower plant are generally the dam, inlet, intake, power station and outflow. When the head is large, the inlet and outflow routes are relatively long and may consist of canals, tunnels or tubes. For low heads the intake, power station and outflow are often combined into one unit.

Types of dam

A dam is a structure constructed on a river which makes it possible for water level to be raised above the normal and to regulate discharge, for instance in conjunction with hydropower production, irrigation or water supply. Discharge can then be adapted to the need. The surplus water is stored during snowmelt or rainy periods, to be used when the natural flow is small, during the winter and dry periods. Dams are also used to protect low-lying areas from being flooded when flows are high. In connection with a hydropower plant, the dam often has the function to impound a stretch of rapids or a number of smaller heads, so that the overall head over the total distance is concentrated at one point in the river.

Dams are generally expected to have a long life, often more than a hundred years. This means that the choice of material is of great significance in dam construction. At present, dams are generally built of concrete or rock or earth fill. In Sweden and also globally, about 25 per cent of all dams are concrete dams and about 75 per cent embankment dams.

The buttress dam is a common type of concrete dam in Sweden. It consists of a relatively slender, inclined concrete wall supported by buttresses that resists the water pressure. The photograph shows the 40 m high dam Storfinnforsen on the river Faxälven in the north of Sweden. Photo: E.ON



This rockfill dam (Höljesdammen) is typical of Sweden, with an impervious core made of moraine and a fill of gravel and broken rock. The rockfill was obtained from blasting for the power station and tailrace.

The choice of construction material must also be seen from a resource and environmental perspective. Local supplies are important. Often there is an ample supply of broken rock from adjoining tunnels and underground power stations. In some countries, as in Sweden, there is normally an ample supply of moraine, while the core or impervious membrane may, in other countries, be made of local clays or of asphalt or concrete. It is very important that the excavation of moraine or clay encroaches on nature as little as possible.

Dams affect the environment

While hydropower is a clean and renewable energy source, with relatively little emission, development of hydropower causes an impact on the environment in the rivers that are exploited. The encroachment affects both the physical environment – soil, water and air – and the natural environment, i.e. flora and fauna.

The changed water conditions in a developed river cause changes in nutrient supply, temperature and the highest flow. This has effects on the entire ecosystem that encompasses the running water and riverbanks, as well as the plant and animals species which depend on these environments. In a developed river, the transport of dissolved nutrients and minerals is reduced. This means that the transport of substances down to the sea may be altered by regulation. A changed temperature affects both the reproduction of fish and the viability of the fry. Water temperature is also of importance for the various benthic animals, and also for the plant communities.

Since flood discharge is reduced, transport and sedimentation conditions are changed, which alters the river bottom and its biological significance. In a naturally flowing river, changes in level have an annual rhythm which makes for a specific flora and fauna regarding both species composition and structure. The altered rhythm of water level in a regulated river affects many organisms. Migrating fish such as brown trout and salmon may find it more difficult to reproduce in a developed river, inter alia because of sedimentation in areas where the flow is constant and calm. Dams and power stations also obstruct migration to spawning grounds upstreams.

Regulation of rivers may accelerate erosion of riverbanks downstream of the outflow. This means that the productive bankside environment is negatively affected. There is also an effect on ducks and waders through changes in the supply of forage, water level variations and changed vegetation. Development of hydropower may also affect the local climate along the river through increased occurrence of mist in the winter when the water is free of ice downstream of some regulating reservoirs.

Technology and legislation mitigate environmental impact

It is essential that development of hydroelectric power should be carried out in a socially, economically, aesthetically and environmentally sustainable manner. Environmental requirements in conjunction with the establishment of new hydropower plants are today much stricter. There are now many ways of mitigating environmental impact. Underground power plants often make it possible to reduce the heights of dams and thus the reservoirs. These are also safer from earthquakes and make less of an impact on the landscape. Several small dams cause a lesser environmental impact than a few large ones, without radically reducing the energy generated. The limit for the minimum permissible flow in the old river and the construction of diversion channels of natural design creates a better environment for flora and fauna.

The EU has issued a directive (85/337/EEC) which requires that an environmental impact assessment (EIA) be drawn up in the case of major infrastructure projects, for instance the establishment of a hydropower plant. An EIA implies that consultations must be held with the affected public, alternative locations must be assessed, and details must be given of preventive measures to minimise the environmental impacts.

The purpose of an environmental impact assessment is to make it possible for an overall assessment of the environmental impact to be made before a decision is arrived at. The requirement concerning an EIA is specified in a number of countries outside the EU and also in international organisations such as the World Bank.

Environmental impact assessments according to international standards make it possible to identify environmental impacts at an early stage, so that an assessment may be made whether the establishment of a new project is compatible with sustainable societal development. Arriving at a proper balance between the impact on the local environment and access to renewable energy is a very delicate matter. A holistic approach and knowledge are of key importance in this context so that a balance may be found that provides the sustainable societal development aimed for.

The EU framework directive (2000/60/EU) for water lays down how a good surface water status is to be achieved. The directive states, inter alia, that member countries must protect and improve all artificial and extensively modified water resources in order to achieve a good ecological potential by the year 2015 where this is reasonable. In rivers that have already been developed, several environmental improvements can be made, for instance a more natural flow regime can be simulated. Action can also be taken to reduce erosion, and to recreate or reinforce migration routes which bypass dams for e.g. salmon. Experiments have also been made to supply nutrients with the aim of developing methods and strategies for the restoration of impoverished ecosystems in developed lakes.

Environmental impact and the consequences for the local population, tourism and fishing are factors that have resulted in stringent requirements being imposed concerning improvements in technology, both to make existing plants more efficient and in conjunction with the establishment of new hydropower plants.

Advanced turbine technology and tunnelling technology that causes less vibration and reduces losses of head may result in greater power generation in both new and existing plants.

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The effect of dams on biodiversity

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Dams alter the ecosystems and biodiversity of rivers. In the old industrialised countries, development now is towards the decommissioning of dams rather than the construction of new ones, but in many developing countries exploitation of rivers is proceeding at a fast rate. The question is how dams affect biodiversity in tropical and subtropical rivers. In many cases, the negative impacts may be expected to be greater in tropical regions than those seen in temperate and boreal regions.

Rapids without water. Dams are generally built on rapids and near waterfalls, the fauna and flora of which suffer when the flow of water decreases or disappears.Photo: Bengt Hallberg, Johnér.

The construction of large dams had an important role when Europe and North America were industrialised. It is therefore not surprising that new dam projects are high on the agenda in many countries in Asia, Africa and Latin America. But dams give rise to extensive changes in riverine ecosystems, and many riverine species have disappeared or greatly decreased in abundance as a result of impounding and environmental changes due to dams.

The effects depend on the scale

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Dams generally cause a decrease in biodiversity, but the effects are highly scale dependent. Few species have completely disappeared from the developed rivers in Sweden. They remain somewhere along the river, even though in fewer numbers. On the other hand, the number of species per river section is radically reduced. Between a quarter and a third of vascular plants have, on average, disappeared on a 200 m long stretch of riverbank. However, it is only a few Swedish species whose existence is primarily threatened by the development of hydropower. Hydropower is given as the primary threat for about 5 per cent of the threatened animal species and 3 per cent of the threatened vascular plant species. The reason that more species are not threatened is that many species have viable populations in the rivers that are protected from exploitation, and also that the flora and fauna of the region are very young. The species managed to spread to Scandinavia after the end of the last ice age just under 10,000 years ago, and they are as a rule generalists with large geographical distributions.

In tropical and subtropical regions many species have very limited geographical distributions, and a large proportion of the flora and fauna may be unique to individual river systems. While river systems in temperate and boreal regions have few endemic fish species, over half of the fish fauna may be endemic in rivers at lower latitudes. For instance, 50 per cent of the fish fauna in the Olifants River in Southern Africa and the Jordan River is endemic, as well as 42 per cent of the fish species in the Red River (Yuan Jiang) that runs through China and Vietnam. Other groups also have many endemics. Both the Mekong and Yangtze (Chiang Jiang), for instance, have endemic species flocks of closely related gastropods (over 100 species per river). Exploitation of a river in these regions implies not only that species will become rare locally, but may also result in global extinction.

The impact of a dam on biodiversity may be divided into upstream effects caused by the impounded water, downstream effects caused by changes in flow and the quality of water released, and effects that occur because organisms, materials and energy are prevented from passing the dam. Dams may also promote invasion by alien species.

Upstream effects

Construction of a dam generally means that areas upstream of the dam are flooded and are permenantly put under water. In some cases, attempts have been made to move large animals when the reservoir began to be filled, but when these animals cannot be offered new habitats, this only delays extinction for some time. In some cases attempts have even been made to relocate plants that were to be drowned. This happened when the Itaipu Dam on the frontier between Brazil and Paraguay was to be filled, which threatened several rare plants. However, transplantation was unsuccessful.

Some dams affect such large areas that the habitat of entire species is put under water. One example is the riparian plant *Myricaria laxiflora*, the total world dispersion of which will be flooded when the Three Gorges Dam on the Yangtze in China is completely filled in 2009. Material of the species has been collected and is kept at the Wuhan botanic gardens, in the hope that it can be reintroduced in the future. But the plant is strongly adapted to its unique riparian environment: It is dormant from May to October, and then rapidly grows and sets seed during the winter when water levels in the river are low. The seeds are spread by the wind and by floating on the river. Without a natural water level regime, it is unlikely that the plant can manage to compete with other plants.

The reservoir is generally much more species poor than the riverine environments it replaces. Fluctuations in water level are often extensive and are temporally controlled by human water needs rather than by natural conditions. The riparian zones are often impoverished of species. Riparian vegetation along storage reservoirs in Sweden and Canada has, on average, decreased by 84 per cent in degree of coverage and by 34 per cent in species numbers compared with unregulated riverbanks. Owing to the unnatural water level fluctuations, benthic fauna is more or less absent within the zone that is periodically drowned and exposed. In the long term, the productivity of the reservoir greatly diminishes, since the only photosynthesising organisms that can cope with the water level fluctuations are pelagic phytoplankton that move up and down with the changing water levels. The fauna is mainly confined to pelagic zooplankton and the fish that live on these.

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It has been claimed at times that the impoverishment of species is temporary and that recovery occurs in time when species that disappeared when the reservoir was filled gradually manage to recolonise. Little is known about the situation in tropical regions, but in the north of Sweden, where exploitation of rivers began as long as about 100 years ago, studies have been made of how riparian vegetation along reservoirs develops over time. There was nobody who started any studies when the first dams were built. Reservoirs of different ages, from a few years up to 70 years of age, were therefore compared. It was found that some recovery does really take place. The species richness of riparian plants increased during the first 30 – 35 years, probably as a result of successive recolonisation. However, species richness was never as large as along freely flowing rivers in the region, and in reservoirs that were 35 to 70 years old, species richness decreased with increasing age, probably because the fine material on the banks was gradually eroded away.

Downstream effects

Species that are associated with rapids, waterfalls or the humid microclimate that arises in their vicinity diminish in numbers or completely disappear.

Downstream of dams the habitats along the rivers are altered because the sediment and organic material that is normally carried along by the flowing water is held back by the dam and sinks to the bottom or is spread on the banks of the reservoir. Flow in the rapids and waterfalls decreases or completely disappears when water is diverted to power stations or for irrigation. Species that are associated with rapids, waterfalls or the humid microclimate that arises in their vicinity diminish in numbers or completely disappear. The local species richness decreases, but few species are eradicated from the river system. In Sweden it is primarily a number of rare mosses and lichens, which do not tolerate desiccation, that have been hit.

Even in the case of these environments there is a risk that species in tropical regions will be hit harder by dams. One current example is the Kihansi Ravine in the Udzungwa Mountains in Tanzania. The Udzungwa Mountains are part of the Eastern Arc range that is a hot spot for biodiversity and has one of the world's oldest continuous rainforests. A stable climate over millions of years has made it possible for a large number of endemic species with small geographical distributions to develop. In 1994 construction of a dam began on the Kihansi River, partly with Swedish aid. The dam cut off flow of water to the ravine. After dam construction had already commenced, an endemic toad species was discovered in the ravine, the Kihansi spray toad *(Nectophrynoides asperginis)*, together with a large number of new insect species and at least four endemic plant species, including a new species of coffee. All these species depended on the flow in the mist shrouded ravine. But in spite of this discovery, dam construction continued, and instead of letting some of the river water to continue running through the ravine, an advanced sprinkler system was installed in the ravine that would replace the spray and mist from the rapids and waterfalls of the ravine. The sprinkler system appears to have rescued the wetland plants, but the Kihansi toad is by all accounts extinct in the wild. Ironically, the death blow for the species was probably a fungal infection that may have been unintentionally introduced by the sprinkler installers or biologists in their attempts to rescue the species. The Kihansi toad is now found only in the terraria in the Bronx and Toledos zoos in the US.

Fragmentation

Dispersal and migrations are important for most riverine species, since the riverine environments are generally dynamic and are repeatedly destroyed and recreated. The species must therefore be able to spread and to colonise newly created areas as a substitute for those that have vanished. Access to forage and resources varies in time and space, which makes it important for many animals to make use of different parts of the river system during parts of their life cycles. Dams act as barriers which obstruct the movement of organisms that swim or passively float on the water. What is best known is that salmon migrating from the sea are prevented from migrating up the rivers to spawn, but many other groups of organisms also suffer. Many aquatic insects, for instance, reach new areas by voluntarily or involuntarily floating along with the stream. Large quantities of seeds are spread by rivers in the same way; some of these strand on the banks, germinate and become established. The transport of both insects and seeds is blocked by dams.

Even though the majority of the original salmon species in North America and Europe are today eradicated or threatened, relatively great efforts have been made to bild fish ladders so that migrating fish can bypass the dams. But it is difficult to build effective fish ladders since salmonid fish tend to follow the strongest stream, which is generally the outflow from the power station. Tropical rivers also have many fish species migrating from the sea that have been eradicated or greatly reduced because of dams. In the Pearl River (Zhujiang), the second largest river in China, over three thousand dams have been built since 1950. This has practically eradicated Reeve's shad *(Tenualosa reevesii)*, which formerly gave rise to lucrative fishing in both the Pearl and Yangtze rivers. Several other spectacular fish species, such

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as Chinese sturgeon *(Acipenser sinensis)*, Yangtze sturgeon *(Acipenser dabryanus)* and Chinese paddlefish *(Psephurus gladius)* have drastically decreased in numbers since dams have obstructed access to spawning grounds. Where fish ladders have been constructed, the design has been copied from salmon ladders, and they have often been ineffective since these fish do not have the ability of salmonid fish to proceed up fast flowing rapids by leaping up the ladder. One example is the Pak Mun dam in Thailand where a fish ladder for 800,000 US dollars could not be used by the local fish species whose stocks it was hoped to rescue, since they formed the basis of a fishery important to local communities.

Dispersal of plants by flowing water is also obstructed by dams.

Dispersal of plants by flowing water is also obstructed by dams. In boreal rivers, large quantities of the seeds of many species are dispersed by the flowing waters during spring floods. The seeds can be dispersed over large distances. In an experiment with dummy seeds in the form of small wooden cubes, the longest distance covered by the cubes was 150 km. Floating seeds can only bypass dams if they are sucked into the turbines in the power station (which is improbable), or if they pass the gates on the occasions that these are open (which is seldom). Owing to the barrier effect of dams, the bankside flora along rivers has also been fragmented. In a free-flowing river the species composition of the banks changes gradually along the river, but in developed rivers changes in the composition of the riverbank flora occur at the dams. Species composition differs between riverbanks situated upstream and downstream of a dam, even though the riparian environment is largely similar. It is mainly species whose fruits and seeds float badly in the water that are found only on one side of the dam. It is likely that in many cases these species find it difficult to spread past the dam, since they risk sinking before they have the chance of a passage. Species whose seeds float for a long time have a greater chance to get past. The relationship between the dispersal of riparian plants and dams has been demonstrated only for rivers in the north of Sweden, but since dams generally constitute a barrier to dispersal this is probably true for other areas also.

The barrier effect of dams impacts not only on the populations whose movements are prevented, but may also have indirect effects on ecosystems situated upstreams. When fish migrating from the sea, such as salmon, return from the sea to rivers to spawn, they can account for a significant import of nutrients such as phosphorus and nitrogen to the river ecosystems. This greatly contributes to the growth of riparian forests. In addition, they are an important source of food for e.g. grizzly bears and white-headed sea eagles along rivers on the west coast of North America. When dams block salmon migration and the import of nitrogen and phosphorus, this may alter nutrient composition in the entire river ecosystem. Another example of the indirect ecosystem effects of dams has been documented in Puerto Rico. Here, as in other parts of the tropics, there are several species of sea-migrating crustaceans and fishes. Rivers upstream of dams have been found to have greatly reduced populations of crustaceans and fishes, which had a number of indirect effects. For instance, calm flowing stretches had nine times as much biomass of algae, 20 times as much organic matter on the bottoms, and four times as much biomass of aquatic insects as rivers without dams.

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Invasions by alien species

We live in a time when the exchange of species between biogeographical regions is greater than perhaps at any time since the supercontinent Pangea split up about 200 million years ago. Intentionally and unintentionally, humans transport a steady stream of species to new regions. Most river systems nowadays house a large proportion of species that originate from other continents. In many cases, environmental changes caused by dams have made it easier for alien species to spread at the expense of native species.

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Many dams release cold bottom water. This transforms the environment downstreams, especially in hot regions, to the detriment of native species. The Colorado River in the west of North America previously had 32 fish species, two thirds of which were endemic. Dams have transformed the river from a turbid warm water river (several native species were blind) into a cold water river with clear water. At present, 68 alien species have become established, many of them adapted to cold water, and most native species are greatly reduced in abundance or eradicated. In south-west USA tamarisk *(Tamarix spp.)*, a bush from Asia, has also spread along the rivers, and now dominates large areas at the expense of native poplar and willow species. Tamarisk has been favoured by the hydrological changes caused by dams; for instance, high flows that inundate the riparian zones and moisten the soil have become much less frequent. This favours tamarisk that has deep roots which can reach the groundwater and is therefore less dependent on a natural flow regime.

In order to mitigate the negative effects of dams, it is essential to rapidly develop better knowledge of how the biodiversity of rivers is affected, especially in those regions of Asia, Africa and Latin America where new dams are built at a fast rate. A growing human population necessitates the use of large proportions of freshwater resources, but one challenge for the future is to do this in a sustainable manner that does not jeopardise the biodiversity of the rivers.

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Restoration of fish stocks in oligo-trophicated regulated reservoirs

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Dams give rise to oligotrophication in nutrient-poor lakes that are converted into regulated reservoirs. Three types of measures have been used to restore fish stocks. Enhancement stocking of fish and introduction of forage organisms have ecological consequences that are undesirable. On the other hand, good results have been achieved with compensatory nutrient enrichment that strengthens the natural fish stocks. But nutrient enrichment must be carried out under controlled conditions to ensure that it does not cause unacceptable eutrophication downstream.

Sampling on Stor-Mjölkvattnet in Sweden, an oligotrophicated regulated reservoir where experiments have been made with compensatory nutrient enrichment. Photo: Tobias Vrede.

Many naturally nutrient-poor lakes have been oligotrophicated by hydropower regulation, mainly in temperate and subarctic regions. In this way, the biological production of the ecosystems has decreased from an already low level. One of the consequences has been that the natural fish stocks have been greatly reduced. There are three principal reasons for oligotrophication: the dams hinder the migration of salmonid fish from the sea, the dams change the flows of nutrients, and heavy erosion has destroyed the bankside zone.

Many species of salmonid fish spend most of their lives at sea, but migrate up into lakes and rivers to spawn. After spawning, many fishes die, their bodies decompose and the nutrients in them are released, nutrients which originate in the marine environment. This "salmonid nutrient pump" imports nutrients from the sea into the lake ecosystems and accounts for a large proportion of the total nutrient supply. The nutrients stimulate production of plants in both the bankside zone and the free body of water in the lake. The plants constitute the basic resource in the food web. Nutrients from the spawning salmon are therefore an essential condition for satisfactory growth of the next salmon generation. Because dams obstruct migration, and also because of overfishing, the salmonid nutrient pump has drastically decreased in many places and lake ecosystems have been impoverished of nutrients.

Dams also have the effect that the nutrients present in the regulated reservoir are buried on deep bottoms more effectively than in unregulated lakes. Because of this, the flow of nutrients to the lakes situated downstream will diminish. In turn, this reduces biological production in the lakes.

Water levels in many regulated reservoirs fluctuate very greatly over the year, often by as much as 10-20 metres.

Water levels in many regulated reservoirs fluctuate very greatly over the year, often by as much as 10-20 metres. The level is generally highest in the autumn and then decreases to the minimum level in the winter, both because most water is released when the need for electrical energy is greatest, and because there is practically no inflow in winter. Owing to the drop in water level in winter, the bottoms situated between the highest and lowest water levels are heavily eroded. Initially, this gives rise to an increased availability of nutrients, which stimulates the biological production in the ecosystem. After the initial positive inundation effect, the bank has been eroded so heavily that only coarse inorganic material is left behind. The bankside zone resembles a rocky desert where only a biofilm of microorganisms remains. The bankside that is normally so productive has turned into wasteland. Fish stocks reflect this development. Thanks to the positive inundation effect, growth increases during the period immediately after regulation. After this, oligotrophication gradually causes deterioration to levels far below the natural levels (Fig. 1).

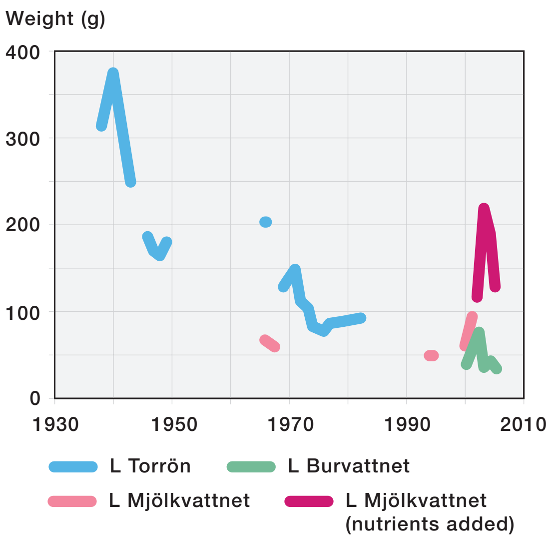

Fig. 1. The weight of char *(Salvelinus alpinus)*, all five summers old, in three Swedish regulated reservoirs. Torrön was regulated in 1938, and Burvattnet and Mjölkvattnet in 1942. Owing to an initial positive inundation effect, char exhibits good growth straight after regulation; after this, growth rate drastically decreases. As an effect of compensatory nutrient enrichment, growth rate of char in Mjölkvattnet increases during the period 2002-2005. (Rydin et al, unpublished data).

Heavily eroded bankside zone at Mjölkvattnet, Sweden, at a water level about halfway between highest and lowest level. Photo: Tobias Vrede.

Fishery conservation measures in regulated reservoirs

In order to stimulate fish production in regulated reservoirs, three types of measures have been taken in both Scandinavia and North America: enhancement stocking of fish, introduction of forage organisms, and compensatory nutrient enrichment.

Enhancement stocking of fish

Enhancement stocking of salmonid fish has been, and is being, made on a large scale in regulated rivers in order to maintain viable stocks. One important assumption on which the method is based is that the damage to fish stocks is caused by disruption in the reproduction of the fish. This is probably due to the destruction of their natural spawning environments or to the inability of the fish to migrate up to these. These problems are most acute in the case of fish migrating from the sea, but not necessarily in the case of stationary stocks. We argue that the low stocks in many regulated reservoirs are due to poor growth of the fish because of lack of food, rather than to limited reproduction abilities. The strong reduction in individual growth rate that occurs decades after regulation (Fig. 1) suggests that availability of food is restricted. If the cause had instead been obstacles to reproduction, a continued high individual growth rate would be expected, even though the population size might diminish. One drawback of enhancement stocking is that the farmed salmonid fishes are, as a rule, genetically different from the natural stocks that are adapted to the local conditions in the home rivers, and this can affect survival and growth. In a longer perspective, genetic diversity is also adversely affected.

Introduction of forage organisms

It had been hoped earlier that by implanting forage organisms, primarily opossum shrimp *Mysis relicta* but also other crustaceans, the growth of planktivorous fish might be stimulated. The method has been tested with mixed results in a number of lakes in both Scandinavia and North America. By introducing a suitable forage organism for planktivorous fishes, an "energy pump" could be created that replaces the benthic fauna lost through bankside erosion. It was found instead that Mysis often acted as a competitor for forage, and at the same time it avoided being eaten itself. Mysis migrates up and down in the water column. It spends the day in the deep water where, thanks to the dark, it cannot be detected by fishes, and it spends the night in the shallower waters where there is a more copious supply of prey animals. Through these vertical movements it effectively avoids being eaten. The zooplanktivorous crustaceans which it consumes are also on the menu for the fish, and these are therefore subject to greater competition for forage than before the introduction of Mysis.

Perhaps the most serious problem with the introduction of forage organisms is that it is a permanent measure. The introduced species which become established permanently and irreversibly alter the biodiversity and ecological function of the lakes, and there is also a great risk that they will spread downstream. Since the introduction of new organisms is a permanent measure and the consequences of the introduction are often difficult to predict, there are very pressing reasons not to take this measure.

Compensatory nutrient enrichment

A third way of restoring fish stocks to a status similar to that prior to regulation is to stimulate production in the ecosystem by the addition of nutrients. Through this measure, the production in primarily the plankton food web is increased. But the measure does not solve the fundamental problem, since regulation and the loss of a normally functioning bankside zone remains. The reasoning behind this restoration measure is that the fish stocks are weak because of a lack of forage. By the addition of plant nutrients, production of phytoplankton is stimulated, which leads to a greater amount of zooplankton and thus greater resources for the fish. The method has been tested on a whole-lake scale in, primarily, North America, but experiments have also been made in Scandinavia. Some of the most significant experiments have been made in the regulated lakes Kootenay Lake and Arrow Lakes Reservoir in British Columbia, and in the lake Mjölkvattnet, Sweden.

Kootenay Lake is a large (395 km^2) regulated reservoir in the Columbia River (Canada) which had an annual nutrient load of 140 tonnes of phosphorus prior to regulation and 51 tonnes of phosphorus after regulation. The stocks of kokanee salmon, *Oncorhynchus nerka*, were drastically reduced during the 1980s because of oligotrophication. Since 1992 compensatory nutrient enrichment has been undertaken in the northern part of the lake. The result is that the biomass of planktonic crustaceans, as well as recruitment, individual growth and the stock size of kokanee have markedly increased. One problem in Kootenay Lake is that Mysis had been introduced previously, and this species is also favoured by nutrient enrichment.

Arrow Lakes Reservoir is a large (456 km^2) regulated reservoir on Arrow River which is a tributary of Columbia River. As in the case of Kootenay Lake, the ecosystem in Arrow Lakes was damaged by regulation and the introduction of Mysis. A five-year project of compensatory nutrient enrichment was begun in 1999 with the objective of restoring the kokanee stock. Nutrients were added in the upper part of the lake from a regular road ferry. As a result of nutrient enrichment, phytoplankton production, zooplankton production, as well as egg production, individual growth and the stock density of kokanee have increased. This has occurred without any deterioration in water quality in terms of total phosphorus content, phytoplankton biomass or water clarity. This indicates that nutrient is taken up and transported further in the food web to the fish in an effective manner.

Mjölkvattnet is a regulated reservoir of medium size (13 km^2) in the catchment area of the Indal River (Sweden) which was regulated in 1942. The fish stocks mainly consist of char *Salvelinus alpinus* and brown trout *Salmo trutta.* Although fishing was very good in Mjölkvattnet during the period immediately after regulation, stocks and individual growth have been drastically reduced. Addition of nutrients in the period 2002-2005 resulted in an increase in primary production, phytoplankton biomass and zooplankton biomass. However, the species composition of the plankton community was not altered. Char, which is the dominant fish species in the lake, responded very early to nutrient enrichment through increased growth (Fig. 1).

To sum up, nutrient enrichment has been a successful strategy for strengthening the natural fish stocks in oligotrophicated regulated reservoirs. This has also taken place without alterations in the fundamental character of the systems as nutrient-poor lakes, and without changing the natural biodiversity in the plankton communities. In our opinion, the method can be applied to selected oligotrophic regulated reservoirs, provided that addition of nutrient takes place under controlled conditions.

Problems and opportunities

The negative effects of compensatory nutrient enrichment are that the added nutrient is partly lost downstream, and that the nutrients that have been used so far are not ecologically sustainable. Downstream losses of nutrients can give rise to eutrophication in waters immediately downstream, and in already eutrophicated coastal waters. In our opinion, however, this is a small risk if nutrient enrichment is carried out in a correct way. A compilation of results from North American and Scandinavian experiments shows that total phosphorus content was changed insignificantly, or not at all, in 17 of 29 lakes. But these relatively small changes in total phosphorus content resulted in clearly increased fish production in almost all cases. One consequence of lakes being regulated is also that much of the nutrient that is added remains in the lake. The increase in nutrient load in waters situated downstream, which are also oligotrophicated because of the dam, is therefore only moderate. It is also perfectly possible to adapt the nutrient dosage so that the intended effect on the fish stocks is achieved but the negative effects are negligible. The results from whole-lake experiments also demonstrate that the measures are reversible. Already a year or two after nutrient enrichment stops, nutrient contents return to the original. As regards eutrophication of coastal areas, it may be said that the effects of compensatory nutrient enrichment are expected to be small since nutrients are to a large extent retained in the river system. Even though the contribution to eutrophication of coastal areas is small in extent, it is obviously of the greatest importance that the effects of this should be kept to a minimum, especially if the method is to be applied to several waters.

One important problem is that the nutrients used have consisted of phosphorus and nitrogen which do not come from closed cycles. The supplies of mineral phosphorus are a finite resource, and production of artificial fertiliser from gaseous nitrogen is a very energy demanding process. These sources of nutrients are therefore not ecologically sustainable. In agriculture and the processing of organic waste from households and industries, methods have been developed for the processing of waste in such a way that it can be re-used. Through digestion, for instance, energy is recovered from the organic material in the form of biogas. The residual product is very nutrient-rich and can be used as fertiliser on arable land. In North America, experiments are also in progress to recover phosphorus in the form of struvite from digested sludge in sewage treatment plants. We consider that methods like these could be used to produce nutrients for compensatory nutrient enrichment.

To conclude, we wish to emphasise that the objective of compensatory nutrient enrichment is not to create fish farms at whole-lake scale but to restore the natural productivity of natural fish stocks in heavily and irreversibly damaged ecosystems. Experience from the North American and Scandinavian experiments shows that achievement of this without serious negative consequences is perfectly possible.

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Social consequences of dams

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Hydraulic structures such as large dams are intended to bring more benefits than trouble. The larger the projects, the more manifold and diverse are both the positive and negative consequences. The comparison of such manifold and diverse impacts tends to be a very demanding task. Not only are the impacts on many water uses difficult to measure using a single scale, but even more challenging is to trade-off impacts that go to different groups of people; the dilemma tends to be that the groups of people who benefit are different from those who lose.

The social impacts of large dams are the more diverse and manysided, the bigger the project is. This holds for both positive and negative impacts. One of the positive impacts that often results from dams is electrification. Photo: Olli Varis.

It is hard to imagine any aspect of water resources development which evokes as much emotions, public concern, and trouble to policy makers as dam and reservoir construction. Some want to store water, generate electricity, irrigate, or ameliorate living in other ways by constructing dams. Others are against because dams and reservoirs destroy valuable ecosystems, and push people away from river valleys where they have dwelled over millennia.

The starting point is that water is distributed unequally in time and space. Natural supply does not coincide with demand. This is a typical problem in Sweden with strong seasonal variations in river discharge, as well as for instance in the demand for irrigation water and electric power. Most people of the earth are subjected to corresponding, although not fully similar seasonal patterns, often also boosted by temporal patterns. The floods are devastating in many places, and, on the other side of the coin, the dry seasons often culminate in droughts. Controlling and damping these variations which are harmful in many ways, prompted by the desire to develop hydropower and navigation, are typical arguments for constructing a dam.

Positive and negative impacts

It is important to recognise that feeding the growing population on this planet will require increasing amounts of irrigation water.

Nothing comes for free. The concern about destroying invaluable cultural, human, and ecological assets has arisen in the last few decades, and turned public opinion very much against dam construction in most parts of the world. It is important, however, to recognise that feeding the growing population on this planet will require increasing amounts of irrigation water. Today, 20 per cent of the world's agricultural land is irrigated, and that area accounts for 40 per cent of the world's agricultural production. The growth in irrigated area has stabilized at the level of 1.3 per cent per year. Every second large dam has been constructed solely or primarily for the purpose of supplying water for agriculture. These provide 30 to 40 per cent of all irrigation water.

Every second large dam has been constructed solely or primarily for the purpose of supplying water for agriculture.

Water supply for human settlements, particularly large cities, is an important reason for constructing storage capacity by dams and reservoirs. Globally, about 12 per cent of large dams are primarily for this purpose. In Africa, their share amounts to 20 per cent, whereas in Asia only to 2 per cent of all large dams. Reservoirs remain a feasible option for securing water supply for rapidly growing cities in Africa and Asia.

Flood control is one of the major functions of dams. Flood waters are stored in a reservoir, and then utilized in the dry season. This function is particularly important in regions where seasonal variations in runoff are strongest. Yet, only 2 per cent of Asia's and 1 per cent of Africa's dams are primarily constructed for controlling floods. However, the flood protection function is almost always one of the secondary functions of any large dam, be it constructed for irrigation or hydropower. The total world figure for large dams with the primary function of flood control is as high as 13 per cent.

A strong tendency these days is to favour dams with multiple purposes. 26 per cent of Asia's and 21 per cent of Africa's dams bear this label. The present reservoirs have elevated the secure water supply of mankind by 28 per cent, and this figure is expected to grow to 34 per cent by 2025. The water renewal time of the world's rivers has decreased dramatically as a consequence of dam and reservoir consumption: from 20 to 100 days. This means that a raindrop that falls on a river basin ran to the ocean on average in 20 days before the dams were constructed, but now it takes five times longer. The self-purification capacity of rivers has decreased, yet more pronounced environmental consequences are due to the profound changes in the rivers' hydrology and ecology.

A strong tendency these days is to favour dams with multiple purposes.

Social impacts

The social impacts of large dams can thus be either positive or negative. Positive impacts are irrigation, employment, energy production, recreation, improved benefits due to flood control and reduction of associated damage, and so on. Negative impacts are decline in fisheries, disruption of traditional livelihoods, resettlement of people, adverse health effects due to the spread of malaria and schistosomiasis, and so forth. These lists provide only examples, and both positive and negative social effects represent a great diversity from situation to situation.

Often, the trade-off between positive and negative social impacts is highly demanding, since issues which cannot be measured in the same or comparable units usually hit a variety of social groups in an inequitable way. It is typical that some benefit and others feel the negative side effects. Social impacts and their balance is often a very heavily value-laden matter. Proponents of dams may see direct economic and other benefits as superior to the losses and negative impacts, whereas the dam opponents may consider this balance in a fully opposite way.

Social impacts and their balance is often a very heavily value-laden matter.

The picture looks very different whether we discuss the social impacts of a dam during the construction phase, a newly finished dam, or a dam which has been in operation for a long period of time. The construction-time effects are typically minor to the long-term impacts. Often, however, the construction-time effects are emphasised in the political debate. The construction phase typically includes employment opportunities, on many levels from planning, assessment and construction work itself. Negative impacts are often related to fears of losing livelihoods, resettlement, and similar.

The resettlement issue is typically the most painful negative impact of the early phase of the lifeline of a dam. It has been estimated that between 1986 and 1993 four million people were displaced worldwide each year by the 300 large dams that were constructed annually. The total number of resettled people due to large dams has been estimated to be as high as 60 millions. Rivers are cradles of civilizations and therefore displacements are often connected to ethnic and cultural confrontations.

The floods of the Tonle Sap lake in Cambodia raise the water level by 9 metres during the rainy season. The people and their economic activities, as well as nature, have adapted to these changes. There are serious fears that the dam construction upstream disturbs the fragile ecosystem and livelihoods of the Tonle Sap area. Photo: Olli Varis.

As the dams become operational, the benefits start gradually to become evident, and some of the negative effects, although not all, diminish in importance. Electricity starts to be generated; irrigation systems are set in operation, flood control also, and so forth. A big risk of contrasts is due to the fact that subsistence livelihoods, smallholders, and family-scale fisheries often do not gain much from dams, which tend to benefit bigger-scale economic units such as commercial farms. Also dams often benefit urban middle-class dwellers more than the rural (or urban) poor, although this does not necessarily occur in all cases.

Case study – Mekong

The monsoon zone is one of the globe's most critical climatic zones within the development context, with almost 80 per cent of the world's rural people and 60 per cent of urban dwellers being exposed to strong rainy seasons which bring most of the annual rainfall in a few months, and the rest of the year is much dryer. The monsoon zone has over half of the world's high dams, but most of the new dams are in this zone. Therefore, our case study comes from the monsoon belt.

Mekong is one of the most pristine large rivers of this planet. The river basin is shared by six nations, China, Myanmar, Lao PDR, Thailand, Cambodia and Vietnam. In recent years, however, the river and its tributaries have seen a rapid intensification of dam construction activities, partly as a result of the pacification of the region and speedy economic development. China is now constructing a cascade of eight huge hydropower dams in the mainstream of the Mekong, and other countries are constructing dams in some of the main tributaries, a few of which are already in operation.

Along with the rapid urbanization and industrialization in the region, the contemporary water confrontations are expected to grow more severe. The most important regional issue is hydropower. Along with agricultural intensification and irrigation growth – relying on dam construction – energy demand expands in this urbanizing and industrializing region. Plans to develop Mekong's hydropower go back for decades. In the late 1950s, the newly established Mekong Commission carried out surveys and studies in the Mekong region, and released a plan for constructing about 100 dams in the basin. Dams were seen as a universal solution in combating the region's underdevelopment. The model behind this approach was adopted from the famous Tennessee River Valley development scheme.

First wars, political tensions, trade embargoes, and then the growing resistance of conservationists and other nongovernmental organisations (NGOs), have disabled the realization of the plan. At present, only ~1 per cent of the hydropower potential of Mekong's lower reaches has been exploited. This potential augments to 40,000 MW, which is 2.5 times the installed hydropower capacity of Sweden. Three of the other major rivers, Irrawaddy, Salween, and Song Hong (Red River), are still less exploited.

The present level of electrification is 4–11 per cent in Indochina, except Thailand, which is over 70 per cent electrified. Obviously, these countries would like to see infrastructure development and better energy supply. Ironically, the greatest driving force behind power development in the region is the well-powered Thailand. This is because its energy potential is very low in comparison to its needs. Therefore, it looks to neighbors in its thirst for electric power, particularly to Lao PDR and China. These plans translate into a manifold increase in the hydropower production of Lao PDR. However, the power consumption of Laos will grow from the present one 60 W bulb per four persons, to one bulb per two persons by 2020. Thailand, to the contrary, is expected to consume more electricity in 2020 than Japan or Singapore today. However, there is much suspicion concerning these growth rates.

Generally speaking, the existing and planned dams of the Mekong benefit primarily the modern sector. There is no doubt that such activities and groups should be enhanced in

Banks of the Mekong close to the Cambodian capital, Phnom Penh. People are not only living by the Mekong, but very much in the river. Any changes in the river will influence the livelihoods of these people. Photo: Olli Varis.

The Nam Ngum dam in Laos has the capacity of producing 150 MW of electricity. It produces most of the electricity used in Laos and 70–80% of electricity exports to Thailand, which is an important income for the poor country. Photo: Olli Varis.

the Mekong region, but problems arise when this happens at the cost of others (above all rural poor) and the environment. Negative impacts are experienced in the first place by fisheries and fish production, environment and traditional farmers that live on floating rice or recession agriculture. There is a concentration of poor, landless and ethnic minority people among those that feel the negative impacts.

Epilogue

It is too easy to criticize dam construction by highlighting only their adverse effects. It is equally easy to pledge the beneficial impacts of dams, and forget all the rest. A dipolar – strongly polarized – discussion has characterized the field over years and years. However, the gap seems to be narrowing, or at least some bridges have been constructed over it recently.

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Expected lifespan of dams

Professor Anders Wörman, Department of Biometry and Engineering, Swedish University of Agricultural Sciences, and Tomas Ekström, Ph.D. Civil Engineering, Carl Bro AB.

The fact that dams can become very old in most cases indicates that the aging and expected lifespan of dams cannot be estimated easily from statistics on completed dam lifespans. Rather we have to rely on a scientific and technical understanding of the complex conditions surrounding the water diversion system which determine the age of dams. This article describes the critical aspects controlling the lifespan of Swedish embankment and concrete dams. The lifespan is the time during which all the performance requirements for the structure are satisfied.

Storfinnforsen is a Swedish buttress dam of concrete. It is one of the types of dam described in the article. Photo: Tomas Ekström.

Man has used embankment dams in several millennia. The oldest discovered embankment or earthfill dam is probably the Jawa dam in Jordan, which is about 5,000 years old and has a fairly complicated structure with several inbuilt masonry walls. The oldest earthfill dam still in use is the Konfi dam on the Lakissa River in Greece, which was built in 1260 B.C. Concrete dams have been built in Sweden since the late 19th century and most of these still remain.

In an international perspective, the expected lifespan of a dam is generally not determined by structural constraints. This is because sediments carried in the flowing river water tend to settle in the reservoirs upstream of dams where the water flow is slower. For instance, the deposition of sediment in the reservoir of the Aswan dam in Egypt decreases its volume annually by about 1 %. Certain UN reports indicate that this volume decrease can be substantially larger in rivers with an even higher sediment load than the Nile River. This means that the lifespan expectancy of water diversion systems is often likely to be less than a hundred years unless a proper maintenance and operational scheme is implemented.

Sedimentation in the large Swedish reservoirs is significantly lower, but we do not know the exact rate of deposition from measurements. Since deposition in the northern reservoirs is probably dominated by allochthonous (produced in the catchment) material, a very rough estimate of the deposition rate would be about 0.5 cm per year. On average the expected lifespan of Swedish reservoirs would therefore be several hundred years. This implies in a short- or medium-term perspective that the lifespan of Swedish dams is more dependent on structural constraints such as deterioration of concrete dams, aging effects of embankment dams and dam failure. The latter issue is obviously of great concern not only for the expected lifespan of dams, but also for the risk it represents to society.

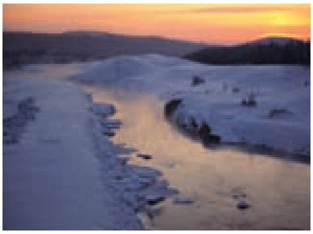
Water seeping through concrete dams continuously dissolves substances in the concrete and corrodes the reinforcing bars, which undermines the strength of the structure. Such deterioration has been observed on many Swedish concrete dams. Other investigations undertaken by the Swedish hydropower industry clearly show that a majority of embankment dams higher than 15 metres exhibit some kind of structural change caused primarily by erosion of the granular material or settlements. Furthermore, during the latest one and a half decade the hydrological society of Sweden has re-evaluated the view on the maximum spring flood that can be expected to impose the maximum load on the dam system. In effect, the expected lifespan of the dam structure itself is a statistical problem associated with significant uncertainty. The dam age is determined by complicated interactions between a highly variable hydrological load, operational strategy and the structural behaviour of embankment or concrete dams.

What do we know about changes in earthfill dams?

A survey among Swedish dam owners showed that more than half the earthfill dams have some sort of observed deterioration of the dam body. The damage is spread over a range of causes from erosion of riprap protection on slopes to leakage through the embankment with associated internal erosion and sink-holes. One example of such a process was observed in Suorva earthfill dam in the north of Sweden, in the autumn of 1983. Muddy water was seen emerging at the toe on the downstream side of the dam in which the water in the reservoir reached its maximum level ever at that time. A sink-hole appeared on the dam crest as a result of the internal loss of material, which indicates that the dam was adaptable in a proper manner during the initial stabilization process.

Leakage through the embankment dam at Suorva in the autumn of 1983 is shown in this picture as a small stream forming at the dam toe. The picture is taken in the downstream direction with the embankment behind the photographer. The lower part of the picture shows the stone blocks of the dam toe. People living in the houses just below the dam noticed the small stream and notified the Swedish State Power Board that took immediate action (currently Vattenfall AB). Photo: Alf Linderheim, Vattenfall Utveckling.

The Suorva example is typical of structural changes in earthfill dams. Normally, embankments undergo initial settlements and some internal leakage that stabilize during the first years of operation. If the dam is stable during the first years, it is very unlikely that a slow deterioration will significantly affect the aging of the embankment dam. Two factors are probably the most important for the lifespan. The dam could fail, for instance, owing to temporary accidental overtopping and, especially, in connection with an unexpected change in the hydraulic load. These two factors are discussed below.



Spillway canal at Stenkullafors earthfill dam. Photo: Anders Wörman.

What do we know about changes in concrete dams?

A concrete dam is in actual fact an artificial rock face that has been placed in nature to impound water. A gravity dam relies on its own weight for stability against imposed loads. A buttress dam consists of a watertight front wall of concrete which is supported by a number of columns on the downstream side. An arch dam is curved in the horizontal plane and sometimes also in the vertical plane. Water load is transmitted through arch action to the abutments at the ends of the dam.

Most concrete dams in Sweden are beginning to be relatively old. Most were built in the 1950s and 1960s, and many were constructed as early as the 1910s and 1920s. Quite a lot of them are exhibiting damage caused or aggravated by environmental action. The most common environmental action on concrete dams is leaching and frost attack.

Concrete is largely made of the same material as the natural rocks. Cement is made primarily of lime, clay and sand which are blended and calcined at a high temperature.When cement is mixed with water, it is hydrated, i.e. the water is chemically bound to the cement accompanied by evolution of heat and forms a number of hydration products into a hard and porous material, cement paste. If sand and gravel are also added, the resulting material is called concrete. In concrete the cement paste surrounds the grains of sand and the gravel and binds these into a strong mass. During the continuous hydration process, which may take many years, water must be available. If there is not enough water to enable all cement grains to react with water, the reaction ceases. The more cement that can become hydrated, the stronger, tighter and heavier the concrete will be.

In the beginning of the 20th century very stiff concrete was made with relatively little mixing water. To make the concrete homogeneous, it was compacted by tamping. For surfaces in contact with water, concrete with a high cement content was made, which made the surface watertight and strong. Inside the structures the concrete was in most cases much more porous and less watertight. If there are cracks in the surface or if there is much leakage, extensive through flow and leaching may arise inside the structure. In the 1920s the concrete made was very wet, with a lot of water in relation to the cement and with the same mix in the whole structure. In this way it was much easier to fill the formwork with concrete without manual tamping. However, in most cases this type of concrete was, at last partly, very inhomogeneous, pervious and weak. Later in the century concrete technology improved, but even then there were problems, such as cracking.

The concrete in a concrete dam is a relatively porous material that is greatly affected by its environment.

The concrete in a concrete dam is a relatively porous material that is greatly affected by its environment. Concrete in a good environment and with access to water gains strength with age because hydration can continue. A concrete dam is almost always exposed to a harsh climate and large stresses. The single largest environmental factor that acts on a concrete dam is the water upstream of the dam. Sooner or later, this water will penetrate into the dam. Water can dissolve the constituents of concrete and remove these (leaching), or it can carry aggressive substances into the concrete so that it is broken down chemically and physically, through e.g. salt attack. If water on its way through the concrete is exposed to low temperatures it may freeze and degrade the concrete. The thinner the dam, the greater is the risk of frost damage, especially if the downstream side has no thermal insulation. On the downstream side of the dam the concrete mostly has a relative humidity of 80-90 per cent, and oxygen may be available. In such cases the reinforcement may start to corrode. If the concrete is porous and pervious, water will flow through the concrete more rapidly, and attack and degradation will accelerate.

In most cases, environmental action weakens the material or removes material from loadbearing parts. This reduces loadcarrying capacity. If material is weakened in a part of the dam that is not essential for the loadcarrying capacity of the dam or is not exposed to high stresses, this is not so serious from the standpoint of safety. But it may be negative in other respects, for instance from the standpoint of increased maintenance costs or aesthetic considerations.

Lifespan can be defined as the period during which all the performance requirements for the structure are satisfied. The most important performance requirement for a dam is that it should be stable in response to the loads acting on it. In most cases, loads do not change appreciably during the life of a dam, while on the other hand loadcarrying capacity may both increase through continued hydration and decrease over time because of environmental action. Other performance requirements may be that operating and maintenance costs should not increase by much or that the public should not perceive the dam as ugly or unsafe.

The most important performance requirement for a dam is that it should be stable in response to the loads acting on it.

Dam failure

The ultimate fate by which the lifespan of a dam is terminated is sudden failure caused either by an extreme load condition not accounted for in the design, or by deficiencies in construction or operation. Generally, concrete dams do not fail accidentally. There are even examples where concrete arch dams have been significantly overtopped without any noticeable structural change. On the other hand statistics suggest that of the 11,192 embankment dams constructed in the world up to 1999 (excluding China and Japan pre-1930) about 136 have failed, i.e. slightly above 1%. Overtopping and internal erosion caused by through-flow, a mechanism called piping, stand for the majority of failure modes. In addition, more than two thirds of the piping failures occurred within the first five years of operation. These observations suggest that the lifespan expectancy of dams that have established operations is more susceptible to overtopping failure than to any other failure mode.

In Sweden, one of 120 dams larger than 15 m has failed. The Noppikoski earthfill dam in northern Dalarna failed due to overtopping in the autumn of 1985. This unfortunate accident occurred when the spillway gate was jammed in combination with intense rain and quick run-off conditions. Since the relatively small reservoir was filled up in a day or two the dam was overtopped and rapidly eroded to its base in the course of 15 minutes. The surge wave from the reservoir caused destruction in the downstream river valley, but luckily no significant material damage occurred and no human life was wasted.

Since dam failure is very rare and environmental action may take a long time, it is often very difficult to state with precision a lifespan for a specific structure.

Since dam failure is very rare and environmental action may take a long time, it is often very difficult to state with precision a lifespan for a specific structure. Recourse is often made to various theoretical models and measurements in the structure concerned. What theoretical models are used depends on the type of environmental action and the type of structure. These models are often based on laboratory studies in standardised environments. The lifespan calculated with such models is not the actual life but a potential life. The more measurements and calibrations that can be made between the real structure and its models, the more realistic, it is hoped, the result will be. Owing to real statistical variations in loads and loadcarrying capacity or to lack of knowledge about these, a calculated lifespan will be associated with uncertainties. In Sweden, the power industry has established a fault reporting system for dams. One of the objectives is to provide information, for statistical processing, about events which have affected, or may affect, the safety of dams.

Changing climate and hydraulic load conditions

A rapid expansion of the hydropower production occurred in Sweden during the 50s and 60s. In this period estimation of the design floods was based on the relatively long and frequent record of river discharges. This statistical method was later on questioned, however, mainly because the return time of the design floods (time period at which the design flood is expected to repeat) is generally much longer than the duration of the record. Recent models of the water run-off take into account the controlling physical factors, such as precipitation, landscape characteristics and energy radiation.

The Final Report of the Swedish Committee on Design Flood Determination for Dams was published in 1990 and this indicated that maximum possible floods estimated from hydrological forecast models exceed the old statistically estimated design floods. Therefore, the Swedish hydropower industry has undertaken a reconstruction of many of the large dam facilities to comply with the new design approach. In addition to this change in practice, we are experiencing a real change in the climate as well as hydrological conditions. At this point, we do not clearly know how possible climate scenarios will affect either the hydraulic load conditions or the water quality. The latter aspect could be important also for the deterioration of concrete dams.

Improved dam safety and prolonged lifespan

Because of the variety of factors affecting aging of dams their expected lifespan is uncertain. The age of embankment dams that have survived the first five years of operation is primarily determined by the risk of failure. Both Swedish and international investigations suggest that the probability of dam failure is about 1 % over the life of the dam. Hence, the recent Swedish guideline for dam safety (RIDAS) stipulates that the high-priority dams should withstand also extreme and very unlikely through flow.

In the case of concrete dams it is very important that they should be inspected regularly and any damage repaired without delay. One important principle in ensuring that a concrete dam will have a long life is to keep it as dry and warm as possible. In most cases this can be achieved by sealing any leaks on the upstream side and installing thermal insulation on the downstream side.

In the case of concrete dams it is very important that they should be inspected regularly and any damage repaired without delay.

However, it is not easy to determine either the cause of damage or the way such damage will affect the safety of the dam against failure. More research and development are therefore needed with regard to the development of degradation models, especially when several degradation mechanisms are simultaneously involved, and the development of a method for statistical calculations of dam safety.

Hydropower production can be seen as a sustainable energy source in a medium-term perspective. However, important future issues for the expected lifespan of dams involve consideration of the effects of climate change and additional measures to reduce the risk of dam failure. Climate change may increase the risk of extreme weather conditions and very large floods, which can lead to extraordinary demands on the dam structures. Further, research is needed to improve our understanding of these aspects and to ensure a safe and sustainable hydropower production.

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Removal of dams

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Over thousands of years, man has built dams to control the distribution of water in time and space. Many dams are now getting old and must be upgraded to meet safety requirements. In other cases, costly measures are needed to mitigate their effects on e.g. fishing. In many cases, it makes better economic sense to remove the dams. Removal of dams is now regarded to be a cost effective solution to restore rivers and to achieve environmental objectives.

The removal of the St Etienne de Vigan dam on the Upper Allier River.
Photo: ERN European Rivers Network – SOS Loire Vivante.

"I always wonder, what it is about the sound of a sledgehammer on concrete that evokes such a reaction? We routinely demolish buildings that have served their purpose or when there is a better use for the land. Why not dams? For whatever reason, we view dams as akin to the pyramids of Egypt – a permanent part of the landscape, timeless monuments to our civilisation and technology".

Bruce Babbit, American politicians and advocate of dam removal.

All over the world, there are at least 45,000 large dams that are more than 15 m high or have a storage capacity in excess of 3 million cubic metres of water. The number of smaller dams can only be guessed at, but there are probably several hundreds of thousands. In the US alone, there are about 75,000 dams with a storage capacity greater than 61,000 m^3.

Many of these dams no longer perform any function, but they are still in place. According to the Swedish register of dams, there are at least 5,300 dams in Sweden alone. Approximately 1,800 are used for hydropower production, but a large number of dams have little or no practical public function, just as in the US. However, when the removal of dams is proposed, there is often unexpectedly great opposition.

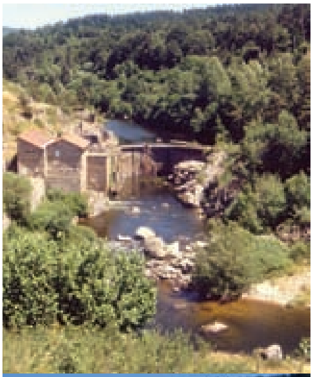
Four reasons to remove dams

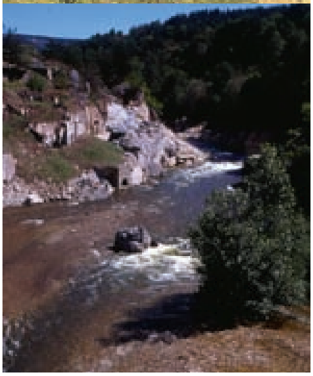
However, something has happened in the past decade. Removal of mainly small dams has started to gather momentum all over the world, but it is mainly in the US that most dams have so far been demolished. 500 dams have already been removed, most of them relatively small (less than 12 m high) and in small or medium rivers.

The reasons for removing dams vary. The earliest removals were often due to the dam being a safety risk. Dams age and the material, chiefly concrete, deteriorates. The options many owners face are either to upgrade the dam so that it satisfies the safety requirements, or to remove the dam. In many cases, removal offers the greatest economic advantage. Another reason may be that there has been so much sedimentation that the dam has no storage capacity left. The dam has lost its original function and its profitability. A third reason may be that the dam is quite simply no longer cost effective, perhaps because of old or defective technology, or because the need for e.g. electric power has changed over time.

A fourth reason may be that the dam inflicts such great damage on the natural environment that its retention can no longer be justified. Hydropower is often seen as a nature friendly way of producing electricity, compared with the burning of fossil fuels or nuclear power, but at the same time the construction of hydropower installations causes a radical disruption of the ecological functions in the river. Aquatic and terrestrial food chains have developed over thousands of years, and dams obstruct the natural flows of energy, nutrients and organisms through the landscape. When a river is dammed, the variations in water level in most cases also change, and this obviously affects the organisms. Local regulation of flow by a dam has cumulative effects in the whole river because the flow regime is changed. There is also clear evidence that sediment transport along the river is disrupted. Sediment is deposited by the slow flowing water in the reservoir, while the section downstream of the dam is exposed to erosion.

We know that rivers with several dams along their course have impoverished flora and fauna, both in the water itself and along the riverbanks. According to IUCN (The World Conservation Union), 40 per cent of freshwater fishes in North America are estimated to be under threat owing to the loss of their habitats. Fragmentation of rivers by dams is a strong contributory cause.





The St Etienne de Vigan dam on the Upper Allier River, a tributary of the Loire River in France, before and after removal. This dam was removed to open up access to salmon spawning grounds. The removal is part of "Plan Loire Grandeur Nature", a programme launched by the French government with the aim of reconciling population safety, environment protection and economic development, in a perspective of sustainable development in the Loire River.
Photos: ERN European Rivers Network – SOS Loire Vivante, and Roberto Epple/ERN European Rivers Network.

Fishing an important driving force

One clear consequence of dams in rivers is that the natural fish fauna is impoverished. Fishing is often an important source of income for people who live along the river. If we look at the loss of income caused by the loss of fishing, in many cases we find that the monetary value of fishing is greater than the value of the power produced. A functioning fishing industry is important, not only for those who are directly dependent on it for their livelihood, but indirectly also for the local economy because it attracts more tourists. Fishing may therefore often be a strong reason for removing dams. Such removals were made to improve the access of Atlantic salmon to their spawning grounds along the Loire and its tributaries.

Some researchers at the Swedish University of Agricultural Sciences carried out a questionnaire survey among anglers who had visited the Storsjö fisheries conservation area in north Härjedalen in Central Sweden. The investigation revealed that a regulating dam situated at Nordsjö-Kapell influenced the value that the anglers placed on the catch. A large fish was valued an average SEK 60 with the dam retained, and increased to SEK 123 if the dam was removed. The value of a day spent fishing increased by an average SEK 537, with no change in the fish stock, if the dam was removed. Removal of the dam is expected to have positive effects on the stock of fish. For the scenario that the stock will be three times as large, the increase in the value of a day spent fishing was estimated at an average SEK 1,813. Such a scenario was also expected to increase the attendance frequency by 72 per cent, from 2,000 to 3,440 fishing days per season.

Two examples from USA

In some cases, the money spent by the state may be more than what it would be if the dam were removed.

Large resources are devoted to attempts to retain threatened fish species in regulated rivers. In the US, it is conservatively estimated that 1.7 billion dollars have been spent in the past 20 years to keep migrating salmonids at sustainable population levels. Often, the methods used have not produced the desired results. In many cases, the activity associated with the regulation (power production, transport, irrigation, etc) also has to be subsidised by the state to be profitable. In some cases, the money spent by the state may be more than what it would be if the dam were removed. Such an example is the Snake River, Idaho, where it is estimated that the annual amount spent by the state on retaining four dams in the system is more than 236 million dollars. This includes expenditure on the dams and on retaining salmon in the river, and expenditure on transport and irrigation. The annual expenditure, if the dams were removed, would be less than 150 million dollars. This includes expenditure on the actual restoration, substitute power, alternative transport, and money spent on buying land and paying compensation for lost harvests.

Another example where the value of fishing has been a strong contributory reason is the forthcoming removal of two major dams (32 and 64 m high) on the Elwha River in Washington State: the Elwha dam and the Glines Canyon dam. The Elwha River and its tributaries make up a high proportion of the nature reserve Olympic National Park that is located in the territory of the Klallam Indians. These two dams, which were built in the early decades of the 20th Century, block practically all the migration routes for the fish species in the river, and have in this way greatly curtailed the livelihood to be gained from fishing, fishing from which the Klallam Indians had earned their livelihood and on which their culture was based.

Already when the dams were built, requirements were imposed that there should be functioning fish runs so that fish migration should not be disrupted.

Already when the dams were built, requirements were imposed that there should be functioning fish runs so that fish migration should not be disrupted. Instead of this, a fish hatchery was constructed near the dam by way of compensation, but this never worked as planned. Of the original ten fish species that had lived in the river, one has probably completely disappeared, two are left only in very small populations, and all others have been drastically reduced. During the 1980s, licensing of the dams became an increasingly delicate matter, both because the area is within a nature reserve, and because nature conservancy organisations and the Klallam Indians demanded that the dams should be removed so that fish stocks and other natural values may be restored. In 1992, there was political support, and it was decided that the only way fishing and natural values in the river could be restored was to remove the dams. Obviously, the cost of the project is enormous, 135 million dollars, but the expected gains from chiefly tourism, recreation and commercial fishing are expected to come to 163.6 million dollars. At the present time, removal is scheduled for 2008.

What happens when a dam is removed?

Although several dams have been demolished, we know very little of what actually happens when a dam is removed. The main reason for the demolitions made on ecological grounds was to bring fish back to the rivers, and the effects have in most cases been positive. We know relatively little of what happens to the rest of the ecosystem, since few removals have been accompanied by scientific observations and evaluations.

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In a study in Wisconsin State, some of the effects observed from the removal of a number of small dams are summarised. This synthesis is probably the most comprehensive one that is available at present. The rivers studied were all small or medium sized, and the dams that had been removed were all small (less than 12 m high). It was found that the response to removal occurred at different rates in various parts of the system. Aquatic macro-invertebrates were the group that recovered most quickly, while riverbank vegetation took the longest time to recover.

It probably takes one or two decades before it can be fully determined what ecological effect a removal has on riverbank vegetation, and, generally speaking, there are no long term studies that show what development has been like for specific dam removal schemes. Some general conclusions can however be drawn from studies. In the first place, it has been seen that the initial colonisation of the exposed substrate proceeds rapidly, and that the proportion of bare sediment rapidly decreases (to less than 1 per cent). It is therefore not likely that exposed sediment will remain bare for a long time, something that had often been feared by the public in conjunction with dam removal. In the second place, researchers have found that the plant community develops over time, and does not get stuck in early successional stages as had been feared might happen. The reason for these fears is likely to be the combined effect of the following: many reservoirs have been colonised by invading alien species which may alter the competitive situation and therefore also the succession of species; flow is often different from the normal because of regulations in other parts of the river; and the sediments

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that are exposed are often nutrient rich. All this may result in the alien species being favoured and enabled to remain for a long time, and in this way to delay or even prevent a natural succession.

The Rockdale Millpond in Koshkonong Creek, Wisconsin, USA. a) September 2000: taken from right side of dam facing upstream in the morning of dam breaching. b) 24 hours after breaching, facing upstream from right side of the dam. Note initial formation of headcut upstream and flat flow across reservoir further upstream. Also note that reservoir was completely filled with fine sediment. c) May 2001, 8 months after removal. Reservoir sediment in lower portion of reservoir is primarily stable as sediment has dewatered. Vegetation is what was planted immediately after dam was removed. d) August 2001, 11 months after removal. Note substantial colonisation of sediment and actually some narrowing of downstream channel. Photos: Martin Doyle and Emily Stanley.

The way vegetation develops in the former reservoirs is important for how stable the channel will be. A riverbank with well developed trees and bushes is considerably better reinforced than a riverbank with only grass and herbaceous plants. The effect of removals was most unfavourable for mussels, nor did they recover over the period of the studies. One of the reasons for this is that many mussels became attached to the sediment previously retained in the dam when the water levels dropped, and that a greatly increased sedimentation after removal caused many mussels to be covered by sediment in areas downstream of the dam.

The problem of sediment

All over the world, there is an estimated 100 billion tonnes of sediment retained behind dams, something that creates serious problems for the function of reservoirs and also for communities near the rivers and for ecosystems. This sediment can also create problems when dams are removed. Since the reservoir upstream of the dam often contains large quantities of sediment, removal of a dam will mean that the sediment is redistributed in the river; in turn, this entails large geomorphological changes and also stress for the plant and animal communities in the river.

If major dams are removed in heavily sedimented rivers, it may safely be assumed that the changes will take a long time and that they will extend over a large area.

Demolitions where all structures are removed at the same time often result in large quantities of sediment being released in a short time, and this can give rise to a lot of undesired effects on the surrounding environment, both from the aesthetic and ecological standpoints. The changes in geomorphology, i.e. the way the actual channel is altered and the amount of material that is redistributed, are also of fundamental importance to the way an ecosystem will respond to a dam removal. It is therefore important to estimate, as far as possible, what these changes will be like by investigating how much sediment there is stored in the reservoir and by trying to predict how this will be redistributed in the river. According to the Wisconsin study, however, it appears that most changes in small to medium rivers take place in the first five years, which is in line with the changes that can be seen, for instance, after extremely high floods and landslides. Most of the changes that occur also appear to be of relatively local nature, both in the reservoir itself and in the reaches immediately downstream of the dam. If major dams are removed in heavily sedimented rivers, it may safely be assumed that the changes will take a long time and that they will extend over a large area.

In many rivers, particularly if they are situated in agrarian or urban regions, the stored sediments may often contain large quantities of nutrients, but also potentially toxic substances such as heavy metals that are mobilised when the dam is removed. Such an example is the demolition of the Fort Edwards dam on the Hudson River in New York State. Large quantities of oil and PCB were released into the river when the stored sediment was mobilised. The very fact that the previously retained sediment is exposed and oxygenated changes the chemical dynamics of the compounds that are stored in the sediment. Removal of dams gives rise to changes in flow regimes and alters the water temperature, which may cause drastic changes in the carbon budget and nutrient dynamics in the previous reservoir. This may, in turn, have an impact on the ecosystems downstream of the dam.

Dam removal gives rise to many positive changes in the system. But it is important to realise that removal of a dam not only means that the river is restored, but that it also entails a

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disturbance of the ecosystem. This may cause damage to the system, at least temporarily. It is therefore essential that every removal should be preceded by an evaluation of the ecological impacts of the measure itself. In order that we may have a better knowledge of what are the effects of dam removals, it is essential that these should be accompanied by scientific studies, both before and after the removal. These studies should also make it easier in future to design tailormade restoration and management measures for dammed rivers.

Further reading

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R6:2006

ISBN 91-540-5975-5

ISSN 1653-3003

Swedish Research Council Formas

Editors: Birgitta Johansson and Björn Sellberg

Planning group: Lars Bengtsson, Lars O Ericsson, Jan Lundqvist, Britt Olofsdotter

Translation: Lewis Gruber

Design: Lupo Design

Print: august 2006. Elanders Gotab, Sweden

Formas, the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning, is a governmental research-funding agency. Formas encourages and supports scientifically significant research related to sustainable development.

Photo: Arnulf Husmo. The Alta Dam in Norway.

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