

## Land-use change and floods: what do we need most, research or management?

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**Abstract** Land-cover change (urbanisation, deforestation, and cultivation) results in increased flood frequency and severity. Mechanisms include reduced infiltration capacity, lower soil porosity, loss of vegetation, and forest clearing, meaning lower evapotranspiration. Major research challenges lie in *quantification of effects* in terms of flood characteristics under various conditions, ascertaining the *combined effects* of gradual changes over long time periods, and developing *model tools* suitable for land-use management. Large floods during the 1990s gave a new focus on these problems. Reference is made to the Norwegian HYDRA research programme on human impacts on floods and flood damage.

The paper *concludes* that land-use change effects on floods are most pronounced at small scale and for frequent flood magnitudes. Model simulations of effects of land-use change can now be used to reduce flood risk. Modern flood management strategies have abandoned the position that dams and dikes are the only answers to mitigating flood disasters. Today, the strategic approach is more often: *do not keep the water away from the people, keep people away from the water*. Flood management strategies should include flood warnings, efficient communication, risk awareness, civil protection and flood preparedness routines, effective land-use policies, flood risk mapping, ... *as well as* structural measures.

**Keywords** Deforestation; floods; flood management; flood risk; land use; urbanisation

### Setting the stage

There is a perception that land-cover change in the form of urbanisation including road-building, deforestation, and cultivation will result in increased frequency and severity of flooding. The main mechanisms put forward, include:

- reduced infiltration capacity, leading to higher surface runoff;
- lower soil porosity, reducing the water-storing capacity;
- loss of vegetation will mean lower evapotranspiration, thus allowing a greater part of precipitation and snowmelt to run off;
- forest clearing will mean less interception losses, and more intense snowmelt on the ground.

When land-use changes are accompanied with measures intended to speed up runoff, such as gutters and culverts or drainage of wetlands, timing and magnitude of floods will be influenced.

The reality of such effects is not in doubt. The major research challenges today lie in:

- *quantification of the effects* in terms of flood characteristics (volume, peak discharge, frequency etc.) under various conditions (topography, catchment size, climate, type and degree of human impact, etc.);
- ascertaining the *combined effects* of many different gradual changes over a long period of time, distinguishing effects of land-use changes from concurrent climate changes poses a particular challenge;
- developing *model tools* suitable for land-use management.

### Recent focus

Large floods in many parts of the world during the 1990s have given new focus on these

problems. Examples are numerous from e.g. North America, Europe, East and Southeast Asia and Southern Africa. In most instances the question of human impact has been raised. Only two cases will be mentioned here:

In **China**, the flood catastrophes of 1998 in the Yangtze, which killed more than 2,000 people, were caused by a succession of flood peaks, each having a return period of only about 10 years. The cause of the floods was certainly natural, occurring in the mid-monsoon season. However, both deforestation and intensive land development have been called into question for aggravating the catastrophe (Brown and Halweil 1998).

In several Chinese rivers, increased silting of rivers and lakes contributes to inundation, even when streamflow rates are modest. At the city of Kaifeng on the Yellow river for example, the river bottom is now 6 metres above the level of the city. Because of urban spread into former farmland, farmers faced with decreasing areas of available land encroach on the lakes and river beds, thus increasing flood damage vulnerability. Adding to the vulnerability is the practice of designing flood dikes for a return period of only 10–20 years (Yangtze) or 60 years (Yellow River) (US Embassy Beijing 1998, 1999; Verburg 2001).

The Chinese State Council, seeing the connection between deforestation on one side and soil loss and inundations on the other, issued an emergency order in August 1998, calling for an immediate halt to all illegal forestry and a one year moratorium on all conversion of forest land to other purposes. A major five-year reforestation program is intended to reduce soil loss on the upper reaches of the Yangtze and Yellow River and so reduce silting as well as flood risk. In addition, the state timber company work force will be cut by one million workers and wood production will be reduced by 10 million cubic metres. It is easy to understand the difficulties of enforcing such dramatic measures.

In the **USA**, the policy of levees-only, which had dominated since the mid-1800s, was literally washed away in the great 1927 flood on the Mississippi when 50,000 km<sup>2</sup> were flooded, and 700,000 people were displaced (Barry, 1997; Platt, 1995). It was realised that the river could not be contained within levees. Reservoirs have been built on the tributaries, and the river itself has been allowed to spread out in a controlled way. “Nonstructural” floodplain management and “watershed management programmes” are now part of the national policy. Then came the 1993 flood in the Midwest states, causing 12 billion USD of damage, and damaging 100,000 homes. The inter-agency assessment report after the flood concluded i.a. that confining the river system within levees removed enough floodplain to increase downstream flood levels. However: “Levees did not cause the 1993 flood. During large events such as occurred in 1993, levees have minor effects on floodstage, but may have significant localized effects” (Platt 1995). Along the same line, the assessment report concluded that upland wetlands restoration can be effective for smaller floods but diminishes in value as storage capacity is exceeded in larger floods. The theory that the 1993 flooding would have been reduced if more wetlands had been available to store rainfall and runoff, was not supported.

## **Land-use and floods: state of knowledge**

### **Previous studies**

The important role of forests in regulating discharge and protecting soils are well known and acknowledged. Not surprisingly, much of the early research on land-use impacts and floods therefore centered on the impact of forests.

Rodda (1976) summarised the knowledge accumulated during the IHD period (1965–1975), focussing on representative and experimental basins, as well as selected earlier studies. Early studies included the Swiss catchments of Sperbelgraben (largely forested) and Rappengraben (largely pasture), starting in 1927. They showed less

infiltration and lower evapotranspiration from the pasture basin. The very early Wagon Wheel Gap paired basin experiments (Rio Grande) started in 1910. Forest was shown to reduce the magnitude of ordinary seasonal floods, and reduce erosion. Forests also maintain streamflow in dry weather. The effects of climate, soil, and topography different from these early experimental sites, motivated a number of long-term experimental studies in all parts of the world, where also other forms of land-use change than forest felling have been studied. Among later studies, the effects of, for instance, reforestation of farmland, fire, cropping, grazing, urbanisation, and air pollution have been investigated.

The studies made in the Coweeta watershed (North Carolina, USA) have become classical in the investigation of the effects of forestry on streamflow. Results concern, for instance, changes in summer storm runoff after clearing a forested catchment, and letting it first be used for mountain farming, before rehabilitation. Quicker flood rise and higher flood peaks characterised the deforested phase. Not surprising, the flood enhancing effects of clearcutting (peak discharge, time to peak, recession time), are less prominent when the trees felled are left in place.

Substitution of a tropical rainforest with tea plantations gave in one instance a 40-fold increase in flood peak in the early stages of clearing, being reduced to a 4-fold difference after 5–6 years of regrowth (Pereira, 1967; quoted by Rodda, 1976). Early German studies in the Harz Mountains (Liebscher, 1972; quoted by Rodda, 1976) confirmed the yield – and flood modifying role of forests.

The early studies, concentrating on forestry impacts, largely concluded that in well-watered parts of the world, reduced forest cover leads to an increase in runoff. The main mechanisms effecting this change are the higher interception and evapotranspiration of dense forests. Impeded surface flow and higher infiltration in the forest soil due to leaf litter, contribute to reduced flood peaks and total water yield.

Under some conditions, both average annual runoff as well as flood runoff have been reported to be greater from well forested than from less forested areas. In such cases the explanations seem to be related to factors such as forests being located in areas of higher precipitation, and effects of forest age.

#### Recent studies

The early studies on land-use effects mostly concerned agricultural and forested land and changes in the rural environment. Since about 1960 much effort has been extended to include urban hydrology, not least for the purpose of better sewer design. The particular problems of water supply and sanitation in urban areas require particular attention, not least in view of the rapid increase in the urban population world-wide. The growing number and size of the world's megacities pose dramatic problems (not just “challenges”). According to UN estimates, half the world will be living in cities by 2006. The most obvious effect of urbanisation is the increase in impervious surfaces. The urban hydrograph reaches a higher peak in a shorter time than the rural, and it recesses more quickly.

The scientific literature on land-use effects on floods has grown enormously in recent years, and this paper in no way attempts to review the literature extensively. Only a few selected research efforts will be mentioned here.

Modelling of land-use change impacts within the “Floodaware” programme (EU 1998, Dautrebande and Laime) confirms other findings that flood sensitivity to land-use changes, *in casu* replacement of grassland into urban areas or increase in corn crops, diminishes with increasing flood return period (more rare frequency). The explanation given is that during large (less frequent) floods, the surface will be more or less saturated over large parts of the catchment, and act as an impermeable cover. Under such circumstances the effects of local urbanisation or other land-use change will be barely noticeable.

There is a broad consensus that solving flood problems in urban areas must deal with reduction of volume, preferably by increased infiltration (e.g. Rowney *et al.*, 1999).

Studies of near-surface processes indicate significant decrease in infiltration rates and saturated hydraulic conductivity with decreasing vegetation cover: forest tall grass mowed lawn bare ground, (Rahman, 1989).

Drainage of agricultural land and planting of forest on the land of poorer quality, are quite common land-use changes taking place in Europe. Popular views have held that agricultural drainage speeds up the runoff and *increases* peak flows downstream, because of shorter flow paths, and removal of the water storage capacity of former wetlands. On the contrary, there have also been popular beliefs, not least among farmers, that drainage *reduces* peak flows by creating more storage capacity in the ground after lowering of the groundwater table.

In fact, observations show that drainage may *increase or reduce* peak floods, according to soil (e.g. clay content, compaction) and drainage characteristics (e.g. pipe capacity and spacing, decay of drainage ditches, location within catchment). As forest trees start to grow on the drained ground, any initial flood peak increase tend to disappear (Robinson, 1989).

Another interesting observation is that the reduction in peak flow from mature forest is particularly marked for *small* floods, when the interception capacity is not exceeded. During *larger* floods there is little difference between flood peaks from drained forest and undrained grassland.

Recent studies in north-western USA, (23 coniferous forested catchments, 66 years of record, 14–1,600 km<sup>2</sup>), show an apparent increase in flood peaks of logged catchments, relative to control catchments. The explanation given is greater snow accumulation in clear-cut areas compared to canopy interception and subsequent evaporation in the forested phase (Bowling *et al.*, 2000). The magnitude of the peak flood increase decreases with increasing return interval up to about the 10-year return period. For larger return periods, there is no apparent change in flood magnitude, which can be attributed to logging.

The authors have also reviewed previous studies of logging impacts on flood hydrology in the same region, and reports that removal of forest on *plot-scale* can cause substantial increases in both snow accumulation (less interception and ablation), and snowmelt (increased wind speed and heat transfer). On *catchment scale* in the 1–1,000 km<sup>2</sup> range, results are less conclusive. The greatest changes are associated with small catchments and moderate-sized snowmelt flows. For instance, in very small catchments (0.6–1.0 km<sup>2</sup>), peak flow increases of 5–25% have been reported for return periods greater than 2 years. Other studies have found no trend in peak flows following clear-cutting. Explanations given include the “noise” effects of antecedent soil moisture, specific weather patterns and topography, and the effects of forest roads, which may impact in various ways according to road position.

#### **The Norwegian HYDRA research programme**

The late winter of 1995 gave large amounts of snow over south-eastern Norway, about 150% of normal. At the end of May warm weather, accompanied by heavy rainfall led to 100-year floods, and in some locations 200-year floods, in the Glomma basin. This river basin is Norway’s largest, about 42,000 km<sup>2</sup>.

The floods led to material damage at USD 200 million, 700 people were evacuated from their homes, 140 km<sup>2</sup> of farmland were inundated, and one person perished. Just prior to the flood, the Norwegian Water Resources and Energy Directorate had called for a national research programme on floods and flood risk. The working hypothesis was that the sum of human interventions in the form of land-use changes, river regulation for hydropower, flood protection works etc. may have increased flood risk. The spring flood of 1995 in the

Glomma basin undoubtedly triggered the organisation of the HYDRA programme, 1996–2000. The programme involved more than 50 researchers from 17 institutions. The studies concentrated on the Glomma river basin itself, having an ample information base after the 1995 flood, and being of central importance in the economy of the country.

The main results of the HYDRA programme are summed up below.

- Regulation reservoirs built for hydropower production constitute the main human impact on the Glomma floods. The regulation in general aims to save water from the humid summer half-year to generate power during the winter. In the Glomma basin 16% of the normal runoff can be stored in reservoirs. This means that the draw-down is highest just before the spring snowmelt, and consequently so is the flood-reducing potential. The greatest flood-reducing effect in 1995 was achieved in the eastern river branch, with 1 m lower stage at culmination at Elverum, 2.3 m in the downstream lake Øyeren. In the western branch, stage reductions at culmination were 0.4 m at Otta, and 0.4 m in lake Mjøsa, which is Norway's largest lake, surrounded by numerous towns.
- Urbanisation causes increased floods locally, but this impact is almost unmeasurable in the main Glomma river basin, urban areas covering just 0.5% of the total area. The impact of urbanisation was modelled for 25 urban agglomerations within the basin. The average increase in flood volume for these cases was 22% in 1995 compared to the pre-urban state. Another important conclusion is that urbanisation will increase the frequency of floods. Whereas floods in the pre-urban state will be concentrated in the wet period of the year when soil moisture content is naturally high, the urban state will be flood-prone even in the drier part of the year, because of impermeable surfaces. The instantaneous flood peaks in the urban state were in some cases simulated to be 2–3 up to 7–8 times the corresponding pristine condition.
- Today there is growing attention to other sides of the urban water system than optimising sewer design in order to get rid of flood water. Improved infiltration capacities, better use of surface areas for retention of flood water, and the planned use of water in the urban landscape for recreation and aesthetics, are now in the focus of interest.
- Changes in forestry and the state of forests have not led to measurable changes in the Glomma floods over the 1920–1990 period. The forest studies centred on two tributaries, judged to be representative of the forest cover and growth in biomass which has taken place. In one case, annual runoff volumes have been reduced by 0.5%, average spring-flood discharge has been reduced by 0.3%, and autumn rain floods have been reduced by 0.5%. These differences are within data uncertainty limits. Although the forests of the Glomma river basin have become denser in the 1920–1990 period, which would tend to reduce runoff, there has also been a forestry practice of clear-cutting since the 1950s, expected to lead to less transpiration and greater runoff. The total impact is very slight.
- Simulations in small forested tributary catchments, using the LANDPINE distributed model, indicated that complete deforestation from 100 to 0% could increase annual runoff by 150–200 mm, and increase flood peaks by nearly 60%.
- Flood protection works are dikes built along the river to keep water from inundating land areas. Impacts during the 1995 Glomma flood were mainly studied in the Elverum-Kongsvinger area, where the largest flood works are located. For this area, the flood protection works resulted in a water level rise very locally of up to 0.5 m, and a speeding-up of peak time of 10–20 hours along the ca. 100 km reach. Such impacts will obviously be a challenge for flood warning and emergency services. The increase in peak discharge caused by the flood protection works amounted to about 1.5% in the lower end of the protected reach.
- Within the HYDRA programme it was found necessary to improve the methodology for

flood loss assessment, in order to benefit land-use planning, and cost/benefit analysis of flood mitigation measures. The results include:

- standardised damage functions for buildings, roads and railroads, and agricultural areas;
- improved methodology for producing flood zone maps, including use of airborne laser scanning;
- improved regional flood frequency analysis.

The final report of the HYDRA research programme, (Eikenæs *et al.*, 2000) contains complete references to the 60-some scientific reports behind these results.

### **Socio-economy and natural science: vulnerability and hazard**

Which strategies for flood protection are sustainable, fulfilling present needs without compromising future generations to meet their needs? Destructive floods are in themselves a threat to sustainability, so it lies in human nature to protect ourselves from disruption. However, large protective structures like dams and embankments may be criticised for disturbing ecosystems and reducing the options for future generations.

Flood defence in the light of sustainability is now discussed more and more often (e.g. Kundzewicz, 1999; Rowney *et al.*, 1999). There is a growing consensus that as we cannot avoid floods, and as flood protection works never can be fail-safe, softer alternatives implying getting out of harm's way, and controlling flood source mechanisms better are becoming a new paradigm. Economic incentives are part of the new principles, expressed for instance as "risk-taker pays".

A few examples of the new thinking are mentioned here.

- There is a trend today to link hydrologic models of flood behaviour (including effects of land-use change) to the management of catchments, and to decision systems. A recent attempt on European level at this integrated approach is the *European River Flood Occurrence and Total Risk Assessment System*, EUROTAS, now in progress. The *Floodaware* programme 1996–1998 (mentioned above) contributed to a European methodology for flood management and damage mitigation. Another ambitious development is the *European Flood Forecasting System*, EFFS, aiming to deliver daily information about river flow and flood development in European rivers for 4–10 days in advance. There are now examples of simulation tools allowing the operator of a river management system to play interactively with risk situations (weather and streamflow forecasts), technical installations (dams, levees), relations to other actors (rescue authorities, mass media) etc.
- The "Inondabilité" method (France) consists of quantifying the level of flood risk at a certain location, by comparing its level of physical flood hazard with its level of vulnerability, which obviously is a function of land-use. In order to be able to compare the two (risk = hazard × vulnerability), the vulnerability is also expressed in frequency terms, using the concept of "Maximum acceptable risk". Because the economic damage depends on both the duration of overflowing and the water depth, local curves of flow-duration –frequency (QdF) are used, transforming river flow into water stage, (Oberlin *et al.*, 1993; Agences de l'Eau, 1998).
- The Norwegian HYDRA programme mentioned above, has led to a set of recommendations for good flood management:
  - authorities must share flood knowledge with the public;
  - authorities and regulating bodies should take fuller account of the flood-mitigating effects of existing hydropower reservoirs;
  - municipal land-use planning must be based on flood risk information;
  - every flood-prone municipality must develop emergency plans for flooding;



- central authorities and the insurance sector should co-operate to improve insurance systems for flood damage;
- relevant authorities should promote alternative ways of managing urban runoff;
- risk analysis should be included in all flood management;
- research results should actively be incorporated into management practice.

## Conclusions

- Land-use change effects on floods are most pronounced at small scale and for relatively frequent flood magnitudes. However, even in large basins and for less frequent flood events, land-use change is now often called into question as a cause.
- Model simulation of possible effects of land-use change is now realistic, and could be utilised together with flood risk mapping to reduce flood risk. Hydrological models are basic for any integrated management of catchments.
- There is room for a broader scope of water in urban design (improve infiltration to reduce flood damage and subsidence) and landscaping. Reuse and recirculation of urban water will be parts of the solution.
- Modern flood management strategies have abandoned the position that structural measures (dams and dikes) are the only answers to mitigating flood disasters. Structural measures may even create a false feeling of safety. Today, the strategic approaches are more often: *do not keep the water away from the people, keep people away from the water, and the risk-taker should pay.*
- Elements in any modern flood management strategy should be flood warnings, efficient communication networks, maintaining risk awareness, civil protection and flood preparedness routines, effective land-use policies, flood risk mapping etc. *as well as* structural measures.
- Land-use policy and flood risk mapping (risk = vulnerability × hazard) are of particular interest. Flood management should imply “negotiations” in the river catchment/basin context between water volumes/discharges on one side and land-use on the other. Land-use will impact on flood behaviour, and flood behaviour will limit the land-use options.

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