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Flood and Excess Water Control Techniques and Technologies

The general subject of floodwater and excess water control

The EU Floods Directive (Directive 2007/60/EC on the assessment and management of flood risks) came into force on 26 November 2007. Member States were required to assess if watercourses and coastlines are at risk from flooding. In a first step, the flood extent, assets and people at risk in these areas should be mapped. In a second step, the flood risk should be reduced by adequate and coordinated measures. The directive states that the public has the right to access this information and to have a say in the planning process.

All measures to reduce the flood risk should be in accordance with the EU Water Framework Directive (Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy). Therefore, it is not allowed to make the water environment worse while implementing flood damage reduction measures.

In Art. 2 of the EU Floods Directive the term "floods" is defined as follows: "flood" means the temporary covering by water of land not normally covered by water. This shall include floods from rivers, mountain torrents, Mediterranean ephemeral water courses, and floods from the sea in coastal areas, and may exclude floods from sewerage systems.

The sources of floods and excess water are described in section *Sources of excess water.* This includes pluvial flooding, fluvial flooding, coastal flooding and groundwater flooding. Section *The management of excess water within the catchment* includes non-structural and structural measures to reduce run-off as well as to decrease the flood peak discharge. In section *The management of excess water within floodplains and along rivers* measures are more focused on reducing flood-induced damages by preventing flooding entirely or by adapting buildings and infrastructure to flooding. Section *The management of flood risk* contains further information about the management of flood risk. Definition of flood risk, the flood risk cycle and information about flood early warning systems are presented. The EU Floods Directive focuses on flood damage assessment and mapping the flood extent. This can be done by analysing historical flood events. Another technique is hydrodynamic modelling which uses numerical methods to calculate the water level in a river reach for a certain design flood event. Using GIS tools, the flooded area can also be determined. A short introduction to the numerical methods to calculate flood extent is given in section *Modelling floods.*

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Sources of excess water

Pluvial flooding

Local rainfall and snowmelt can create pluvial floods. The amount of water from rain or melted snow that accumulates on the surface depends on the surface characteristics, the rainfall event and the topography of the area affected.

The surface in the area affected can be characterised by the surface material, soil type, land cover and land use. In order to describe the rainfall event, we use the rainfall intensity and duration. If the rainfall intensity is higher than the infiltration capacity water remains on the surface and accumulates in local flow paths and low lying areas. In an urban area, flow paths can be on the surface or under the surface (in the sewerage or sewer system). In low lying areas, overland flow can be increased when water is flowing out from the sewer or stormwater system.

Urban areas, where for the most part the surface is paved, areas with soils with low infiltration rates or areas with an even surface profile are more prone to pluvial floods. Rainfall on a frozen surface is also prevented from infiltration. Water from melting snow can add to the runoff in that case.

Fluvial flooding

Fluvial floods occur if the runoff and/or groundwater enter the waterways and the river water levels rise above a certain threshold. Fluvial floods depend on the rainfall event and valley and river characteristics.

Figure 1. Fluvial flooding at the river Elbe (left photo taken by the author, note the temporal flood protection walls) and coastal flooding in Wismar, Germany (right photo taken by Matthias Menzel)

Rainfall events with high intensity in small catchments with a steep land surface slope like mountainous catchments can create so-called flash floods. They are characterised by a short time to peak as well as a relatively short flood event time, critical or supercritical flow, significant sediment transport and mobilisation of additional floating debris like tree trunks and rootstocks. It is likely that sediment and floating debris block narrow river cross sections, bridge cross sections or weir cross sections during such an event increasing the water level upstream of these structures additionally.

The term "fluvial flood" is often assigned to long-lasting floods in wide river valleys after long-lasting rainfall and snowmelt events in wider catchment areas (see Figure 1). The flood event depends firstly on the intensity and duration of the rainfall as well as the additional contribution to the flow by melting snow. The river catchment, particularly its size, shape, soils and land use are important here. The level in the waterways themselves is affected by river characteristics such as size and shape. In addition, land elevation, soil material, land use and land cover are influencing the flow propagation. The material of the river bed and the vegetation on its banks determine the main channel flow. Structures in and adjacent to the river like weirs or dikes are important to consider, too. The land elevation of the floodplain determines mainly the local recurrence period of flooding [1]. In case of floods, flood water levels depend significantly on the land cover and the land use in the floodplains. Higher and rigid vegetation decelerates the flow and is connected to a higher water level.

Groundwater flooding

During a rainfall event, water infiltrates into the soil and flows in the groundwater layer towards areas with lower surface level. Over the years, these low lying areas often developed into urban areas. Groundwater flooding is more likely to occur in areas with permeable soils (aquifers). In general, the groundwater level rises after long periods with high rainfall. Due to the low flow velocity of groundwater, the flooding is likely to occur over a long period because the water has no other paths to flow away.

The flooding depends on the rainfall characteristics and the type of soil and rocks which determine the underground flow paths. But also man-made flow paths (e.g. sewer pipes or stormwater pipes) can contribute to these events.

Buildings can be damaged with or without visible exfiltration of water. In urban areas, the high groundwater level can flood basements or underground car parks, tunnels for streets or public transport. In agricultural areas, the gropes can also be affected by high groundwater levels.[1]

Coastal flooding

When coastal areas which are normally dry are flooded by seawater, this is called coastal flooding (see Figure 1). Higher sea levels can be originated from unusually high tide level, storm surges or tsunamis. In addition, the sea level itself is rising [20].

1 Further information can be found e.g. on www.groundwateruk.org/faq_groundwater_flooding.aspx

Exceptional high tide levels at the time of new moon or full moon together with storm surges due to strong onshore wind can create very high sea water levels. The flooding is than limited to the time of the high tide but flooding can occur during several high tide intervals in a row. The city of Venice is a well-known example for an urban area prone to flooding due to high tide and onshore wind. Last exceptional flooding occurred on the 29th of October 2018 [25].

The onshore wind itself may cause the water to pile up onto the shoreline. Together with the wave run-up of the wind-induced waves sea water can reach very high levels. The duration of these storm surges depends on the duration of the storm event. The wind wave run-up can erode the shore and sea levees or damage other coastal protection structures like sea walls. In case of a levee or sea wall failure wide areas which may be lower than the normal sea water level e.g. areas in the Netherlands can be flooded [26].

Another cause for coastal flooding is a tsunami wave. Tsunami, which means harbour wave in Japanese, is created by a seaquake. If the sea bottom moves significantly during a seaquake huge amounts of water are moved and a wave on the sea surface is created. These waves propagate in all directions and are characterised by relatively shallow wave height and very long wavelengths [27]. A tsunami wave is a so-called shallow water wave so its propagation velocity depends only on the local depth of the sea. When the tsunami reaches the coastal area, the propagation velocity decreases and the wave height increases. That is why it is called "harbour wave" because it is more distinguishable near the coast and near a harbour than on the open sea. Tsunami waves create a significant flow of seawater into the coastal areas and are responsible for huge damages there. The high water level together with the high flow velocity mobilise a lot of sediment and debris, like ships, cars, trees, etc. and transport them into the hinterland. Examples are the tsunami which occurred on the 26th of December 2004 due to the Sumatra–Andaman earthquake in the Indian Ocean and the tsunami on the 11th of March 2011 due to the Tohoku earthquake in Japan. But many tsunami waves in the Mediterranean Sea are documented, too [19].

The management of excess water within the catchment

Structural and non-structural measures

The management of excess water aims at reducing flood-induced damages e.g. by reducing flood peak discharge and maximum water level or by preventing urban areas or agricultural areas from flooding. Possible measures are divided into two groups: non-structural and structural measures. Non-structural and structural measures can be applied in the catchments as well as along the main watercourse.

Non-structural measures aim to improve flood awareness and flood management as well as try to change the characteristics of the catchment area and with that the creation of floods itself. Financial preparedness of people who live in the floodplains can be increased by taking out flood damage insurance. Proper spatial planning and early flood warning systems can reduce flood risk by reducing possible flood damages. Further information is found in sub-section *Early flood warning systems.*

Changes in land use like reforestation and other measures at smaller tributaries can reduce the amount of runoff and with that the flood peak and volume of the flood wave. More information is given in sub-section *Structural and non-structural measures.*

Structural measures aim at reducing the flood discharge, the flood water level or at the protection of the buildings and infrastructure along rivers. The measures discussed in the following sections are:

- the improvement of rainwater retention and infiltration in the urban watershed (sub-section *Small scale retention measures*)
- the creation of flood retention basin as permanent storage or flood detention basin as temporary storage (sub-section *Retention measures in urban areas*)
- the installation of levees, flood-walls or mobile flood protection elements (sub-section *Flood protection structures*)
- the flood control channel or flood relief channel (sub-section *Flood control channels*)
- dike relocation and flood polder (sub-sections *Dike relocation* and *Flood polder*)
- a flood-proof home design increasing the resilience of buildings and allowing for flooding without or with only little damage (sub-section *Flood-proof home design*)

Small scale retention measures

The creation of run-off during a rainfall event depends on land use, soil characteristics and rainfall intensity and duration. In order to increase the infiltration and retention of water on the surface, land use change and smaller green infrastructure or nature-based solutions can be applied.

In general, these measures have a small effect on floods with small return periods and tend to have no effect on extreme flood events. Nevertheless, if applied in a whole catchment, their effect can sum up. Normally, these measures cost much less than traditional (so-called grey infrastructure). These retention measures may provide additional services like new habitats for birds and insects, recreational areas, preventing erosion or mitigating droughts [9].

In general, these measures are uncontrollable, automatic and potential water retention capacity is difficult to predict. They should be carefully assessed regarding their cost and water retention effect including all the additional ecosystem services, too.

As an example, reforestation can increase water infiltration significantly. Nevertheless, the selection of areas for reforestation may be restricted by other land uses like agriculture.

Other small retention measures aiming at delaying the run-off in a catchment include the creation of plants protective belts, woodlots shrubs or the creation of terraces [11]. Measures on agricultural land include the selection of proper agro-technics, the increase of organic matter content in the soil, anti-erosion measures or the run-off regulation from drainage systems. The widening of the area of wetlands, peatlands and swamps and rewetting of peatland are also possible. Their main objective is to increase water storage in these areas.

Retention measures in urban areas

Urban areas with their paved and sealed surface are prone to fast run-off during a rainfall event. Impervious surfaces include roofs, streets or parking lots. Other highly sealed areas are ports, airports or construction sites. The soil sealing in percent of the urban zone ranges from over 20% to almost 80% for European capitals (see Figure 2).

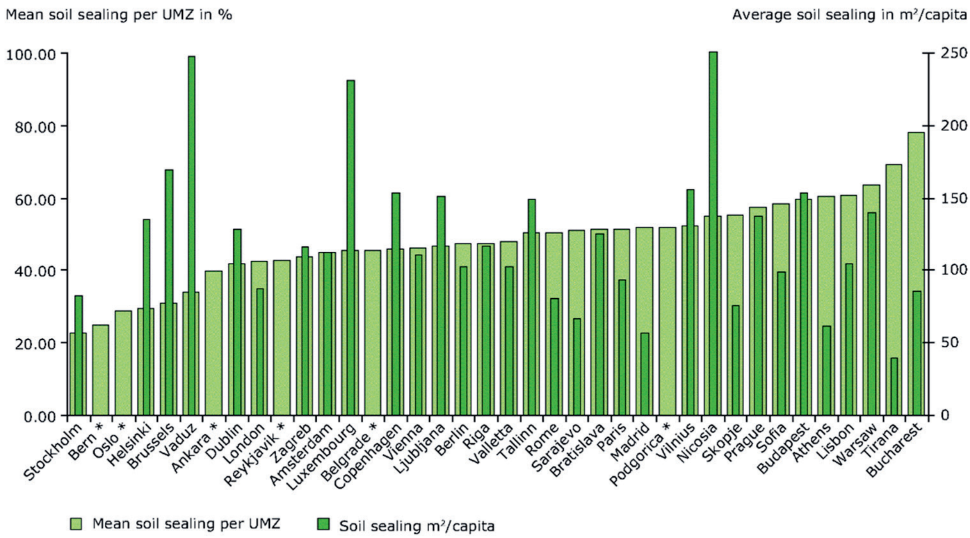


Figure 2. Soil sealing in European capitals [28]

Regarding urban areas, retention measures aim at reducing the run-off by increasing infiltration, storing it in areas where no damage occurs or delaying it by temporal storage.

Possible measures are:

– dams and reservoirs (see sub-section *Dams and reservoirs*)
– ponds and infiltration wells for storage and increasing infiltration
– temporal flooding of playgrounds or sports grounds
– green roofs for storage and delaying run-off
– the adaptation of streets as temporal water flow ways

All these measures are summarised in the concept of a "Sponge city" [7]. Implementing this concept needs a combined effort of hydraulic engineering, land-use planning, urban politics and the citizens themselves because many measures are implemented on private land.

Dams and reservoirs

In order to hold back water in the upper parts of a river catchment, dams can be used. When building a dam, a reservoir is created in the area where the water is stored. The design of dams depends mostly on their height. In general, a large dam is a dam with a height of ≥ 15 m above the lowest foundation or a dam between 5 metres and 15 metres high impounding more than 3 million cubic metres (so-called ICOLD[2] criterion [29]).

Reservoirs (see Figure 3) can have a permanent water volume stored behind the dam (permanently filled reservoirs, flood retention basins) or can be empty or partially filled during normal weather and only completely filled when an increased inflow due to rainfall or melting snow occurs (non-permanently filled reservoirs, flood detention basins). The advantages of non-permanently filled reservoirs are free migration routes for water-bound animals like fish and amphibians. There is no permanent disruption of the wildlife corridor because during normal weather the river flows through the empty reservoir like in the natural parts of a valley.

The reservoir can be situated in the main valley or beside the river like a polder (see sub-section *Flood polder*) or at some distance from the river like the upper reservoirs of pumped storage power plants. In order to fill the latter, additional channels or pipes have to be built.

The dam is a structure resisting the hydrostatic pressure force of the stored water column. Different types of dams are established:

- gravity dams made from masonry or concrete
- earth filled dams made from compacted soil layers with (zoned dam) or without (homogenous dam) additional sealing structures
- rock filled dams built using rock fragments or large boulders with additional sealing structures
- roller compacted concrete dams
- arch dams made from concrete
- buttress dams made from concrete

According to the World Register of Dams with 59,071 registered dams, the majority of large dams in the world are earth dams (38,426 dams, 65.1%). The next biggest categories are rock filled dams (7,670 dams, 13.0%) and gravity dams (7,450 dams, 12.6%). The following categories have much fewer dams registered: buttress dams (419 dams, 0.7%), barrages (280 dams, 0.5%), arch dams (2,332 dams, 3.9%) and multiple arch dams (133 dams, 0.2%). Then there are 2,361 dams (4.0%) which are categorised as “others”.

Much less common and often small are metal dams and timber dams.

[2] ICOLD: International Commission on Large Dams.

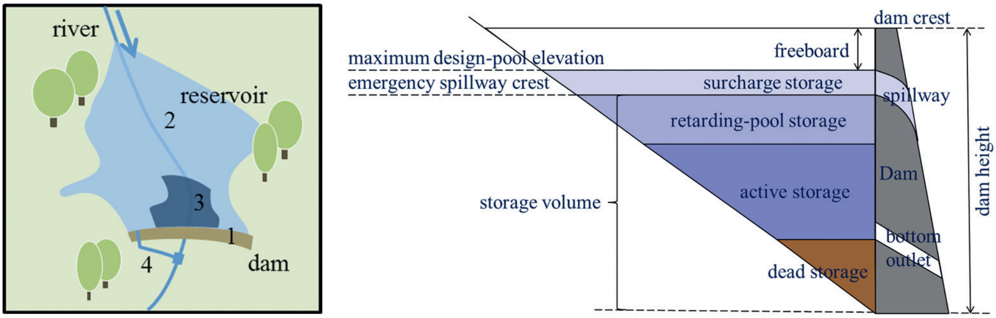


Figure 3. A dam and its reservoir: oblique view with 1 – dam, 2 – water surface in case of a permanently filled reservoir or in case of flood inflow for an empty or partially filled reservoir, 3 – water surface of a partially filled reservoir when there is no flood inflow, 4 – emergency spillway (left), definitions regarding structures, water levels and storage volume for a permanently filled reservoir (right) (compiled by the author)

The volume of water below the minimum pool level is called the dead storage (see Figure 3). This volume can be filled with sediment without endangering the correct operation of the dam and reservoir.

During normal weather and in case of a permanently filled reservoir, water is kept in the dead storage and the active storage. In case of a design flood event, the flood water will be stored in the retarding-pool storage and the reservoir water level will rise until it reaches the emergency spillway crest. This means a full reservoir level. For many dams, this design flood event is a 1-in-50-years or 1-in-100-years flood event. The recurrence period depends on the dam height or storage volume. No outflow over the emergency spillway happens. No damages downstream should be caused by the maximum total outflow discharge during this event.

If a larger flood event occurs, the additional water will be stored in the surcharge storage. Water will flow over the emergency spillway. The type and the dimensions of the emergency spillway have to be chosen in a way that the reservoir water level does not exceed the maximum reservoir level in case of this flood event. In general, flood events for designing the emergency spillway have a recurrence period of 100 to 200 years for smaller dams and up to 1,000 years for large dams.

The general dam safety is assessed using flood events with recurrence periods between 500 and 1,000 years for smaller dams and up to 10,000 years for large dams. No damage to the structure itself has to occur. Minor damages can affect infrastructure or measurement devices at the dam which are not vital for dam operation.

The difference between the dam crest level and the maximum reservoir level is called freeboard. The freeboard is necessary to accommodate additional water level increasing effects e.g. wind wave run-up, water level raised by wind or waves induced due to landslides.

Emergency spillways are very important structures regarding the operation of dams in case of floods. Their type and design have to be appropriate to the type of dam.

Spillways can be located within the body of the dam, at one or both sides of the dam or even completely separated from the dam as a by-pass spillway.

Common types of emergency spillways are (see [22]):

- free overfall or straight drop spillway (for thin arch dams e.g. the Gebidem dam, Switzerland)
- ogee or overflow spillway (the water flows over a weir crest parallel to the dam crest, often at gravity dams, e.g. Eibenstock dam, Germany)
- side channel spillway (the water is collected by a side channel with a weir crest perpendicular to the dam crest in a horizontal plane, after that the water could either flow through an open channel or a tunnel to the dam toe, e.g. Malter dam, Germany)
- chute or open channel or through spillway (the water is conveyed through a very steep channel to the dam toe, often used at earth dams, e.g. Mosul dam, Iraq)
- conduit or tunnel spillway (e.g. reservoir Sylvensteinspeicher, Germany)
- drop inlet or shaft or morning glory spillway (water drops through a vertical shaft to a horizontal conduit that conveys the water past the dam, often used for earth dams, e.g. Monticello dam, California, USA)
- siphon spillway (used mainly for concrete dams, e.g. Murrum Silli dam, India)

Because the water flow accelerates while passing over the spillway or dropping down freely as a water jet, the energy of the flow has to be dissipated before the water enters the downstream river course. Slowing down the water means to create a hydraulic jump which is the transition from supercritical to subcritical flow. The structure where the hydraulic jump should occur is called a stilling basin.

In order to calculate the needed storage volume of a reservoir (retarding-pool storage), it is stated that the change of the water storage volume dS within a reservoir or polder equals the difference between the reservoir inflow Q_{in} and reservoir outflow Q_{out} during the short time period dt:

$$\frac{dS}{dt} = Q_{in} - Q_{out} \tag{1}$$

The inflow into a reservoir consists of river inflow, overland runoff from the valley sides and precipitation within the reservoir itself.

The outflow is defined by outlet structures like mid-level and/or bottom outlets, a spillway or a turbine. The calculation of the outflow discharge takes into account different formula for these different outlet structures.

The calculation is based on the relation between the reservoir level and the storage volume, which can be derived from topographic data. When calculating reservoir retention, the storage as well as the outflow discharge depends on the reservoir water level. That is why an iterative solution is needed.

It is important to note that the peak discharge occurs when the water level within the reservoir reaches its maximum. At the same time, the reservoir storage volume S has its maximum (see Figure 4). This is the case when the outflow structures are fully opened.

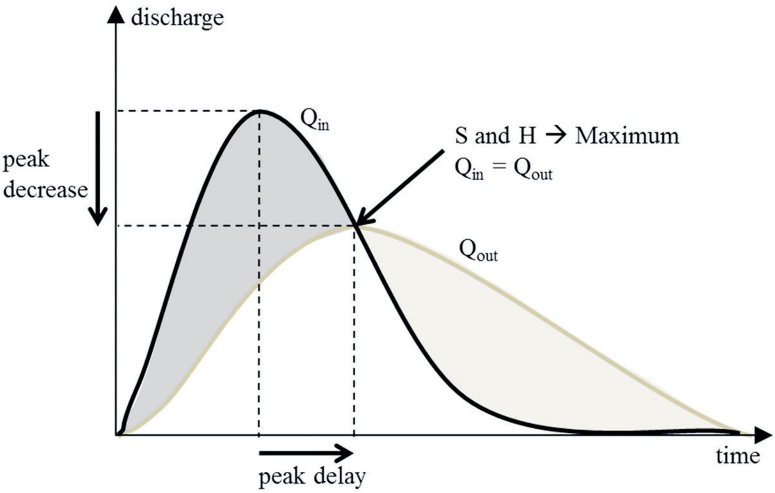


Figure 4. Inflow and outflow hydrograph for a reservoir with fully opened outflow structures, the coloured areas represent the required storage volume S (reservoir flood retention) (compiled by the author)

For a design flood event, the required reservoir storage and dam height respectively depend on the maximum allowable reservoir outflow Q_{out}. The value has to be defined such, that the flow downstream a reservoir or polder is retained within the river banks and no overflow is created. This also depends on the land use in this area because an urban area is more worth protecting than agricultural land. In general, it can be said, the higher the allowable outflow the lower the required storage volume and vice versa (Figure 5).

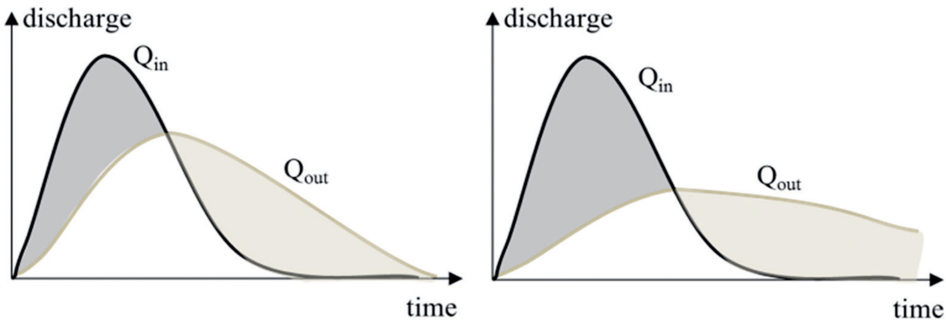


Figure 5. Reservoir flood retention: A higher allowable reservoir outflow in the left picture is connected to a lower required reservoir storage volume (coloured areas) (compiled by the author)

The water volume which is stored in a reservoir or polder is controlled by regulating reservoir outflow. This is an advantage of these flood control structures. In case of the design event or a smaller event, the decreasing effect on the flood peak is very high. Even if an extreme flood event happens, the flood peak can be significantly delayed.

Data from the 2002 flood event in Saxony, Germany [17] or from other flood events [2] [16] showed that very clearly.

If hydrological data e.g. design flood hydrograph are based on short historical flow series, it is possible that they underestimate possible extreme flood events. This is sometimes the case with older dams because when they were built hydrological knowledge was not as accurate as today. But what happens when the flood control or retaining capacity (reservoir volume) is too small compared to the flood wave volume? If the flood storage volume is already filled and the inflow exceeds the spillway capacity, the dam crest could be overtopped. Overtopping is a major cause for dam failure which can lead to catastrophic flooding downstream [18].

The management of excess water within floodplains and along rivers

Flood routing in rivers and floodplains

In case of a flood, water overflows the river banks and streams into the floodplain. If the tributaries do not add further water from their sub-basins, the flood peak declines during flood wave propagation and the flood duration gets longer. This process is called river flood retention. To illustrate this, three river reaches with their according discharge hydrographs for a hypothetical flood event are shown in Figure 6. The discharge hydrograph for the most downstream river reach has a lower peak discharge and a longer duration of high flow than the most upstream river reach.

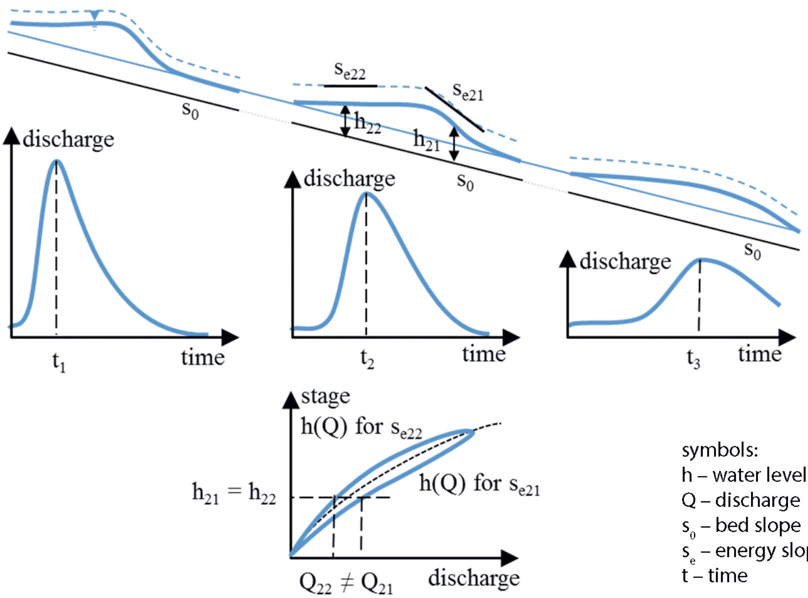


Figure 6. Characteristics of the flow and the hydrograph at three selected cross sections of a river (compiled by the author)

The diagram below shows the hysteresis effect due to the change in energy gradient during flood propagation.

River flood retention is governed by two major processes which are significantly influenced by the land use and land cover within the floodplain.

In general, the water moves slower over the floodplain than within the main channel. In wide floodplains, it is also possible that the water travels with such a low velocity that the floodplain creates an effect equal to a reservoir. That part of the water volume that travels in the floodplain reaches the downstream end of a certain river reach significantly later than the water traveling in the main channel. This lowers the flood peak and makes the flood duration longer.

The other process is driven by the difference in the energy slope during an increasing and a decreasing flood flow. During the rising limb of the flood hydrograph, the water level increases over time. Thus, the energy slope is higher than the longitudinal bottom slope in a river reach (Figure 6, cross section 21). When the flood peak occurs, the energy slope and longitudinal slope are equal for a moment. That is why it is feasible to use quasi-steady conditions when calculating long flood events. And at the falling limb of the flood hydrograph, when the water recedes, the energy slope is lower than the longitudinal bed slope (Figure 6, cross section 22).

Looking at Manning's Formula [8]

$$Q = A \cdot \frac{1}{n} \cdot {r_{hy}}^{2/3} \cdot \sqrt{s_e} \tag{2}$$

with A – cross-sectional area, n – Manning's coefficient, r_{hy} – hydraulic radius, s_e – energy slope, one can easily derive, the gentler the energy slope the smaller the discharge in a channel. It can be concluded, that the flow near the flood peak is more decelerated than the flow during the rising limb of the flood hydrograph. And the flow during the falling limb of the flood hydrograph is more decelerated than the flow around the flood peak.

The relation between the discharge in a certain river reach and the water level is very complex. As the energy slope is higher during the rising limb of the flood wave (see Figure 6 with $s_{e21} > s_{e22}$), so is the velocity. That is why a higher discharge is connected to the same water level ($h_{21} = h_{22}$) when the water level is rising than when the water level is falling. Thus, for the stage–discharge–curve in Figure 6 follows $Q_{21} > Q_{22}$. For this reason, the time when the maximum water level occurs is not equal with the time when the discharge reaches its peak. The maximum water storage in a river reach happens later than the peak discharge. This is called the hysteresis effect.

If a floodplain is covered with higher vegetation e.g. wood (see Figure 7) the flood peak discharge downstream the inundation area would be lower and the flood wave duration longer as in the case of an inundation area used as meadow or field (Figure 8). Accordingly, water would remain longer within the inundation area and the flood water level there would be higher [10].

Figure 7. Riparian forest at the river Elbe near Meißen (left) and agricultural land in a flood plain (right; photos taken by the author)

However, this effect has a lower impact on extreme and seldom floods than on smaller and more frequent floods.

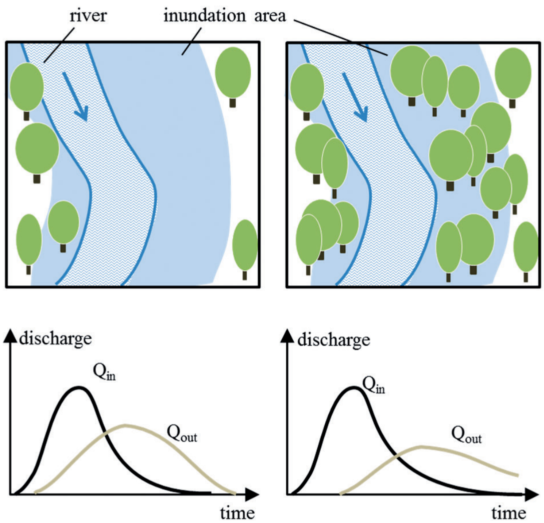


Figure 8. Two river reaches with floodplains characterised by different land use (above = oblique view) representing a lower roughness (left) and higher roughness (right) (compiled by the author)

The diagrams below show the flow hydrographs at the beginning (Q_{in}) and at the end (Q_{out}) of the river reach.

The reestablishment of floodplain woodland and the promotion of river meandering are two measures of river and floodplain restoration projects which try to employ river retention. It will take a long time between the planting of floodplain woodland and any significant effect on flood flows. But in order to initiate these projects, it would be good to quantify the effectiveness of this type of woodland as a mechanism for lowering the flood flow. The effect of high vegetation on flood wave propagation can be modelled using hydrodynamic models (see section *Modelling floods*).

The flood control function of floodplain woodland along a 2.2 km long reach of the River Cary in the United Kingdom was modelled by [15]. The river reach was assumed to be completely forested. This would mean the establishment of 133 ha wet woodland. The study showed an increase in flood storage by 71% as well as a delay of the flood peak arrival downstream by 140 min in case of a 100-year-flood.

Additionally, river retention depends on the characteristics of the river. 200 years ago, rivers were more shallow and wider (Figure 9). In order to use rivers for transport, engineers took measures like dragging and cutting of meanders which created deeper and narrower river beds. Focusing on flood retention it can be beneficial to reverse this development. "The Wise Use of Floodplains" project [1] investigated the potential of reinstating a river channel to its pre-engineered state. This would induce more frequent flooding of its floodplains and with that an increasing effect of flood retention. The study included calculations for the Cherwell catchment in the United Kingdom. It was shown that the flood flow downstream the study area could be reduced by 10 to 15% if the river channel and floodplain are restored to its pre-engineered dimensions.

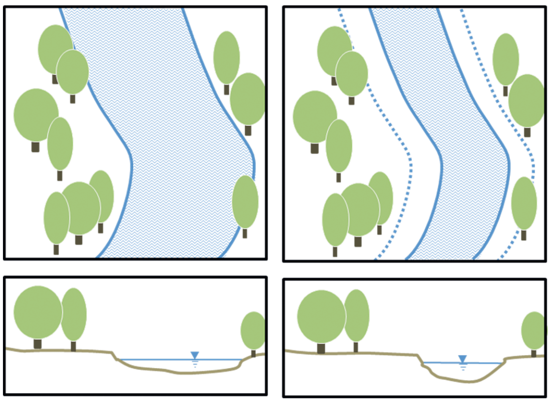


Figure 9. One river reach in its pre-engineered state (left) with a more shallow and wider cross section and in its engineered state (right) with a deeper and narrower cross section (above: oblique view, below: cross section) (compiled by the author)

The implementation of these measures could be restricted if the river is used for transport (navigable river).

Flood protection structures

Flood protection structures along rivers or along the coastline are levees or dikes, flood walls or demountable flood barriers or demountable flood protection structures. They prevent areas from flooding by increasing the local surface level. The design height of a flood protection structure depends on the local ground level, the design water level and the height of an additional freeboard.

The local design water level can be set to a certain height, can be the water level of a historical flood event or can be calculated by means of hydrodynamic models (see section *Modelling floods*) for a design flood event. The freeboard height is necessary to accommodate additional water level increasing effects e.g. wind wave run-up, water level raised by wind or the backwater effect of ice jams.

Levees or dikes are permanent embankments. They are situated in parallel to the coastline or the river channel axis and made out of the local soil. In general, their surface is covered with grass. This provides protection against erosion and additional sealing. Embankments need a lot of free space because their two faces are sloped between 1V:3H to 1V:6H. A 5 metres high dam with a dam crest width of 2 metres and a riverward side sloped 1V:3H and a landward side sloped 1V:2H has a width at its foundation of 27 metres.

Flood walls are more suitable for urban areas with less open space available. They are also permanent structures. They can be made out of concrete, masonry, steel or even glass. They have to withstand the hydrostatic pressure force and have to be well grounded to prevent tilting. Their construction design has also been checked if it can withstand the impact of floating debris.

Demountable or moveable flood barriers can be of various shapes, design and out of very different materials. They are non-permanent structures. They are often used to close gaps in permanent flood protection structure like wall openings for access to the riverside or street crossings. A certain time is needed to establish them. A good flood forecast is necessary to apply these structures. The construction should be easy enough to be conducted fast and get a reliable structure at the end. The structures have to be stored elsewhere in a time of normal river water level. The design has to withstand against the hydrostatic pressure force as well as against the impact of floating debris. The waterproof connection to permanent structures like buildings or walls is a critical point regarding demountable flood barriers.

The simplest and most common form of a moveable flood protection barrier is a sand-bag wall. Other structures are made out of aluminum beams (e.g. in Prague, at the right bank, downstream the famous Charles Bridge), also big water filled bags, sand filled big bags or inclined systems are used.

Flood control channels

In order to accelerate the flood flow or to redirect flood discharge away from an urban area flood control channels or flood relief channels are established. Two different set-ups are possible.

Firstly, the channel can start downstream an urban area. When a certain water level is reached, the flow discharge starts to enter the flood relief channel. Due to the bigger flow cross section, the water level decreases increasing the local energy slope for the flow in the upstream urban area and accelerating the upstream flow. This effect is only temporal but may help to contain the flood water within the set flood protection structures.

An example is the system of the two flood relief channels at the river Elbe in the city of Dresden, Germany. The flooding of the two channels starts at different flood water levels.

Figure 10. Inflow structure "Pretziener Wehr", controlling the inflow discharge to the flood relief channel near Magdeburg, Germany (photo taken by the author)

Secondly, the flood relief channel starts upstream of the urban area. The flood flow is bypassed reducing the flow discharge in the river itself. An example is the "Elbeumflut", an older river bed of the river Elbe near Magdeburg, Germany. This old river bed is only filled in case of a flood event. The filling is controlled by a weir (Pretziener Wehr) built in 1875 with 9 sluice gates (see Figure 10).

Dike relocation

Sometimes it is necessary to build a new levee more afar from a river. This can be in order to give "room to the rivers", to build a higher dike, to build the dike on a more suitable ground or in order to get a better layout of the dike line. An existing levee would then be removed and an additional area could be inundated in case of a flood (Figure 11, left). The setback of levees is one of many flood retention measures which improve ecological parameters as well [6].

If the existing levee remains beside the new levee both can create a so-called polder (see sub-section *Flood Polder*). Two additional structures – an inflow and an outflow structure – have to be built in order to control the moment when polder filling starts and to regulate the inflow and the outflow discharge (Figure 11, right).

The main difference between these two scenarios is the controlled flooding in case of a polder versus the uncontrolled flooding in case of a levee setback [3]. If there is a flood event with a reliable flood forecast, the polder inflow is controlled aiming at lowering the flood peak (see Figure 11). The additional flood area created by the levee setback is flooded always when the water level in the main channel reaches the bank level and is filled as the water level rises. It could be possible that the flood area is already filled when the flood peak reaches the location of the levee setback and no significant peak reduction is achieved.

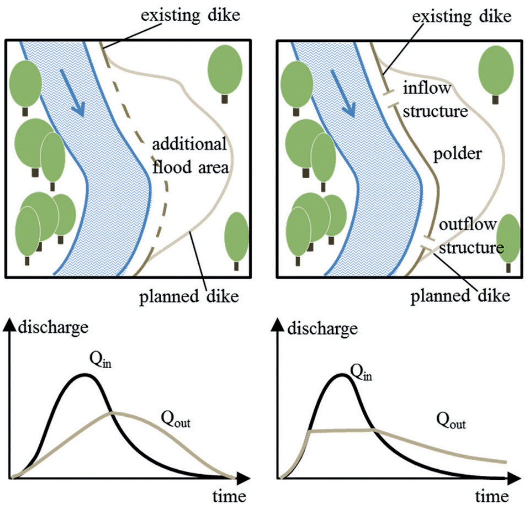


Figure 11. A river reach (above, oblique view) with an additional flood area due to a levee setback (left) or a polder (right). Below are the corresponding flood hydrographs upstream and downstream of the considered river reach (compiled by the author)

Assuming a quite short river reach with subcritical flow conditions which in general applies to our rivers and considering the Bernoulli-Theorem

$$z + h + \alpha \cdot \frac{v^2}{2 \cdot g} = const. \tag{3}$$

with z – height above a datum, h – water depth, α – kinetic energy correction factor, v – flow velocity and g – gravity acceleration constant, together with the principle of continuity

$$Q = v \cdot A = const., \tag{4}$$

it can be stated that a wider flood cross section due to a levee setback causes a lower flow velocity and hence an increasing water depth.

It is important to know which length will be needed for a levee setback reach to get a water level reduction instead of a higher water level. This so-called effective minimal length of levee relocation L_{Aeff} can be estimated using the following formula [10]:

$$L_{Aeff} = \frac{h_0}{s_0} \cdot \left[\frac{r_h \cdot h_3}{h_o} - \frac{h_3}{h_0} + \left(1 - {Fr_0}^2\right) \cdot f_R\left(\frac{h_3}{h_0}\right) - f_R\left(\frac{r_h \cdot h_3}{h_0}\right) \right] \tag{5}$$

with h_0 – normal depth, s_0 – bed slope, h_3 – flow depth downstream of a dike relocation and Fr_0 – Froude number at normal flow conditions (see Figure 12). The expression $f_R(x)$ depends on the shape of the river cross section. As a first estimation, the formula below for a rectangular shaped cross section can be used [10]:

$$f_R(x) = \frac{1}{6} \cdot ln\left(\frac{x^2+x+1}{(x-1)^2}\right) + \frac{1}{\sqrt{3}} \cdot arctan\left(\frac{1+2\cdot x}{\sqrt{3}}\right) \tag{6}$$

with x as a general independent variable. The water depth ratio $r_h = h_1/h_3$ can be derived from:

$$r_h{}^3 - \left(\frac{Fr_3{}^2}{2} \cdot (1 + \varsigma_c) + 1\right) \cdot r_h{}^2 + \frac{Fr_3{}^2}{2} \cdot \frac{(1+\varsigma_c)}{r_b{}^2} = 0 \tag{7}$$

With ς_c – a coefficient describing the local energy loss at the downstream end of a dike relocation, $r_b = b_1/b_3$ and Fr_3 – Froude number downstream the levee relocation.

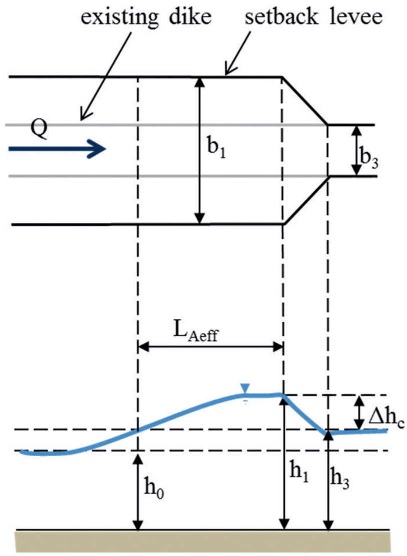


Figure 12. Definition of some parameters (see equations 5–7) within a levee relocation reach (plan view – above) (compiled by the author)

There is a lower water depth within the levee relocation reach and upstream of it if the length of a dike relocation is longer than L_{Aeff}.

[10] stated further, that levee relocations reduce the peak discharge only in case of smaller floods. For floods with higher recurrence periods very wide and long additional flooded areas are needed to achieve a significant effect. The longer and the wider a levee setback area, the higher the decreasing effect on the flow depth. Additionally, it was found that peak reduction is higher in case of shorter and steeper flood hydrographs than in case of long-lasting floods.

Dike relocations provide additional ecosystem services which have to be included in cost–benefit analyses. In the last decades, there was a huge improvement in the knowledge and perception of the river-floodplain system as an ecosystem. Areas which are flooded regularly may provide habitats for plants and animals from the Red Red List (see www.iucnredlist.org/).

Flood polder

There are two main definitions of the term “polder”. One meaning, originating from Dutch, describes a low-lying area which is usually flooded by the sea or a river and which was separated from the water body by a levee. This area would then be drained and used for agriculture and settlements. Here, the protected area is situated inside the levee which is often formed as a ring.

The extreme flood events in the last centuries in Europe let to another point of view regarding these protected areas. If no settlements were created and the land is only for agriculture, it can also be used to store flood water temporarily. In that case, the area which is flooded is inside the levees. The latter meaning is the one which will be used further.

A polder is an area alongside a river. Its filling in case of a flood event can be controlled by an inflow and an outflow structure. These are normally weirs with gates like sluice gates, flap gates, mitre gates or radial gates. As an example, the polder Löbnitz at the river Mulde (Germany) has a weir with flap gates as an inflow structure and a weir with mitre gates as an outflow structure. The old dikes prevent filling during flood events with a recurrence interval of $T \leq 25$ years. If a larger flood occurs, the polder area is flooded providing up to 15 million m^3 additional flood storage.

The controlled flooding is an advantage of a polder because it gives a significant potential for reducing downstream flows [1]. If there is a flood event with a reliable flood forecast, the polder inflow could be controlled aiming at lowering the flood peak (see Figure 11). In the last two decades, many polders and polder systems which can significantly influence the flood flow were newly established at big European rivers. Additional structures are still in the planning stage. Some examples are:

- river Havel (Germany), this polder system is able to reduce the flood peak in the river Elbe, too
- river Rhine, e.g. polder Ingelheim and polder Söllingen/Greffern in Germany, further measures are planned (see program “Rhein 2020”)
- river Danube, e.g. polder Riedensheim in Germany (under construction), further measures are planned but they are highly controversially discussed by stakeholders

In case of a more technical approach and with focus on flood retention, land use in polders should be restricted in order to maintain a maximum storage volume and to propagate a fast inflow and filling process [3]. In addition, land use should not stimulate additional sedimentation of fine river sediments. That is why polders are often used as grassland.

In addition, this temporarily flooded land can offer additional ecosystem and other services like providing habitats or the opportunity for recreation. Then optimising the additional uses is mandatory and the polder area should consist of different types of land use like riparian woodland, wetland and agricultural land.

Near the inflow and outflow structure, flow velocity is higher and the bottom should be covered with a material which is less prone to erosion. Inflow and outflow structures are constructions including a paved or concrete bed, concrete pillars and a control room.

The management of flood risk

Flood risk

The EU Floods Directive states in its Art. 2 that 'flood risk' "means the combination of the probability of a flood event and of the potential adverse consequences for human health, the environment, cultural heritage and economic activity associated with a flood event".

In general, flood risk r can be calculated using the following formula:

$$r = c \cdot f \tag{8}$$

where c stands for the consequences of a flood event and f is the recurrence frequency of this flood event.

The consequences include all the negative impacts of a flood event equal to the definition of the EU Floods Directive. Consequences for the human health include injuries or death but also long-lasting effects of mental stress. Floods can destroy habitats with their flora and fauna and can have long-lasting effects like changes in the ecological system. Cultural heritage sites like old city centres with their old churches, libraries and town halls or monasteries are often very prone to flooding because the material of the buildings is old and standards in design and construction were lower in former centuries. In addition, cultural heritage sites may hold many old and valuable artefacts which can also suffer from damages due to the flood water. The economic activities in an inundated area suffer immediately during the flooding because of lost production but also afterward when a lot of money is needed for cleaning and rebuilding.

If it is possible to quantify all the consequences, the risk can be expressed in cost per year.

The flood damage depends mainly on the type of the structure and the local water level as well as the flow velocity. In order to calculate the possible damages, so-called flood damage functions are used. They are empirically established based on data of historical flood events about real damages and flood characteristics [24].

Flood risk management and flood resilience

Flood risk management includes all measures relating to floods, like measures affecting run-off creation or flood flow, damage mitigation measures, flood rescue missions, land management and also financial schemes providing money in case of flood damages [12].

The so-called flood risk management cycle includes all the measures and shows their relation to each other (see Figure 13).

When a flood event is about to happen, response measures follow first. The flood forecast centre gives information about possible flood water levels, flood warnings are distributed, fire brigades or inhabitants prepare for the flood. They establish mobile flood protection structures and monitor other flood protection structures like levees.

If necessary, roads and bridges are closed, the evacuations of potentially flooded buildings start and affected inhabitants are provided with temporal shelter, food and other aid supplies.

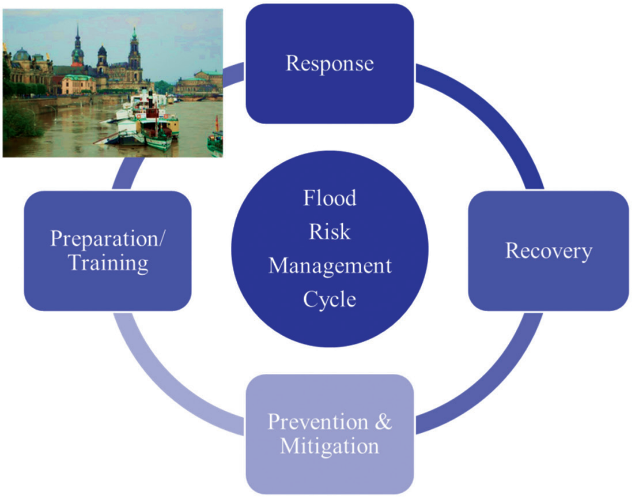


Figure 13. The flood risk management cycle (compiled by the author)

After the flood, recovery measures are important. Basements or underground parking lots have to be pumped empty, flood damages at buildings, infrastructure and the waterways have to be repaired. Financial schemes to help the affected people or communities are very important here.

After recovery or even during this time, it is important to assess the causes of flood damages and to take possible measures to mitigate or prevent them should the same flood event occur again.

The next step in the flood risk management cycle is preparation and training. This focuses on implementing further flood mitigation measures and maintaining a high level of flood awareness and preparedness. Flood awareness and preparedness usually decrease over time [4]. High flood water marks at prominent buildings, exhibitions or special TV programs about historical flood events and cultural events help to remember past floods.

Flood resilience describes the ability of communities to deal with floods. Small flood-induced damage together with a fast recovery after a flood is connected to high flood resilience.

Communication about floods and its consequences has been significantly enhanced over the last two decades. Information to the public is easily available on many governmental websites (e.g. www.chiefscientist.qld.gov.au/publications/understanding-floods/; www.gov.uk/browse/environment-countryside/flooding-extreme-weather).

Hazard maps, risk maps or inundation maps are important for exact action planning in case of a flood. Flood risk management plans together with decision support systems and appropriate maps provide information to take quick and adequate measures. Operational forces need information about the area affected, required measures as well as lists with affected people and companies, hospitals, senior residents, schools and others. Management plans and flood maps should contain information about frequent as well as rare and extreme flood events to cover all possibilities.

Early flood warning systems

In urban areas, structural flood protection measures are often restricted by limited space, environment protection or the attempt to conserve the cityscape. That is why demountable flood protection elements (see sub-section *Flood protection structures*) or non-structural measures like an early flood warning system might be more welcome by the inhabitants to mitigate potential flood damage.

A flood warning system provides information about the flood arrival and peak water level necessary for flood damage mitigation and rescue measures by fire brigades, private persons and companies. The success of an early flood warning system depends on the availability of forecast models and their input data as well as short information paths (see Figure 14) and clearly and understandably formulated warning messages [5]. A flood warning system is one of the non-structural measures with best cost–benefit ratio. In Europe, there are many flood warning systems in operation but only a few are applied to small and urban catchment areas.

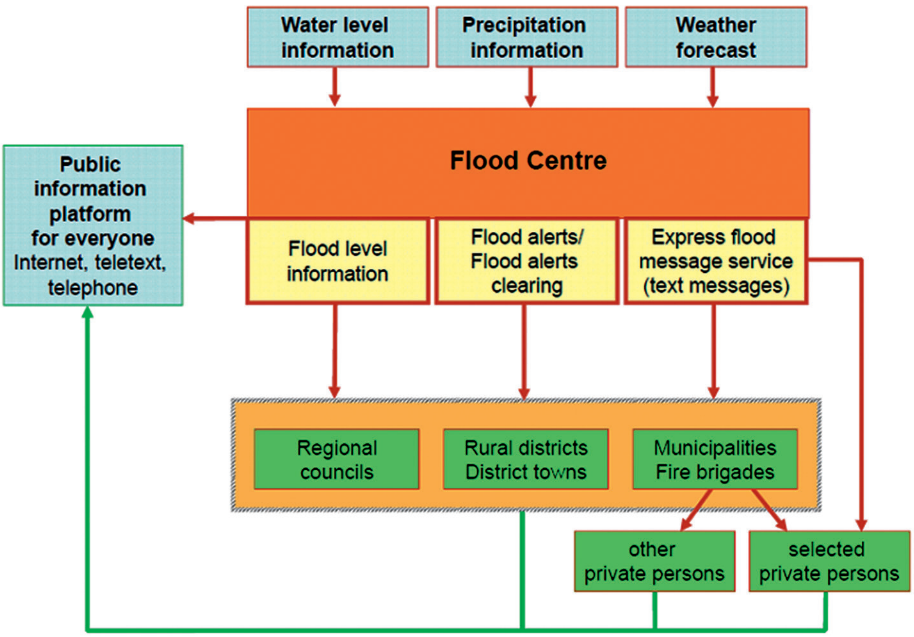


Figure 14. Example for short distribution paths within a centrally organised flood warning system [5]

Note: Flood Centre stands for an organisation which is responsible for the distribution of early flood warning messages

Flood centres are responsible for centralised data collection, running of forecast models and warning messages distribution to all affected entities at the same time. They should be established on a national scale in smaller countries or on the scale of federal states, regions or wider catchment areas in larger countries. It has to be assured that all data transmission to and from the flood centre is uninterrupted.

It is as important to get accurate information about upcoming flood events in small catchment areas as a very fast warning message distribution. In Figure 14 an example of an advanced flood warning system is shown with short information paths and simultaneous warning distribution to local administration, responsible fire brigades or other rescue workers and inhabitants.

In general, flood warning systems are characterised by a discontinuous information path or warning chain. The staff of a flood warning centre have to gather the raw data first and run some checks to eliminate errors from the measurement devices like river discharge gauges or errors due to data transmission or to validate the results of rainfall-runoff models. After that, warning messages are released [5]. In the case of flash floods, this approach shortens the available forecast lead time significantly.

Automatic flood warning systems are today research topics or in the planning stage. Here, the link between the forecasted rainfall and the flood-induced damage is very complex. Automatic warning systems concerning accidents and disasters involving hazardous material are very common. Automatic warning systems concerning rockslides or landslides are in operation lately but operational experiences are still not available. In these cases, damage-inducing processes are directly related to mostly local impacts. We can learn from these systems that automatic warning systems in small (catchment) areas should be highly equipped with different types of sensors to obtain valid data and to provide the opportunity to check released warning messages. In addition, local observers and uninterrupted observation and/or measurement systems can help to compensate for the general lack of knowledge.

The prediction of rainfall in small catchment areas is not exact today. Small catchment areas are often prone to convective rainfall events which are smaller than the spatial resolution of today operational national weather models. Measurement data of rainfall are only local (weather stations) or only qualitative (radar data). Transformation in quantitative areal data needs time and errors can occur. Rainfall data in small catchment areas with no or few rainfall gauges should be improved by information of local observers and installation of additional rainfall gauges.

Flood forecast models including rainfall-runoff calculation are very complex models which need a lot of input data. Inaccuracies in modelling are mainly based on the real-time input data like precipitation or soil moisture. When including river gauge measurements, the amount of input data decreases while the accuracy increases. The flood wave propagation modelling uses hydrodynamic models. These models are more common for rivers with middle and large catchment areas. A short introduction to hydrodynamic numerical modelling is given in section *Modelling floods*.

Short and complete warning message distribution is essential to give the inhabitants of a city or town the vital hours they need to prepare and protect their properties. Action forces have to establish demountable flood protection structures. Rescue workers need this information to prepare the evacuation of flood-prone areas. Short warning dissemination chains are important for the quick warning. Multiple information distribution paths (acoustic devices, TV, radio, Internet) assure that affected as well as concerned inhabitants get all needed information if available.

Weather and flood forecast is characterised by increasing uncertainty considering higher forecast lead time. In a very early state, flood warning messages are often vague and refer only to lower flood water levels which cause no extra precautions. If an event proceeds, higher flood levels are expected but then there is only a very short time to prepare for flood damage mitigation actions. This is why experts often confirm the existence of flood warning messages but inhabitants report that there was no early warning. This is described in the very detailed and extensive report about flood management during the extreme flood event in Saxony in 2010 [14]. That is why it is important to give an honest and understandable description of what kind of information actual forecast models can provide.

Sirens, diaphones or loudspeakers are cost-efficient methods to disseminate warning messages to a local limited set of affected people even if they have no access to public media like TV, radio or internet. In case of flood, people must know what the signal means and what measures are required. To provide more information sirens which can also disseminate voice messages or megaphones are helpful. Additional information (information about proper behaviour, evacuation, development of situation) should be provided by community helpline or TV and radio. Light signals or traffic signs are necessary to block roads or close other public places.

The review of warning systems and documentation of operation experiences was often only triggered by extreme flood events. As intended by the EU Floods Directive and due to the great number of flood events all over in Europe, this improvement process has become more continuous in the last two decades and should go on.

Flood-proof home design

Flood-proof home design was developed in riverine and coastal communities and is very old.

The most obvious form of a flood-proof home is an elevated house (see Figure 15). The flood level does not reach the important components of the building and no damage occurs. The house can be built on stilts, on a raised platform, or on a bank of earth or concrete. This design is more suitable for flood events with low recurrence periods when no other measure is feasible. A disadvantage of this design is the restricted accessibility in case of a flood.

During the “Room for the Rivers” program in the Netherlands farmers living in the Overdiepse Polder were relocated on higher dwelling mounds (so-called terps) which have been newly built against a levee (www.ruimtevoorderivier.nl/river-widening-over-diepse-polder/). Now the farmers and their families are safe in case of a flood event but still have easy access to their farmland in the polder.

New designs and approaches aim at floating houses. These are houses which are normally on land and only float in case of a flood.

Figure 15. Left: Elevated restaurant at St. Peter-Ording at the North Sea coast. Right: elevated houses near the river Elbe (photos taken by the author)

Sometimes it is not possible to protect an urban area by levees, flood walls or demountable flood protection structures. Causes may be that the area is situated in a low lying area and the protection structures would be too high. Or the protection structure is too expensive in relation to the prevented flood-induced damage. In these cases, it is better to improve the design of buildings already situated in flood-prone areas (so-called floodproofing).

Figure 16. Elevated door sill and door flood barrier at Sóller in Mallorca (photo taken by the author)

In case of flash floods with short flooding periods, it is sufficient to elevate the door sill or thresholds or to install a barrier in front of the door (Figure 16). In case of long-lasting floods, the whole building has to be watertight. This includes the walls too. Windows, doors, air-bricks and garage doors have to be flood proof. Non-return valves for all above and below the ground inlet and outlet pipes together with sealing technology for all gaps around pipes and cables entering the property are required.

If it is not possible to keep the water out of the building, measures could be taken to minimise the damage caused by flooding. Solid floors instead of wooden floors minimise damage. It is even better to have tiled floors and walls to make cleaning after the floods easier. There should be no power outlets or heating devices below the expected flood water level. And if any furniture is necessary, it should be fixed and made out of a material that can safely take a soaking.

Modelling floods

In general, the design of flood protection structures like levees and floodwalls are based on the local flood water level for a design flood event. During the planning of flood damage mitigation measures, the assessment of excess water and flood control techniques and technologies is important requiring a cost–benefit analysis. The effect of each measure like a polder has to be quantified in terms of its costs as well as its flood water level reduction effect downstream.

The local flood water level or the flood reduction effect can be calculated by means of hydrodynamic models. In case of unsteady open channel flow, these models are based on the Saint-Venant equations (de Saint Venant 1871). It is a set of partial differential equations which describe the mass and energy conservation.

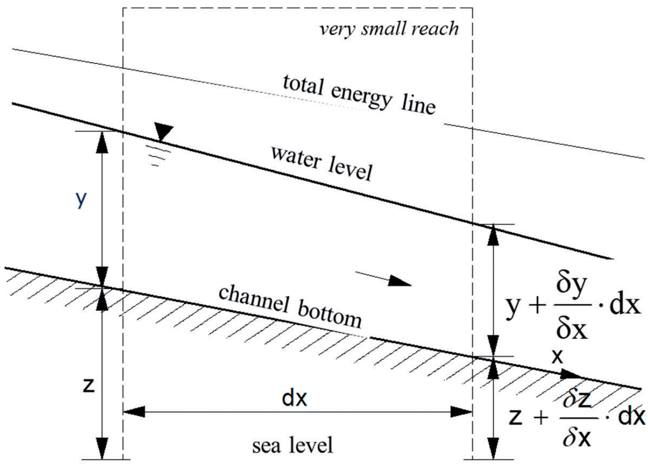


Figure 17. A very small river reach (y – water depth, z – elevation head, x – length coordinate) (compiled by the author)

For a one-dimensional consideration, it is assumed that the difference between the inflow and outflow volume into and out of a very small river reach equals the change in storage dV (see Figure 17):

$$q - \left(q + \frac{\delta q}{\delta x} \cdot dx\right) = \frac{dV}{dt} \tag{9}$$

with q – discharge per m channel width, x – length coordinate, V – water volume and t – time. With the description of dV/dt as

$$\frac{dV}{dt} = \frac{\frac{\delta y}{\delta t} \cdot dt \cdot dx}{dt} \tag{10}$$

the continuity law is derived:

$$\frac{\delta y}{\delta t} + \frac{\delta q}{\delta x} = 0 \tag{11}$$

The equilibrium of forces can be written as:

$$\frac{\Sigma F}{b} = d(\rho \cdot q \cdot v) = \rho \cdot d(q \cdot v) \tag{12}$$

with ρ – the density of water. The following forces should be considered for open channel flow:

The pressure force F_D

$$\frac{F_D}{b} = -\rho \cdot g \cdot y \cdot \frac{\delta y}{\delta x} \cdot dx \tag{13}$$

the gravity force F_g

$$\frac{F_g}{b} = \rho \cdot g \cdot y \cdot \frac{\delta z}{\delta x} \cdot dx \tag{14}$$

and the friction force F_f

$$\frac{F_f}{b} = -\tau_0 \cdot dx = -\rho \cdot g \cdot y \cdot S_f \cdot dx \tag{15}$$

Defining the discharge q per metre channel width as

$$q = y \cdot v \tag{16}$$

and the flow velocity v as

$$v = \frac{dx}{dt} \tag{17}$$

as well as the longitudinal slope of the channel bottom S_0 with

$$S_0 = \frac{\delta z}{\delta x} \tag{18}$$

and if one uses equation 12, 13 and 14 in equation 11 one gets:

$$-\rho \cdot g \cdot y \cdot \frac{\delta y}{\delta x} \cdot dx + \rho \cdot g \cdot y \cdot S_0 \cdot dx - \rho \cdot g \cdot y \cdot S_f \cdot dx = \rho \cdot y \cdot dv \cdot \frac{dx}{dt} \tag{19}$$

Including what the total derivative of v with respect to t gives

$$\frac{dv}{dt} = \frac{\delta v}{\delta x} \cdot v + \frac{\delta v}{\delta t} \tag{20}$$

the energy conservation equation can be derived

$$S_0 - S_f = \frac{v}{g} \cdot \frac{\delta v}{\delta x} + \frac{1}{g} \cdot \frac{\delta v}{\delta t} + \frac{\delta y}{\delta x} \tag{21}$$

As the numerical solution of the equation system (equation 11 and 21) is time-consuming and there is a need for fast models, different simplifications were introduced with regard to different types of flow.

In the case of flood wave propagation which is an unsteady and non-uniform flow all terms should be considered (so-called dynamic wave approach):

$$S_f = S_0 - -\frac{\delta y}{\delta x} - \frac{v}{g} \cdot \frac{\delta v}{\delta x} - \frac{1}{g} \cdot \frac{\delta v}{\delta t} \tag{22}$$

Considering a steady and non-uniform flow, the change of the velocity over the time can be neglected. This can be applied when only focusing on the flow around the flood peak of long flood waves because they can be described as a quasi-steady flow (see sub-section *Flood routing in rivers and floodplains*).

$$S_f = S_0 - -\frac{\delta y}{\delta x} - \frac{v}{g} \cdot \frac{\delta v}{\delta x} \tag{23}$$

A more simple approach is the so-called diffusive wave approach which neglects the change of the velocity along the longitudinal river axis x too:

$$S_f = S_0 - -\frac{\delta y}{\delta x} \tag{24}$$

In case of a steady and uniform flow, there is also no change in the water level along the longitudinal river axis and the energy slope is equal to the bed slope (so-called kinematic wave approach):

$$S_f = S_0 \tag{25}$$

The diffusive wave approach and the kinematic wave approach are often used in rainfall-runoff models. The focus lies here on the description of the runoff generation and the river flow is only described by these simpler wave approaches.

The steady and uniform flow was considered when the Manning's formula (equation 2) was derived. This last statement describes a problem of calculating unsteady and non-uniform flow by means of hydrodynamic models. Most of them use the Manning's coefficient to describe the energy loss caused by water flowing over the river bed or the floodplain. But the Manning's values tabled in the literature (e.g. [8]) came from empirical studies considering uniform and steady channel flow.

Hydrodynamic models can consider flow in one direction along the main channel axis (so-called 1D models). The river and its banks and floodplains are described by different valley cross sections perpendicular to the river axis. The model can calculate the mean flow velocity in the flow cross section and the water level in it.

2D models are more suitable for the flow over a wide surface like a floodplain where the water can flow in different directions. The surface is represented by a mesh containing triangular and/or rectangular cells. The flow is described by a water level for each cell and constant velocity over the water depth. 1D models and 2D models are widely used to calculate flood water level and flood extent.

3D models describe the water flow in a 3D water volume. These models are used to calculate the flow in a reservoir or a tank or around submerged hydraulic structures like sluice gates or turbine propellers. The modelled volume is described by grid cells which can be shaped like tetrahedrons. Structured and non-structured grids are used. The application of these models on flood wave propagation is still a more scientific approach.

To establish a hydrodynamic model the following data are necessary:

- cross sections or topographic information, today often available as high-resolution digital terrain models with a spacing of 1 m, 2 m or 5 m for the flood plain, the river cross section is often derived from additional terrestrial survey data
- information about buildings standing near a river or in the floodplain (e.g. building outlines), buildings create flow obstacles and have to be incorporated into the numerical models
- information about land use and land cover; this can be derived from Orthoimages or is available as polygons (e.g. as shp files) from governmental geographic services
- information about bridges (e.g. height and bridge cross section), weirs (e.g. weir height and width, weir operation in case of a flood)
- hydrologic information like design flood discharge, data from river gauges

Measurement data from a flood event including the water level and the discharge at many locations is necessary in the investigation area as well as information about other flood event characteristics e.g. log jams, bridge clogging, accumulation of floating debris (see Figure 18), heightening of levees using sandbags, levee failure and so on. These data are used to calibrate a hydrodynamic model.

Land use and land cover are represented in hydraulic formulas (equation 2) as well as hydro-numerical models as roughness coefficient [2]. Higher vegetation like riparian woodland is associated with a higher roughness coefficient in a hydro-numerical model. Floating debris which was retained during a flood event e.g. in trees could create additional local roughness elements (Figure 18).

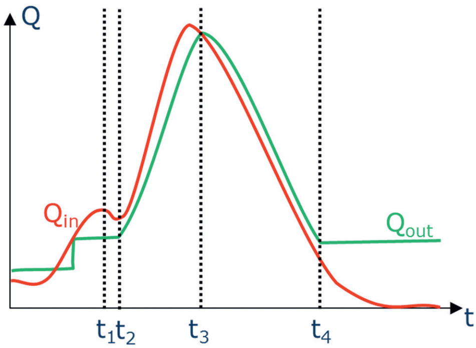
Figure 18. Flood water has deposited all kinds of debris in a tree within a wet woodland (photo taken by the author)

It is also noticeable that vegetation and its influence on flood propagation differ between winter and summer season because vegetation in winter is less dense and/or lower. Hydro-numerical models which were calibrated using a winter flood event may be unfitting in forecasting flood water levels for a summer flood event [13].

Self-study questions

What are the differences between fluvial flooding and pluvial flooding?

You can see below a measured inflow and outflow discharge hydrographs at a dam in case of a flood event. At which time did the maximum reservoir water level occur?



Explain why the calculation of river routing is more complex than calculating reservoir routing and explain appropriate methods for river routing calculation.

What is the hysteresis effect considering flooding?

Describe the flood risk management cycle.

What data are needed to calibrate a hydrodynamic numerical model?

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