Technical Reports

CENTRO EURO-MEDITERRANEO
PER I CAMBIAMENTI CLIMATICI

ISC – Divisione Impatti sul Suolo e sulle Coste

Final document on the third year, second activity: "General methodologies and hydrological-hydraulic parameters supporting the definition of a climate index for changing flood risk assessment"

Prof. Francesco Macchione*

Ing. Pierfranco Costabile*

Ing. Carmelina Costanzo*

* *LAMPIT (LAboratorio di Modellistica numerica per la Protezione Idraulica del Territorio) – Dipartimento di Difesa del Suolo – University of Calabria*

Centro Euro-Mediterraneo
per i Cambiamenti Climatici
www.cmcc.it

July 2009 ■ TR

Final document on the third year second activity: "General methodologies and hydrological-hydraulic parameters supporting the definition of a climate index for changing flood risk assessment"

Abstract

This report is the final document related to the third year, second activity whose title is: "General methodologies and hydrological-hydraulic parameters supporting the definition of a climate index for changing flood risk assessment".
The purpose of the collaboration between LAMPIT (Department of Soil Defence, University of Calabria) and CMCC is to develop an hydrometeorological chain in order to obtain a reliable tool in the context of flood evolution prediction able to provide quantitative information of practical importance within the civil protection activities.
The LAMPIT contribution to the project concerns the mathematical description of both the generation and propagation of flood events at basin scale. The work here presented has been carried out in close cooperation with dr. Pasquale Schiano and dr. Paola Mercogliano.
In order to embrace the problem as a whole, this report starts from a general overview of the characteristics of climate change according to IPPC evaluations, highlighting the main causes that may induce a variation of flood features (chapter 1). The term "flood" is often generically associated to a number of natural events that significantly differ in terms of phenomenological generation. So it seems necessary to recall in mind a possible main classification of flood phenomena in order to underline the flood type discussed herein and his peculiarities in relation to climate change (chapter 2).
In a catchment-wide perspective there is the need to take into account non-climatic drivers, such as land-use change, in the evaluation of changing flood risk: land cover change within a watershed is recognized as an important factor affecting runoff and it is possible that the transformation of land across the globe could have a greater influence on runoff than climate change; that question is explained in the chapter 3.
Chapter 4 is devoted to the general methodologies developed to evaluate the effects of climate change on runoff. They are mainly based on the interconnection between climate and hydrologic models; some features of each model are also analysed to highlight those aspects useful for the evaluation of climate impact on river flooding that link climate models to hydrological model. In order to better characterize the general methodologies, a number of typical results, presented in the literature, are illustrated in the chapter 5.
The analysis related to the impact of climate change on flood risk is affected by a significant degree of uncertainty; some consideration on the uncertainty sources is presented in the chapter 6. Finally in the chapter 7, the concept of climate elasticity of streamflow, considered to be an important indicator identifying the sensitivity of streamflow to climate change, is presented.

Keywords: Hydrometeorological chains, Flood propagation

JEL Classification:

Address for correspondence:
Prof. Francesco Macchione
Laboratorio LAMPIT
Dipartimento di Difesa del Suolo – Università della Calabria
Ponte P.Bucci – Cubo 42/B
87036, Rende (CS) .
E-mail: f.macchione@unical.it

General methodologies and hydrological-hydraulic parameters supporting the definition of a climate index for changing flood risk assessment

1. General Overview

There is a perception that extreme climatic and hydrological events have become more frequent in recent years, and suggestions that this phenomenon may be due to man-induced global warming. That perception is supported by some scientific evidence, but is still not widely recognised (Robson, 2002).
Scientific evidence about global climate change due to human activity and its consequences began to accumulate during the 1980s. In 1988, the United Nations Environment Programme and the World Meteorological Organization jointly established the Intergovernmental Panel on Climate Change (IPCC). In 1995, the IPCC published its Second Assessment Report (IPCC, 1995), representing scientific input from more than 150 countries, summarizing the most recent information on climate change and the vulnerability of natural and socioeconomic systems. The IPCC concluded that the Earth has already warmed by about 0.3-0.6 ºC over the last century, and projected further increases of 1–3.5 ºC by the year 2100. The 2007 Intergovernmental Panel for Climate Change (IPCC) Fourth Assessment Report (FAR) has concluded that the global average surface air temperature has increased by 0.74 ºC during the 20th Century and is projected to increase by 1.8 to 4.0 ºC by the year 2100, relative to 1990 temperatures (IPCC, 2007).
This projection is based on estimates of future concentrations of greenhouse gases like carbon dioxide, methane, nitrous oxide, water vapor, and sulfate particles in the atmosphere due to human activity. Of special concern is the rapid increase of $CO2$ in the atmosphere due to burning of fossil fuels. Human activities, primarily the burning of fossil fuels and changes in land cover and use, are nowadays believed to be increasing the atmospheric concentrations of greenhouse gases.
Such changes in climate will also have significant impact on local and regional hydrological regimes; in particular it is widely recognized that these predicted temperature changes are expected to cause an intensification of the hydrologic cycle at global and regional scales (Huntington, 2006).
This intensification has the potential to produce changes in the temporal and spatial distribution of precipitation. Changes to the magnitude, character and spatial distribution of extreme rainfall may have serious impacts upon many sectors such as agriculture, industry, transport, power generation, the built environment and ecosystems. As a result it has important implications for existing water resources systems as well as for future water resources planning and management. For instance, under the climate change in recent years, the imbalance between water supply and water demands has been increasing, which has given rise to great attention from both the relevant authorities and the general public to water resources planning programs (Guo et al. 2002). Similarly, changes in many of these sectors will affect hydrology and water resources by altering the flow paths of both surface and groundwater (Ekström et al. 2005). Recent extreme rainfall events have pushed urban structures beyond their design limits (Pagliara et al., 1998) and caused failure of many systems, including fluvial flood defences. A possible increase in the occurrence of such events under climate change may exacerbate these impacts.
Trends in fluvial flooding are more difficult to detect, as changes in factors such as land use, reservoirs, drainage or flood alleviation schemes will impact on the flood regime in addition to changes due to the climate. The hydrological characteristics of a watershed are dependent on a variety of factors, including the regional climate and the degree of development. Changes in either or both of these factors can significantly alter the volume and timing of runoff throughout

the watershed. At the watershed scale, the influence of climate change on runoff can be further exacerbated by increased urban development, as well as other changes in land uses and vegetation. Globally, the urban population increased by 100% throughout the last quarter of the 20th century (Chin, 2006). This trend is expected to continue and nearly all of the population growth in the next 30 years is projected to occur in urban areas. One of the repercussions of this expansion will be the potential for significant impacts on local and regional water resources, thus reducing the resilience of their water supply systems. Land cover change within a watershed is also recognized as an important factor affecting runoff (Chang, 2007), and it is possible that the transformation of land across the globe could have a greater influence on runoff than climate change (Vörösmarty et al. 2000). Furthermore, the variety of streamflow characteristics even in adjacent river catchments caused by small scale changes in geology, pedology and land-cover may complicate the detection of climate change effects.
Global climate changes induced by increases in greenhouse gas concentrations is likely to increase temperatures, change precipitation patterns and probably raise the frequency of extreme events (IPCC, 2001). As increased temperatures will lead to greater amounts of water vapour in the atmosphere and an accelerated global water cycle, it can be expected that river catchment areas will be exposed to a greater risk of flooding.
These changes may have serious impacts on society, e.g. on river deltas because of both sea level rise and an increased occurrence of flooding events. Flooding events may cause enormous economical, social and environmental damage and even loss of lives. Flooding is the most common natural hazard in Europe and is increasingly perceived as a consequence of climate change, despite evidence of periods of more frequent occurrence of floods in the past (Beven, 1993). This perception is, no doubt, fuelled by the fact that Europe is currently experiencing a relatively flood-rich period with a spate of major floods across the continent over the last decade (see figure 1); however, in a number of evaluations, the role of changing land use over time, that may have a fundamental influence on the flood generation mechanisms, is not discussed.
In evaluating the effects of climate warming on the generation of floods, the following questions are relevant (Bronstert et al. 2002):

- Is the observed temperature increase accompanied by an increase in precipitation as well as by the greater frequency and/or increasing magnitude of floods?
- Are there any changes in the characteristics (quantity, intensity, extent) and frequency of extreme precipitation events causing floods?
- Are there any changes in the characteristics of storm runoff generation due to an altered climate?

This necessitates the application of robust and accurate flood estimation procedures to provide a strong basis for investments in flood protection measures with climate change.

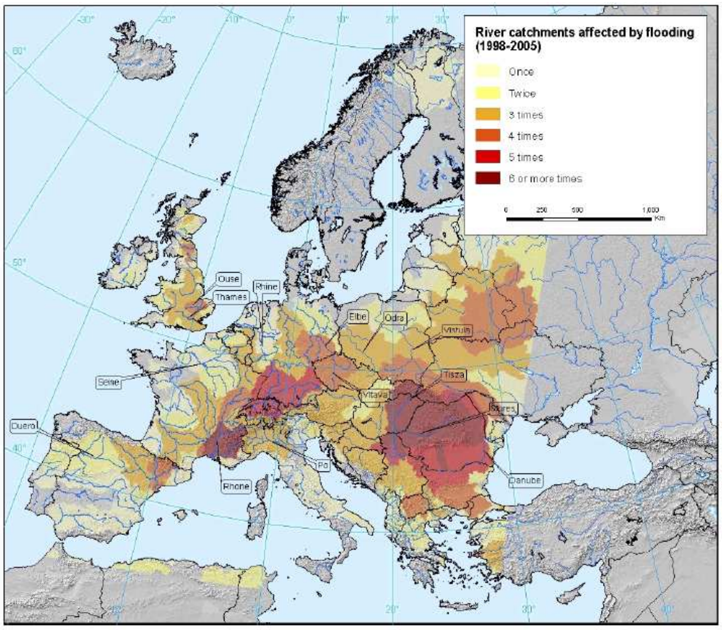

Figure 1. Recurrence of flood events in Europe between 1998 and 2005. *Source:* EEA (2005)

Figure 1. Recurrence of flood events in Europe between 1998 and 2005 (from European Environmental Agency 2005)

2. Types of flood: generation processes

Flood generation processes may be very different. It is useful to differentiate the categories of floods according to the specific flood generation processes involved and to the spatial and temporal scales of the flooding events investigated; it is clear that it is not possible to manage the different situations with the same methodology.
Flooding can take many different forms and the majority of flood occurrences can be classified according to the types described below (Collins & Simons 2007).

River flooding
If the volume of water flowing into the river systems exceeds the capacity of the channels, river flooding will occur. Some floods occur seasonally when winter or spring rains, coupled with melting snows, fill river basins with too much water, too quickly. Unexpected heavy or prolonged rainfall can also produce river flooding. Rainfall saturates the soil, and as a result, an increased proportion of the rain falling flows straight into the watercourses and in turn into tributaries and then the main river channels.

Flash flood
A flash flood can occur anywhere and is the most frequent type of flood. It is caused by very high intensity rainfall over a period of several hours. Under these conditions, the ground is unable to absorb a high proportion of the rain falling and the water simply runs off along the surface. As land is converted from rural to urban usage, it loses its ability to absorb rainfall. Urbanisation can increase water runoff to two to six times above what would be expected to occur on natural terrain. During periods of urban flash flooding, streets can become swift moving rivers, while

basements can become death traps as they fill with water and sewer systems can overload bringing health risks.

Storm Surge

Storm surge is caused by a combination of storm systems and high tides. Storm force winds drive seawater against the coast. When this is coupled with high tides and large waves, huge quantities of water amass along the coastline and can result in large areas of land being flooded. The damage caused by storm surge can be exacerbated by the failure of flood defence mechanisms, such as dikes and levees, which are often erected along large water channels to allow the adjacent land to be used for housing or agricultural purposes. More recently flooding due to storm surge was seen in the USA in 2005 when Hurricane Katrina caused flooding across a wide area, particularly in New Orleans where levees failed.

Dam burst

Large water reservoirs are created by building dams and put the areas lying below them at risk of flooding should a failure of a dam occur. The failure of a dam can occur as a result of high intensity rainfall, landslides, subsidence or defects in the structure's design. For example, recently, in February 2005 five villages were washed away and over 70 people lost their lives when the two year old Shadikor dam burst near Pasni in Pakistan. Another such occurrence was in March 2005 when torrential rains and melting snow caused the Band-e- Sultan dam, which was three years old, burst in south-eastern Afghanistan killing at least six people and causing widespread devastation.

Mudflow

Mudflows or mudslides are caused by heavy rain saturating loose soil on a slope leading to a combination of landslide and flood. Mudflows often occur in combination with flash floods or river flooding. A "lahar" is the name given to a mudflow which occurs on a volcano. Heavy rainfall can result in the ash from a recent eruption being transported downhill as a mudflow. One of the best known examples of a mudflow occurred in Switzerland in 1987 as a result of heavy storms.

Ice Jam

Floating ice can accumulate at a natural or man-made obstruction and ice build ups, called ice jams, can temporarily stop the flow of water. When such ice barriers break up flood waves can be triggered causing flooding downstream. Losses are often avoided as modern technology allows ice jams to be broken up artificially before water accumulates to dangerous levels.

Tsunami

Coastal flooding can also be produced by tsunamis. These are waves produced by earthquakes or volcanic activity on the seabed. Such activity can trigger extremely fast moving waves, which reach shore in the form of enormous breakers. A recent devastating example occurred on 26 December 2004. A magnitude 9.3 earthquake ripped apart the seafloor off the coast of north western Sumatra. This earthquake set off a devastating tsunami that travelled thousands of kilometres across the Indian Ocean.

Groundwater

When the groundwater level is relatively close to the surface, changes in rainfall patterns over a long period of time, extreme rainfall over a short period of time and/or seepage from nearby watercourses can raise the water table. A rise in the water table can lead to basements being damaged by water seepage and the destabilization of building foundations.

An overview of the most common causes of extreme flows around the world are depicted in the figure 2.

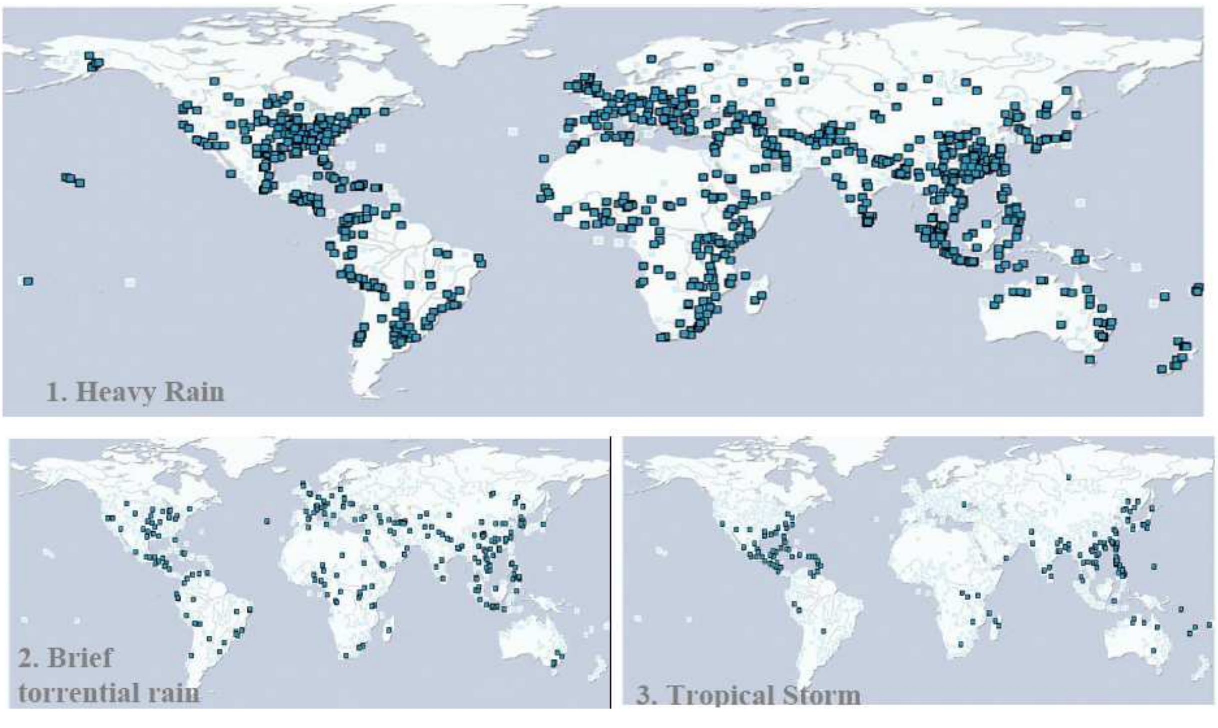

Figure 2. Causes of extreme floods since 1985 (from Few et al. 2004).

It should be note that extensive, long-lasting floods ('plain floods') occur in larger catchments (approximately 1000 km^2 – 300 000 km^2) and are generally caused by rainfall lasting several days or weeks, often associated with the melting of snow and ice and with high antecedent soil saturation. The inundations caused by this category of flooding occur mostly in plain areas when the dykes along the rivers can no longer contain flood discharges. This can lead to flooding over wide areas, as occurred, for example, during the flooding of the rivers Rhine and Maas in December 1993 and in January/February 1995, the flooding of the Oder/Odra in the summer of 1997, and in Yorkshire in autumn 2000 (Bronstert et al. 2002). Local, sudden floods ('flash floods') occur in small catchments (e.g. those of less than 100–1000 km^2) and are mainly caused by intense localized precipitation (e.g. thunderstorms or hurricanes). Flash floods occur primarily in hilly or mountainous areas because of prevailing convective rainfall mechanisms, sometimes intensified by thin soils and high runoff velocities. In general, this type of flood event is short in duration, but is nonetheless frequently connected with severe damage.

3. Effects of land-use change on storm runoff

Prior to focus the attention on the methodologies to analyse the possible connections between climate change and flooding conditions, it is important to observe that in a catchment-wide perspective there is the need to take into account non-climatic drivers, such as land-use change, in the evaluation of changing flood risk. Indeed, land cover change within a watershed is also recognized as an important factor affecting runoff (Chang 2007) and it is possible that the transformation of land across the globe could have a greater influence on runoff than climate change (Vörösmarty et al. 2000).

Both the landscape and the river systems in many parts of the world, in particular in Europe, have undergone major changes in the past, and there is no doubt that these changes have altered storm runoff generation and flooding regimes in these regions.

There are two scale-dependent categories of hydrological and hydraulic processes that may be distinguished (Bronstert et al. 2002): runoff generation in the catchment area, generated either when the infiltration capacity of the land surface is exceeded or when infiltrating rainwater induces a rapid subsurface flow response and/or saturated conditions in the riparian zone, and discharge in the river network.

The hydraulic conditions of the river system are decisive for the transport velocity and discharge rate of water that is not absorbed or retained by the catchment and is thus expelled into the river system. Besides the discharge within the river bed itself, the hydraulic conditions in adjacent flood plains, where a part of the river discharge can be temporarily retained, are considered to be part of the overall discharge conditions as well.

Figure 3 is a schematic flow diagram of the runoff generation and discharge processes discussed above: in particular the runoff generation conditions are mainly included in sections I and II of the figure and discharge conditions can be related to sections III and IV. Human activities and management can alter both runoff generation and discharge conditions. It is evident that activities *within the catchment area* (e.g. agricultural practice, urbanization) mainly influence the former, whereas river engineering and management measures *along the river system* influence the latter.

As stated by Bronstert et al. (2002), only certain flux and storage processes are both affected by land-use changes *and* are primarily relevant for storm runoff generation, namely root zone storage, infiltration-excess overland flow, runoff from urbanized areas, and decentralized retention in the landscape.

Therefore, an evaluation of land-use change impacts on flooding requires identification of the relevant storm runoff generation mechanisms for the specific *catchment characteristics* and *precipitation conditions*. For different categories of rain storms (e.g. convective or advective rain storms), different runoff generation processes can be relevant and contribute in varying proportions to total runoff. This requires that the investigation of storm runoff generation should be both catchment-specific and event-specific. Furthermore, the interactions between precipitation conditions and soil surface conditions (e.g. soil siltation due to high rainfall intensity) have to be taken into account.

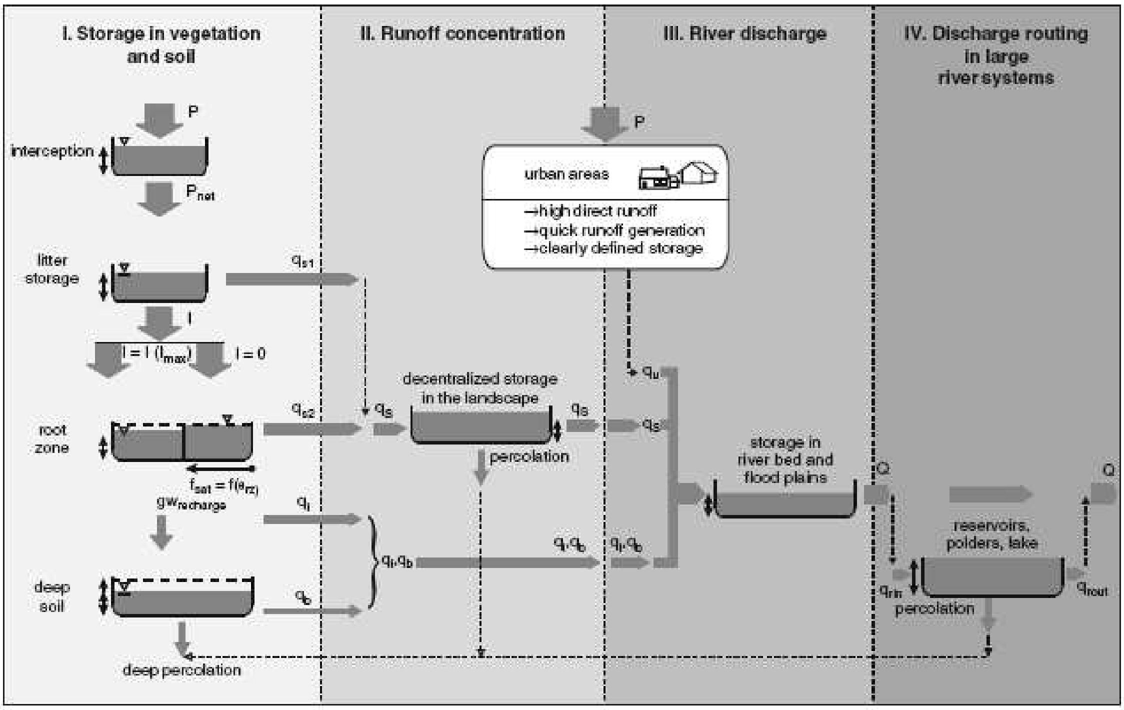

Figura 3 – Flow diagram of the runoff and discharge processes in a catchment. P: precipitation; I: infiltration; Q: river discharge; q_{s1}: surface runoff due to Hortonian overland flow; q_{s2}: surface runoff due to saturation excess; q_i : subsurface stormflow; q_b: groundwater outflow; q_u: runoff from urban areas; q_{rin}: reservoir inflow; q_{rout}: reservoir outflow (from Bronstert et al. 2002)

4. Effects of climate change on runoff: General Methodology

An assessment of the change in the evolution (severity and intensity) of floods calls for analyses that are carried out on scales much finer than global or continental. For such an assessment it is necessary to analyse the changes in hydrological conditions, and especially the characteristics of heavy precipitation, at the regional to local hydrological scale.

Precipitation values for an area of, for example, 500 x 500 km^2 (i.e. one value for 250 000 km^2) cannot supply reliable information on the risk of heavy rainfall in a river basin covering an area even of the order of, for example, 10 000 km^2.

The flood risk analysis under changing climate conditions may be done according to a general methodology that downscales climate model output to the resolution needed for continuous flow simulation and flow frequency estimation

Modelling the influence of land-use and climate changes on flood runoff depends on the magnitude of the rainfall event, the size of the area observed and the scale for which the model was designed, linking climate and hydrological models. Therefore, various techniques have been developed to estimate the climate forcing that drives the hydrological impacts of climate change.

For example, Prudhomme et al. (2003) suggested a main modelling methodology divided into three parts:

- Hydrological simulation is achieved through a conceptual rainfall-runoff model calibrated for each catchment using historical climatic and hydrologic time series;
- Time series of rainfall and potential evaporation for any given time-horizon, for example the 2050s, are constructed from the baseline time series and climate change scenarios expressed as monthly percentage changes in precipitation and potential evaporation;
- The rainfall-runoff model (with the parameters fitted in the first step) is run using the 2050s time series to simulate flow series assumed representative of the 2050s.

Schreider et al. (2000) proposed a methodology to provide the hydrological information needed to estimate changes to flood damage in an urban environments according to the following steps:

- Calibration of the conceptual rainfall-runoff model using historical records of precipitation, temperature and streamflow;
- Testing of the model performance by a so-called validation (or simulation) run;
- Generation of future climatic data series;
- Use of the hypothetical climatic time series as inputs to the rainfall-runoff model in order to produce streamflow discharge and associated stage height data series for the future;
- Estimation of changes in the ARI (Average recurrence interval) for flood events of different magnitudes.

In order to focus the attention on the model interconnections, in the figures 4 and 5 two other methodologies proposed in the literature are shown. The first one refers to a study to quantify the expected impact of climate change hydrology in Irish catchments (Steele-Dunne et al. 2008). In the first stage the HBV-Light hydrology model was calibrated by forcing it with observed precipitation and temperature (P_{ME} - T_{ME}) and comparing the simulated streamflow against observations. The second stage was the validation stage, in which the models have been applied in reproducing the reference period (1961–2000) when forced with simulated precipitation and temperature data ($P_{EC5PAST}$ – $T_{EC5PAST}$) in this period. Finally, the hydrology model was forced with simulated precipitation and temperature data during the future period ($P_{ECFUTURE}$ – $T_{ECFUTURE}$) under a given climate scenario and the expected impacts of climate change on hydrology in the catchments were analyzed. A general circulation model (GCM) was first used to simulate global climate. The resolution of the GCM is on the order of hundreds of kilometers. This was too coarse to capture the fine scale variability in precipitation due to orography and land cover. So, these data were used as boundary condition data to drive a finer resolution Regional Climate Model (RCA3). Comparison of dynamically downscaled precipitation data to gauge data during the reference period revealed biases of up to 78% in mean monthly and annual precipitation. Wood et al. (2004) demonstrate that failure to correct for bias in downscaled climate forcing data can yield implausible results from hydrological models. Experiments found that using uncorrected precipitation data resulted in a bias of up to 50% and 200% in mean winter and summer streamflow respectively. A simple bias correction scheme was therefore necessary to provide a more reasonable validation of streamflow during the reference period.

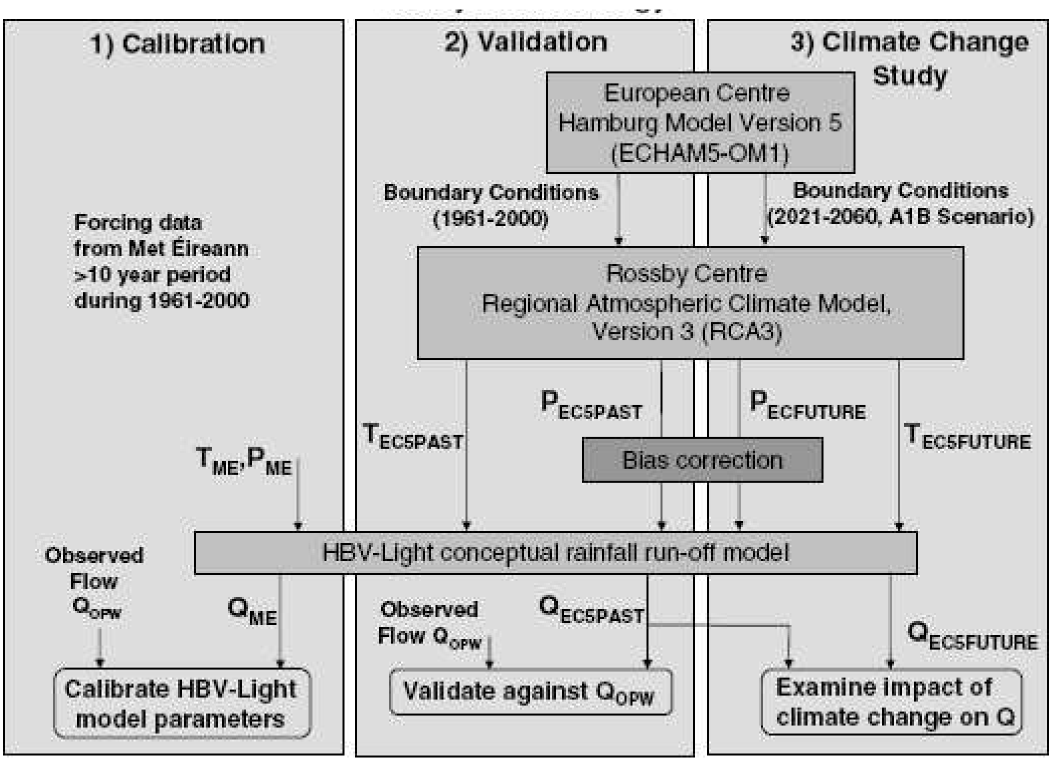

Figura 4 – Conceptual scheme for the evaluation of the effects of climate change on runoff (from Steele-Dunne et al. 2008)

The second one concerns the potential impact of climate change on water systems in Helsinborgs – Sweden (Semademi-Davies et al. 2008). Climate change is simulated for present and future conditions by adjusting the existing high-resolution rainfall series collected by the municipality according to climate change anomalies determined from the output of a regional climate model. Changes in water management and urbanisation are simulated by changing model parameters such as the connected drainage area and the ratio of impervious to permeable surfaces. The combined sewer system was simulated for two 10-year periods corresponding to present (1994–2003) and future conditions (nominally 2081–2090) using the Danish Hydrological Institute (DHI) MOUSE (MOdel of Urban SEwers) model. Storm quick-flow into pipes via inlets is related to the area covered by impervious surfaces. Permeable surfaces are said to contribute to sewer infiltration or slow flow to the pipes. Sewer and pumping station overflows occur when storage in the system is full in much the same way as a linear reservoir model. Surface runoff and pipe flow for the town centre is simulated using the hydrodynamic module (HD) and sewer infiltration using the surface hydrological model MOUSE RDII (Rainfall Dependant Inflow and Infiltration). Nutrient loads (NH4) flowing through the sanitary sewer are modelled using the advection dispersion module (AD).

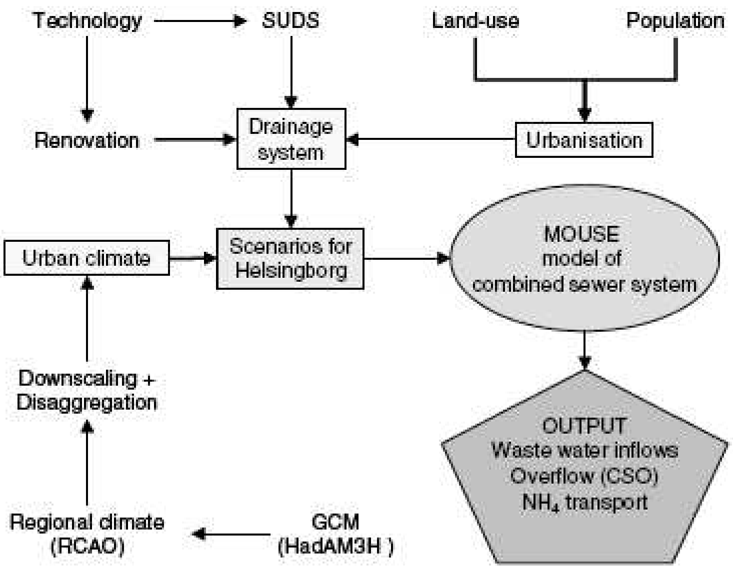

Figura 5 – Conceptual scheme for the evaluation of the Effects of climate change on water systems (from Semademi-Davies et al. 2008)

In the next sections, some general features of the models cascade are described in order to highlight those aspects useful for the evaluation of climate impact on river flooding that link climate models to hydrological model.

4.1 Background on climate models

GCM

Global Climate Models (or GCMs) are tools designed to simulate time series of climate variables for the world, accounting for the effects of the concentration of greenhouse gases in the atmosphere.
Coupled with projections of CO2 emission rates, they produce climate scenarios that can be described as 'pertinent, plausible representations of the future that are consistent with assumptions about future emissions of greenhouse gases (…) and with our understanding of the effect of increased atmospheric concentration of these gases on global climate' (IPCC-TGCIA, 1999).
They are currently the most credible tools available for simulating the response of the global climate system to increasing greenhouse gas concentrations, and provide estimates of climate variables (such as air temperature, precipitation, incoming radiation, vapour pressure, wind speed etc.…) for the whole world. However, it is important to emphasise that they are not predictions. The assumptions behind climate scenarios include future trends in population growth, energy demand, emissions of greenhouse gases and land use change, as well as assumptions about the behaviour of the climate system over long time scales, and in particular the behaviour of the global air surface temperature. Two main parameters are used in GCM modelling: the 'emission scenario', which states what quantities of greenhouse gases (or CO2) are expected to be released in the atmosphere; and the 'climate sensitivity', which is the assumed response of the climate system to a doubling of the 1961–1990 CO2 content in the atmosphere.

GCMs depict the climate using a three dimensional grid over the globe, typically having a horizontal resolution of between 250 and 600 km, and having 10–20 vertical layers in the atmosphere and sometimes as many as 30 layers in the oceans (IPCC-TGCIA, 1999).
In general, most GCMs simulate global and continental scale processes in detail and provide a reasonably accurate representation of the average planetary climate. Over the past decade, the sophistication of such models has increased and their ability to simulate present and past global and continental scale climates has substantially improved. Nevertheless, while GCMs demonstrated significant skill at the continental and hemispherical scales and incorporate a large proportion of the complexity of the global system, they are inherently unable to represent local sub-grid-scale features and dynamics (Wigley et al., 1990).
As for the temporal resolution, the climate change scenarios are most often published at a monthly time-scale, although GCMs usually run at a finer resolution (down to 15 min).
GCMoutputs are therefore generally not considered of a sufficient resolution to be applied directly in hydrological impact studies, and there is a need to derive scenarios with more appropriate scales.
Moreover, GCMs were not designed for climate change impact studies and do not provide a direct estimation of hydrological responses to climate change.
Indeed, in climate change impact studies, hydrological models are needed to simulate sub-grid scale phenomenon. However, such hydrological models require input data (such as precipitation) at similar sub-grid scale, which has to be provided by converting the GCM outputs into at least a reliable daily rainfall series at the selected watershed scale.

Downscaling

As global climate models (GCMs) were originally conceived for the analysis of large-scale circulation systems, they are much too coarse in their spatial resolution to yield usable data for the analysis of floods. Therefore there is a need to derive scenarios with more appropriate scales. This process is usually known as downscaling, with techniques varying from simple algorithms to sophisticated physically based methods (Prudhomme et al., 2002b). They include *dynamical downscaling*, are commonly named Limited-Area-Models or Regional Climate Models (RCMs), that uses complex algorithms at a fine grid-scale (typically of the order of 50-km) describing the atmospheric processes nested within the GCM outputs (e.g. Bates et al. 1998); *statistical downscaling*, that produces future scenarios using statistical relationships between large-scale climate feature and regional characteristics identified from historical records (e.g. Conway and Jones, 1998; Stehlík and Bardóssy, 2002); *stochastic weather generators*, that create sub-daily weather series from a range of summary statistics that could be provided by GCM outputs (e.g. Semenov and Barrow, 1997; Schnur and Lettenmaier, 1998).
It is not clear which one provides the most reliable estimates of daily rainfall time series: no general scientific consensus yet favours one particular technique (Wilby et al., 2002).
Sophisticated methods, such as Regional Climate Models, have the advantage of being physically based. However, while better to describe orographic effects and extreme daily rainfall events than GCMs, they still are very dependant on the signal provided at their boundary conditions, i.e. on the GCM they are nested within—downscaling cannot correct for model inaccuracies. It is not clear how well sub-monthly precipitation series are simulated by RCMs—in particular they are issues to consider when comparing gridded-data against point observation data. Moreover, a serious disadvantage is that the production of scenarios by RCMs is extremely computationally expensive—that disable their use for a rapid assessment.

Statistical downscaling methods generally assume a relationship between GCM atmospheric forcing variables (such as pressure, humidity and wind speed) and station measurements of rainfall (for example: Bardossy and Plate, 1992; Wilby et al., 2003). The relationship often involves a stochastic component allowing for relatively straightforward generation of an ensemble of rainfall series for a particular location under climate change scenarios. However, implicit in the approach is the assumption that the relationship between large-scale forcing variables and local rainfall remains constant under changing climate conditions. Moreover, correlations between atmospheric indicators and climatic variables depend on the period of record used for the analysis, and so their parameters can vary considerably with the period of record used. One of the strengths of statistical downscaling, its ability to be tuned to local conditions with reference to station measurements, may also be a weakness if it is to be applied across large regions (Bell et al. 2007).

Climate change impacts on river flooding: hydrological aspects.

A *quantitative* analysis of the impacts of climate and land-use change on flooding conditions requires simulations of the hydrological system. The models on which the simulations are based must give an adequate representation of the system dynamics *relevant for flood generation*. That means that both the *relevant* internal processes of the climatological–hydrological system and the *relevant* external forces (boundary conditions) must be part of the system to be modelled. This calls for an *integrated (or coupled) approach* of climatological and hydrological model applications. For the analysis of flooding conditions, it is sufficient to realize the integration by means of a one-way-coupling, i.e. the climate model is coupled to the hydrological model by prescribing the climatological forcing of the hydrological model. A two-way coupling (meaning that the climatological model also depends on feedback information from the hydrological model) is not necessary at the temporal and spatial scales that are relevant for flooding analysis (Bronstert et al. 2002).
The appropriate model components have been derived by Booij (2002). The most important processes in the context of climate change impacts on river flooding were found to be precipitation, evapotranspiration, infiltration excess overland flow, saturation excess overland flow, subsurface storm flow, subsurface flow and river flow. The appropriate spatial model scale has been assessed at about 10 km with a corresponding temporal scale of 1 day (Booij, 2003). This appropriate model scale consists of several individual variable scales, e.g. for land use (about 5 km) and for extreme daily precipitation (about 20 km, see Booij, 2002). Surface flow can be modelled with diffusion or kinematic wave-based methods, whereas subsurface flow at a 10–60 km scale can be simulated using simplified equations such as Green–Ampt. Potential evapotranspiration should be preferably calculated using the Penman–Monteith equation or the Priestley–Taylor formulation if not all the data are available. This brief summary of the components of an appropriate model already gives some directives about which kind of model can be used for implementation of these appropriate components.
As regards the choice of a suitable hydrological model, Booij (2005) made a critical review of three main categories of hydrological models. Empirical models are based on mathematical equations which do not take into account the underlying physical processes and therefore are not useful for implementation of the appropriate model components. Physically based models like SHE and IHDM, on the other hand, incorporate physical laws based on the conservation of mass, momentum and energy. The governing equations include a lot of parameters and must be solved numerically. The high amount of parameters may result in different parameter combinations

giving equally good output performances, which is usually labelled as overparameterisation. Besides this overparameterisation effect, physically based models generally incorporate too many processes and too complex formulations at a too detailed scale in the context of climate change and river flooding as revealed by the appropriate components found. Therefore, Booij (2005) suggested the use of conceptual models. Conceptual models are usually able to capture the dominating hydrological processes at the appropriate scale with accompanying formulations. The conceptual models can therefore be considered as a nice compromise between the need for simplicity on the one hand and the need for a firm physical basis on the other hand. In particular, on the basis of an intercomparison between hydrological models, Booij (2005) suggested the use of HBV model of the Swedish Meteorological and Hydrological Institute for implementation of the appropriate model concepts and for subsequently assessing the impact of climate change on river flooding. The dominating processes precipitation, evapotranspiration, subsurface flow and river flow are represented in the model, several sub-basins can be created to obtain the appropriate spatial scale and simulations can be done with different time steps. Surface flow is simulated by storage routing (overland flow) and a modified version of Muskingum's equations (river flow) implying a kinematic or diffusion wave type approach is used.

Another important model used in the climate change impact is the SWAT approach. This is a continuous, physically based, semi-distributed hydrology model first created by the US Department of Agriculture (USDA) and the Texas Experimental Station (TES) in the early 1990s. It was created primarily to determine the effects of climate and land management on hydrology, to measure water quality, and to emphasize continuous time simulation (Arnold and Fohrer 2005).

In a recent paper, Franczyk and Chang (2009) uses the AVSWAT-X model to analyse the effects of climate change and urbanisation in a USA basin. AVSWAT-X is similar to the previous SWAT models, but is entirely contained in the ArcView 3.x graphical user interface. It operates on a daily time-step and can model long-term hydrologic changes using different climate and land-use scenarios (Wang *et al*., 2008). The simulation of the watershed's hydrological cycle is divided into two categories: the land phase and the water or routing phase. The land phase describes the movement of water, nutrients, pesticides, and sediments throughout the sub-watersheds (based on hydrologic response unit - HRU) to their main channel. The water, or routing, phase characterizes how water moves through the water channel system. Figure 6 shows the procedure used by AVSWAT-X to model runoff. That figure is also useful because recall in mind the complex hydrological-hydraulic processes that should be modelled.

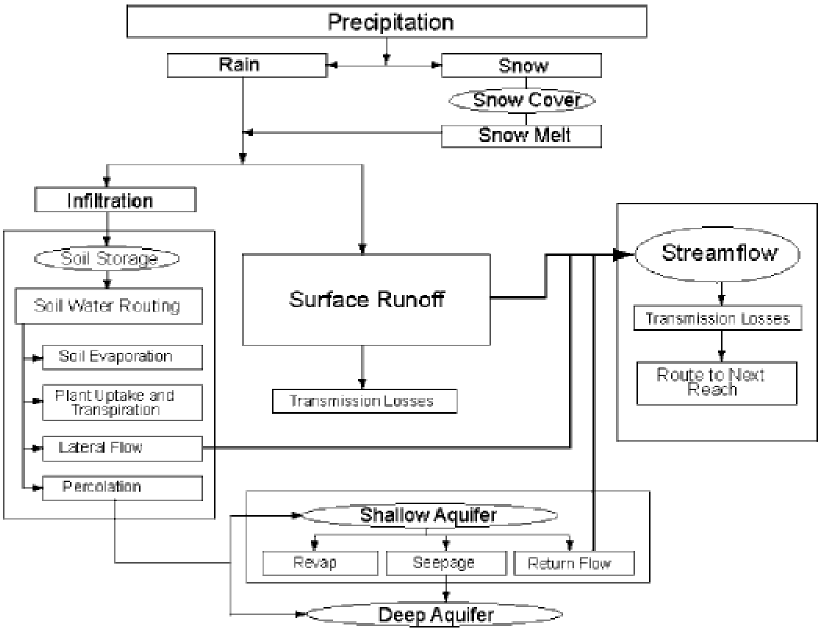

Figure 6. Procedure used by AVSWAT to model ruonoff. (from Franczyk and Chang 2009)

5. Typical results

In order to better understand the main steps of the methodologies mentioned in the previous sections, in this paragraph examples of typical results obtained by other authors are shown. In Wang et al. (2006), with reference to Suir river catchment (Ireland), the HBV hydrological model has been firstly calibrated (figure 7) by using the observed precipitation in the year 1960-1964 as input and then validated (figure 8) using the dynamically downscaled precipitation obtained by atmospheric data from ECMWF 40-year reanalysis project (ERA-40) to run the Rossby Centre Regional Atmospheric Model (RCA).

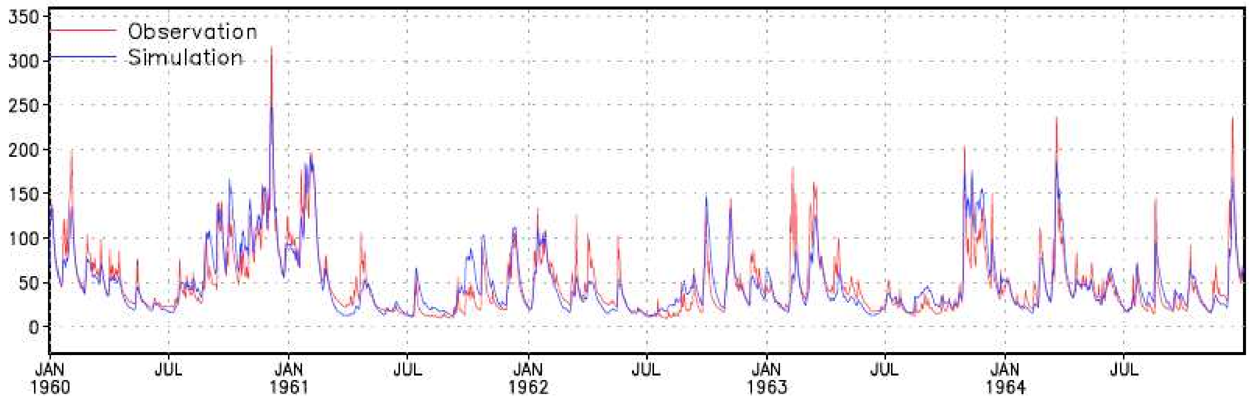

Figure 7. Observed and simulated (using observed precipitation as input) discharge [m^3/s] (from Wang et al. 2006)

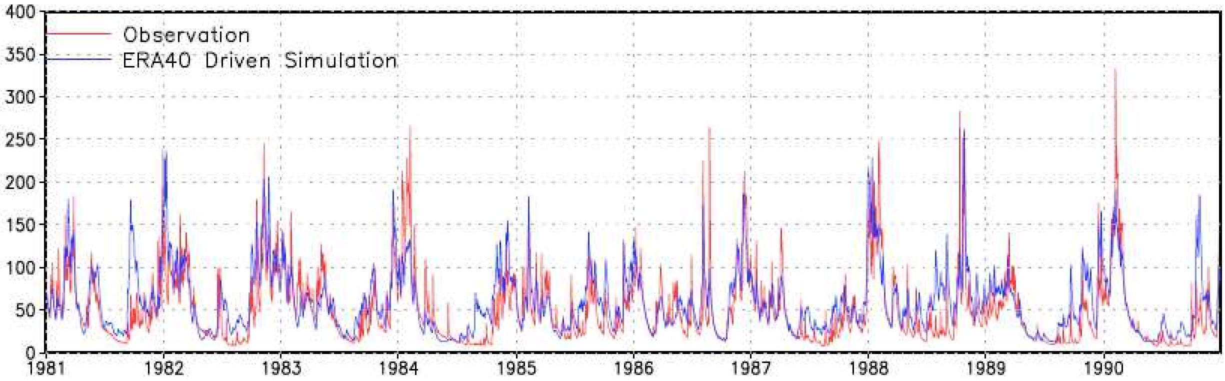

Figure 8. Observed and simulated (ERA-40 driven simulation) discharge [m^3/s] (from Wang et al. 2006)

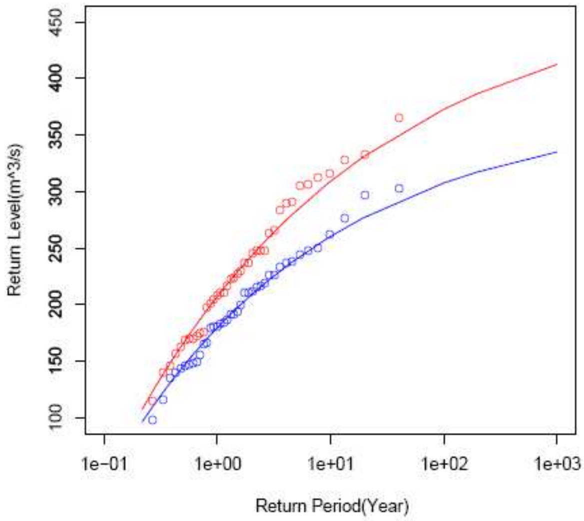

Figure 9. Return values of observed (red) and simulated (ERA-40 driven simulation) (blue) maximum annual discharge (Circles: Values of maximum daily discharge per year, lines: Fit using generalized extreme value distribution). (from Wang et al. 2006.)

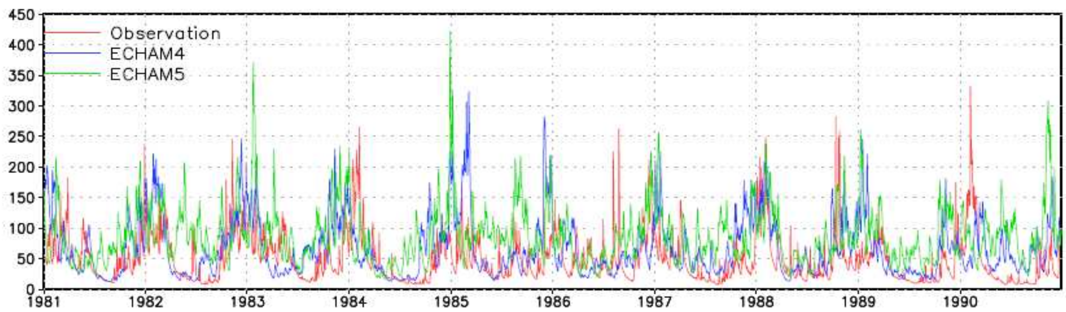

Figure 10. Simulated discharge using the ECHAM4 and ECHAM5 driven RCA simulation and observed discharge [m^3/s] (from Wang et al. 2006)

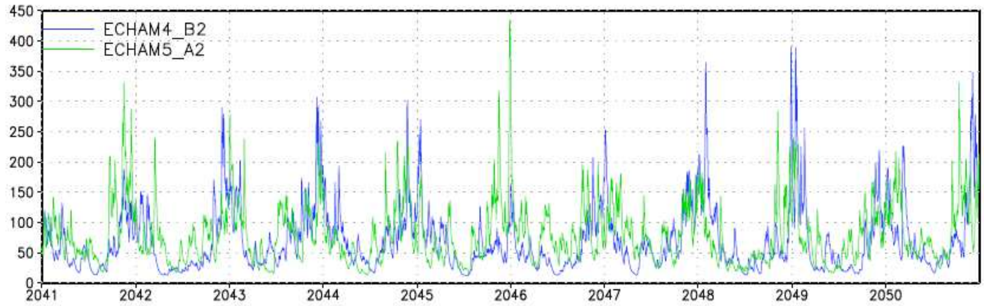

Figure 11. Simulated discharge using the ECHAM4 and ECHAM5 driven RCA simulation for future [m^3/s] (from Wang et al. 2006)

By means of the generalized extreme value method (GEV), the authors computed the return values of the maximum daily discharge using both observed and simulated data (figure 9). To investigate the effect of the climate change under different climate scenarios, the control climate is firstly evaluated. Figure 10 shows the simulated discharge using two different GCM's (ECHAM4 and ECHAM 5) driven RCA simulation data to drive HBV model. As for ERA-40 driven simulation, the results for the period 1981-1990 are shown while in the figure 11 and 12 the simulated discharge for the future and the return values of the simulated maximum annual discharge are respectively depicted. In particular, in the figure 12, the return value analysis shows that the intensity and frequency of heavy discharge events clearly increases according to the ECHAM4-B2 scenario, whereas a weak decrease can be seen in the ECHAM5-A2 scenario. As noted by the authors, there is still large uncertainty in the global climate projections, which are probably mainly connected with the GCM formulation and not so much with the chosen emission scenario.
Some aspects related to the source of uncertainty are summarized in the next chapter.

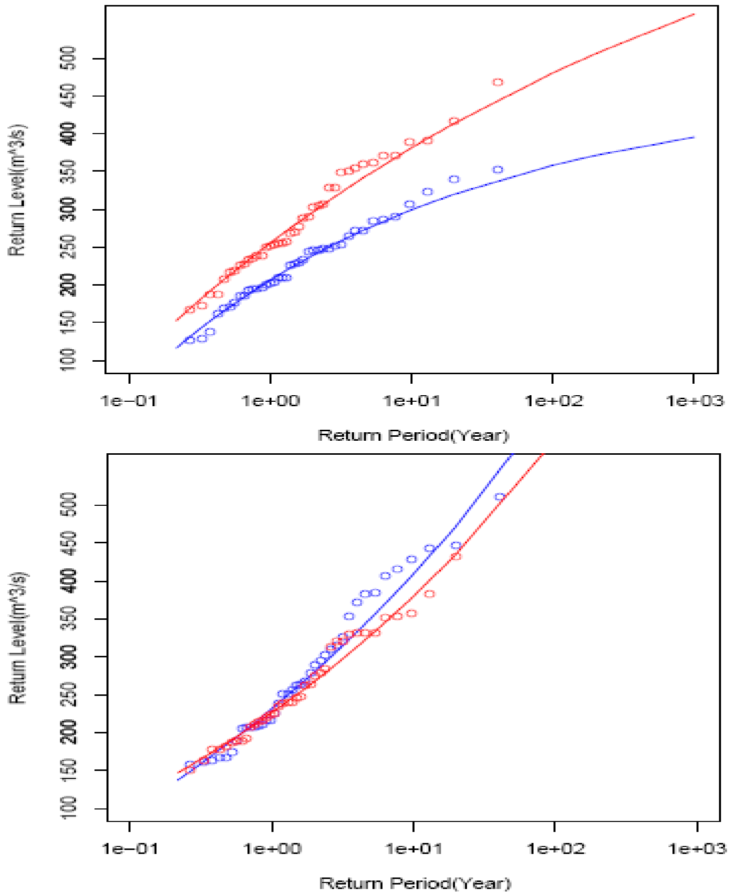

Figure 12. Return values of the simulated maximum annual discharge using the ECHAM4 **(a)** and ECHAM5 **(b)** driven RCA simulation for the present-day (blue) and future climate (red).

6. Uncertainty in the impact of climate change on the river flow

Quantification of impacts on water resources requires modelling at the catchment scale, characterised by two types of uncertainty. The first concerns the difference of scale between modelled climate and that of the flow-generating processes. In addition to some of the physical underlying processes of precipitation not captured at a coarse spatial scale, simulated rainfall intensities as produced by the GCMs are spatially smoothed: for example leeward and windward orographically enhanced rainfall totals are not distinguished (topography is described by the average elevation of each cell within GCMs) and localised short-lived intense convective storms are not differentiated from medium-intensity frontal events (Prudhomme and Davies 2009a).
In terms of flow-generating processes, however, extreme or moderate rainfall events generate different peak flows and thus the direct use of GCM outputs can result in biased hydrological simulations. Techniques that ‘downscale’ the results of GCM integrations to the temporal and spatial scales appropriate for climate change impact assessments have been developed to overcome these limitations, but their skills are variable. For example, Kay et al. (2006) found that the Hadley Centre Regional Climate Model (RCM), typical of the dynamical downscaling method, produced rainfall scenarios appropriate for flood modelling in the UK, while Booij

(2002) found large differences between the 20-year return period precipitation derived from two RCMs driven from modelled and observed data in the Meuse basin
The second type of uncertainty regards the structure and parameters of the hydrological model. Except in a few examples (e.g. Booij 2005; Cameron 2006;Wilby 2005; Wilby and Harris 2006), hydrological uncertainty is often ignored in impact studies because it is assumed that the size of this uncertainty remains the same in the future (Prudhomme et al. 2003). However, Dibike and Coulibaly (2005) found that using the same downscaled series with different hydrological models leads to different changes in mean river flow magnitude.
Prudhomme and Davies (2009b) suggested a number of steps for a robust assessment of climate change impact on river flow. First of all, the use of different GCMs is particularly recommended as well as the use of various downscaling techniques as they can lead to different magnitudes of changes. Then the evaluation of future variability has to be carried out using many time series representative of future projections with the same assumptions (GCM/downscaling/emission scenario combinations) as inputs to the catchment hydrological model. The next steps is assessing the significance of changes by comparing the confidence interval of future projections with the confidence interval of the baseline; that's because changes within baseline variability could occur within a stationary climate and cannot be attributed solely to climatic change. The confidence intervals have to be built from multiple runs representative of different climate change assumptions (GCM, downscaling techniques and emission scenarios). These confidence interval incorporate together both climate variability and climate change uncertainty. Finally the combined climate variability and hydrological uncertainty (due to model parameters and model structure) have to be considered, mainly for catchments where baseline hydrological modelling uncertainty leads to larger flow variations than variation in GCM climate alone.

7. Climate elasticity of streamflow

In this paragraph the attention is focused on a particular climate index called climate elasticity that may be useful in the assessment of climate change impacts on river flooding.
Climate elasticity of streamflow is considered to be an important indicator identifying the sensitivity of streamflow to climate change (Dooge et al. 1999; Sankarasubramanian et al. 2001).

For catchment with streamflow that is not subject to regulation or diversion, the streamflow can be modeled as a function of climatic variables and catchment characteristics:

$$Q = f\left(P, E_0, V\right) \tag{1}$$

where Q is streamflow; P and E_0 are precipitation and potential evapotranspiration, respectively, representing dominant climate factors on hydrological cycle; and V is a factor that represents the integrated effects of catchment characteristics on streamflow. Following equation (1), changes in streamflow due to changing climate and catchment characteristics can be approximated as

$$\Delta Q = f_p^{'}\Delta P + f_{E_0}^{'}\Delta E_0 + f_V^{'}\Delta V \tag{2}$$

where ΔQ, ΔP, ΔE_0, and ΔV are changes in streamflow, precipitation, potential evapotranspiration, and catchment characteristics, respectively, with:

$$f_p^{'} = \frac{\partial Q}{\partial P}; f_{E_0}^{'} = \frac{\partial Q}{\partial E_0}; f_V^{'} = \frac{\partial Q}{\partial V} \quad (3a,3b,3c)$$

In terms of climate change, the potential evapotranspiration instead of temperature is considered herein because potential evapotranspiration better represents effects of climate change on water balance and because it integrates the effects of temperature, wind speed, solar radiation, sunshine duration, and vapor pressure.

On the assumption that the land surface factors are independent of the climate factors, equation (2) can be arranged as:

$$\begin{aligned} \Delta Q &= \Delta Q_c + \Delta Q_v \\ \Delta Q_c &= f_p^{'} \Delta P + f_{E_0}^{'} \Delta E_0 \\ \Delta Q_v &= f_V^{'} \Delta V \end{aligned} \quad (4a,4b,4c)$$

The climate elasticity of streamflow (ε) is defined by the proportional change in streamflow (Q) divided by the proportional change in a climatic variable such as precipitation or potential evapotranspiration (X) and is expressed as

$$\varepsilon = \frac{dQ/Q}{dX/X} = \frac{dQ}{dX}\frac{X}{Q} \quad (5)$$

Thus, equation (4b) can be rewritten as

$$\Delta Q_c = \left(\varepsilon_P \Delta P / P + \varepsilon_{E_0} \Delta E_0 / E_0\right) Q \quad (6)$$

where ε_P and ε_0 are elasticity of streamflow with respect to precipitation and potential evapotranspiration. Is is clear that:

$$\varepsilon_p = f_P^{'} \frac{P}{Q}; \ \varepsilon_{E_0} = f_{E_0}^{'} \frac{E_0}{Q} \quad (7)$$

If the relationship between streamflow and precipitation and potential evapotranspiration is known, the climate elasticity can be derived mathematically. For example, if it is assumed that $Q= aP^b$, it can be shown that b is the precipitation elasticity of streamflow.

The climate elasticity can be estimated in different ways. The model-based approach uses a hydrological model to estimate changes in streamflow with varying climatic inputs. The approach may be physically sound but requires major efforts on model calibration and can lead to remarkably different results because of uncertainty in model structure and parameter estimation (Nash and Gleick, 1991; Vogel et al., 1999a) . In contrast, the nonparametric approach directly uses observed long-term meteorological and hydrological data to identify the response of streamflow to climate changes (Risbey and Entekhabi, 1996). In particular, in Zheng et al. (2009) some expressions of precipitation elasticity of streamflow as a function of the aridity index (evapotranspiration over precipitation) have been shown. In this report the details about the evaluation of climate elasticity by means of model-based or nonparametric approach is not reported; for further information one may refer to Fu et al. (2007) and Zheng et al. (2009). One of the conclusion of the latter work was that streamflow is more sensitive to precipitation than to potential evapotranspiration; however the authors underlined two important aspects: land use and land cover change play a more important role (> 70%) than climate change (<30%); significant uncertainties of the results exists.

Concluding Remarks

For the recent global warming of the twentieth century no general and coherent trends could be observed with regard to increases in annual maximum flows (Kundzewicz et al. 2004). There is an emerging mismatch, or 'conceptual controversy', between modelled increases in future flood risk (inferred largely from precipitation) and the lack of robust trends in observed peak river flows worldwide (Wilby et al. 2008).

For great events, i.e.,100-year floods, however, an increasing risk was detected in 29 basins larger than 20,000 km^2 by Milly et al. (2002). In spite of major uncertainties, there are some studies which claim an increase of major flooding probability for future warming (Kundzewicz and Schellnhuber 2004; Milly et al. 2002). Other studies show similar results with a rather heterogeneous geographical distribution of changes in flooding probabilities (Arnell 1999; Arora and Boer 2001). Yet, in some highly vulnerable regions a significant increase of flooding probabilities has been found under global warming, e.g., for Bangladesh (Mirza 2002), central Asia and eastern China (Arnell 1999). All of these studies are restricted to climate change induced shifts in flooding probabilities and do not take into account other major factors relevant for changes in flooding intensities and frequencies. These factors include land-use changes, modification of streamflows by various water-management schemes like dams or dykes, or, when it comes to the actual damages, the relocation of infrastructure or settlements. On the one hand, this makes assessments easier, but on the other hand it might give unreliable or biased results (Kleinen and Petschel-Held 2007).

Modelling the influence of land-use and climate changes on flood runoff depends on the magnitude of the rainfall event, the size of the area observed and the scale for which the model was designed, linking climate and hydrological models In this context, some requirements for climate modelling may be stated.

The most powerful climate models today are coupled global atmosphere–ocean circulation models (GCMs), which carry out three-dimensional calculations of the equations for mass and energy transport, impulse, humidity of the atmosphere and salt content (in the ocean) for the entire globe. However an assessment of possible changes of flood characteristics resulting from climate change requires models that give reliable information on much smaller scales than the global or continental scale. A realistic description of changes in precipitation is required. This includes both changes of the average value and of the statistical features in space and time. Scenarios that only give changes of the average value are hardly sufficient for the analysis of climate change impacts on flooding conditions. This is particularly important for catchments where floods can be composed of both rainfall and snowmelt events, which is the case, for example, in many central and northern European catchments. Information about the uncertainty associated with the climate scenarios seems to be necessary. This may form the basis for a thorough uncertainty analysis of the coupled simulations of climate and flood hydrology.

A variety of techniques have been developed to derive the climate forcing required for assessing the

hydrological, basin-wide impacts of climate change. The most important of these are regional climate models (RCMs) and statistical downscaling. The climatic conditions at the boundaries of the regional sections are predetermined by the results from GCMs. Compared with a GCM resolution, the spatial resolution of an RCM is definitely more adequate for the estimation of flood-relevant precipitation, particularly with regard to weather conditions connected with large-scale precipitation fields. However, to obtain accurate information on the location, quantity and intensity of precipitation (necessary for the analysis of flood generation processes) and on changes in precipitation characteristics resulting from global climate change, the models are not sufficiently spatially detailed and accurate for a number of reasons.

The boundary conditions of the regional model are obtained from the GCM, and thus frequently contain a systematic error of atmospheric dynamics, which is transferred to the respective region. Errors in the GCM thus directly limit the capacity of the RCM. The resolution of the RCMs is sufficiently detailed to represent large-scale precipitation patterns. However, these resolutions are not yet sufficient to cover small-scale precipitation, such as convective thunderstorms of local orographic rainfall. Flooding is triggered by extreme precipitation. However, the climate models have not yet been sufficiently tested with regard to how realistically they represent such extremes.

Some requirements for hydrological models may be also stated. Analysis of land-use change impacts calls for hydrological models that include the relevant runoff generation processes. The requirements for hydrological models refer to the representation of the soil zone, the spatial distribution and the temporal resolution, the analysis of the correct scale. The behaviour of the soil surface and the unsaturated zone is regarded as crucial for the quick rainfall-runoff process. Models that lump different runoff generation processes are not advisable, in particular if land-use change effects are investigated, which may influence the development of a particular process.

The model applied should operate in a spatially distributed manner, with approximately the same resolution as that used for representing the climatic and catchment conditions. A distributed approach is essential if the flood generation processes are highly variable in space, especially if this variability can be attributed to soil and vegetation characteristics. This is typically the case if, for example, Hortonian overland flow contributes significantly to flood generation. A distributed approach is also required if land-use change impacts are to be analysed in their actual spatial appearance.

If rainfall intensity is relevant for flood generation, this should be reflected in the temporal resolution of both the meteorological data and the modelling time step. This is typically the case in small catchments and/or if Hortonian overland flow contributes significantly to flood generation.

The transformation from rainfall to runoff is highly non-linear and, as a result, scale dependent. Modelling the influence of land-use and climate changes on flood runoff depends on the magnitude of the rainfall event, the size of the area observed and the scale for which the model was designed.

Two flood indicators may be considered:

- Severity of flood events. Described by the change in the magnitude of flood events of a fixed return period.
- Frequency of flood events. Described by the change in the return period (i.e. frequency of occurrence) of a flood event of fixed magnitude.

From the literature, the analysis of potential changes in the flood regime shows that there may be a large variation of results when considering a range of climate change scenarios as input data to the hydrological modelling. From these results, one can conclude that it is difficult, and perhaps speculative, to summarise potential changes in flood magnitude with only a single index, as it would only be representative of a single scenario or set of scenarios at most (Prudhomme et al. 2003). Rather, it is important to display a range of values within which the real estimate is likely to reside. Perhaps arguably, the median of changes is a good indicator of the potential changes estimated by a single GCM when run a large number of times.

On the other hand, no particular GCM has been presented as being significantly better at simulating the climate than any other. In these conditions, and until more credibility is associated with one (or several) GCM, results from any single model should not be considered in isolation, but should be compared with results from other GCMs. Careful examination of the climate scenarios, including querying results with the climate modellers, could help the analysis and ensure that the final assessments are representative for the region/time horizon considered. The greatest differences in the various scenarios considered was found to be due to the GCM, different GCMs producing different monthly climate simulations. This reflects more uncertainty in the final results due to the GCM used than to emissions scenarios or climate sensitivity.

It must be remembered, however, that futurology is a dangerous game in that a scenario is a picture of a possible future rather than a prediction. Decision makers and the methodologies they use (e.g., the design-storm concept) require certainty: yet scenarios are inherently uncertain and require some “degree of crystal-ball gazing” (Semademi-Davies et al. 2008).

As a general conclusion, it seems very adequate the observation of Few et al. (2004): “It is perhaps premature and misleading to attempt to produce a future flood risk map, but it is apparent that some areas at least are highly likely to experience more intense or frequent flood events over the next 100 years(…)”.

References

Arnell, N.W. (1999). "Climate change and global water resources". *Global Environmental Change*, Elsevier, 9(S1): S31–S49.

Arnold, J.G., Fohrer, N. (2005). "SVAT2000: current capabilities and research opportunities in applied watershed modelling". *Hydrological Processes*, Wiley, 19: 563-572.

Arora, V.K, Boer, G.J. (2001). "Effects of simulated climate change on the hydrology of major river basins". *Journal of Geophysical Research*, 106(D4): 3335–3348.

Bardóssy, A., Plate, E.J. (1992). "Space-time model for daily rainfall using atmospheric circulation patterns". *Water Resources Research*, 28: 1247-159.

Bates. B.C., Charles, S.P., Highes, J.P. (1998). "Stochastic downscaling of numerical climate model simulations". *Environmental Modelling & Software*. 13 (3-4): 325-331.

Bell, V.A., Kay, A.L., Jones, R.G., Moore, R. J. (2007). "Use of a grid-based hydrological model and regional climate model outputs to assess changing flood risk". *International Journal of Climatology*, 27: 1657-1671.

Beven, K. J. (1993). "Riverine flooding in a warmer Britain". *The Geographical Journal*, 159: 157-161.

Booij, M. J. (2002). "Extreme daily precipitation in Western Europe with climate change at appropriate spatial scale". *International Journal of Climatology*, 22: 69-85.

Booij, M. J. (2003). "Determination and integration of appropriate spatial scales for river basin". *Hydrological Processes*, Wiley, 17: 2581-2598.

Booij, M. J. (2005). "Impact of climate change on river flooding assessed with different spatial model resolutions". *Journal of Hydrology*, Elsevier, 303: 176-198.

Bronstert, A., Niehoff, D., Bürger G. (2002). "Effects of climate and land-use change on storm runoff generation: present knowledge and modelling capabilities". *Hydrological Processes*, Wiley, 16:509-529.

Cameron, D. (2006). "An application of the UKCIP02 climate change scenarios to flood estimation
by continuous simulation for a gauged catchment in the northeast of Scotland, UK (with uncertainty)". *Journal of Hydrology*, Elsevier, 328: 212–226.

Chang, H. (2007). "Comparative streamflow characteristics in urbanizing basins in the Portland Metropolitan Area, Oregon, USA". *Hydrological Processes*, Wiley, 21(2): 211-222.

Chin, A. (2006). "Urban transformation of river landscape in a global context". *Geomorphology*, 79: 460-487.

Collins, E., Simpson, L. (2007). "The impact of climate change on insuring flood risk". Institute of Actuaries of Australia Biennial Convention 23-26 September 2007 Christchurch, New Zealand.

Conway, D., Jones, P.D. (1998). "The use of weather types and air flow indices for GCM downscaling". *Journal of Hydrology*, Elsevier, 212-213 (1-4): 348-361.

Dibike, Y. B., Coulibaly, P. (2005). "Hydrological impact of climate change in the Saguenay watershed: comparison of downscaling methods and hydrological models." *Journal of Hydrology*, Elsevier, 307: 145-163.

Dooge, J.C.I., Bruen, M., Parmentier, A. (1999). "A simple model for estimating the sensitivity of runoff to long-term changes in precipitation without a change in vegetation". *Advances in Water Resources*, 23: 153– 163.

Ekström, M, Fowler, H. J., Kilsby, C. G., Jones, P. D. (2005). "New estimates of future changes in estreme rainfall across the UK using regional climate model integrations. 2. Future estimated an use in impact studies". *Journal of Hydrology*, Elsevier, 300: 234-251.

Few, R., Ahern, M., Matthies, F., Kovats, S. (2004). *Floods, health and climate change: a strategic review*. Tyndall Centre Working Paper No. 63 November.

Fu, G., Charles, S.P., Chiew, F.H.S. (2007). “A two-parameter climate elasticity of streamflow index to assess climate change effects on annual streamflow”. *Water Resources Research*, 43: W11419.

Franczyk, J., Chang, H. (2009). “The effects of climate change and urbanisation on the runoff of th Rock Creek basin in the Portland metropolitan area, Oregon, USA”. *Hydrological Processes*, Wiley, 23: 805-815.

Guo, S., Wang, J., Lihua, X., Ying, A., Li, D. (2002). “A macro-scale and semi-distributed monthly water balance model to predict climate change impact in China”. *Journal of Hydrology*, Elsevier, 268: 1-15.

Huntington, TG (2006). “Evidence for intensification of the global water cycle: review and sinthesis”. *Journal of Hydrology*, Elsevier, 277: 1-23.

IPCC (1995). in: Watson, R.T., Zinyowera, M.C., Moss, R.H. (Eds.). *Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses*. Cambridge University Press, UK.

IPCC (2001). in: Watson, R.T., Zinyowera, M.C., Moss, R.H., Dokken, D.J. (Eds.). *Special Report on The Regional Impacts of Climate Change, An Assessment of Vulnerability*. Cambridge University Press, UK.

IPCC (2007). *Summary for policymakers*. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), *Climate Change 2007: The Physical Science Basis*. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Kay, A., Reynard, N.S., Jones, R.N. (2006). “RCM rainfall for UK flood frequency estimation. I. Method and validation”. *Journal of Hydrology*, Elsevier, 318: 151–162.

Kleinen, T., Petschel-Held, G. (2007). “Integrated assessment of changes in flooding probabilities due to climate change”. *Climatic Change*, Springer, 81: 283-312.

Kundzewicz, Z.W., Graczyk, D., Maurer, T., Przymusiñska, I., Radziejewski, M., Svensson, C., Szwed, M. (2004). “Detection of change in world-wide hydrological time series of maximum annual flow”. *WCASP-64*, WMO Geneva.

Kundzewicz, Z.W., Schellnhuber, H. J (2004). “Floods in the IPCC TAR perspective”. *Natural Hazards*, 31: 111–128.

Milly, P.C.D., Wetherald, R.T., Dunne, K.A., Delworth, T.L. (2002). “Increasing risk of great floods in a changing climate”. *Nature*, 415: 514–517.

Mirza, M.M.Q. (2002). “Global warming and changes in the probability of occurrence of floods in Bangladesh and implications”. *Global Environmental Change*, 12(2): 127–138.

Nash, L.L., Gleick, P.H. (1991). “Sensitivity of streamflow in the Colorado basin to climatic changes”. *Journal of Hydrology*, Elsevier, 125: 221– 241.

Pagliara, S., Viti, C., Gozzini, B., Meneguzzo, F., Crisci, A. (1998). “Climatic change-uncertainties and trends in extreme rainfall series in Tuscany, Italy: effects on urban drainage networks design”. *Water Science and Technology*. 37: 195-202.

Prudhomme, C., Reynard, N.S., Crooks, S. (2002b). “Downscaling of GCMs for flood frequency analysis: where are we now?”. *Hydrological Processes*, Wiley, 16: 1137-1150.

Prudhomme, C., Jakob, D., Svensson, C. (2003). “Uncertainty and climate change impact on the flood regime of small UK catchments”. *Journal of Hydrology*, Elsevier, 277: 1-23.

Prudhomme, C., Davies, H. (2009a). “Assessing uncertainties in climate change impact analyses on the river flow regimes in the UK. Part1: baseline climate”. *Climatic Change*, Springer, 93: 197-222.

Prudhomme, C., Davies, H. (2009b). “Assessing uncertainties in climate change impact analyses on the river flow regimes in the UK. Part2: future climate”. *Climatic Change*, Springer, 93: 197-222.

Risbey, J.S., Entekhabi, D. (1996). “Observed Sacramento Basin streamflow response to precipitation and temperature changes and its relevance to climate impacts studies”. *Journal of Hydrology*, Elsevier., 184, 209– 223.

Robson, A. (2002). “Evidence for trends in UK flooding”. *Philosophical Transactions of the Royal Society of London* 360: 1327–1343.

Sankarasubramanian, A., Vogel, R. M., Limbrunner, J. F. (2001). “Climate elasticity of streamflow in the United States”. *Water Resources Research*, 37: 1771– 1781.

Schnur, R., Lettenmaier, D.P. (1998). “A case study of statistical downscaling in Australia using weather classification by recursive partitioning”. *Journal of Hydrology*, Elsevier, 212-213 (1-4): 362-379.

Schreider, S.Y., Smith, D. L., Jakeman, A. J. (2000). “Climate change impacts on urban flooding”. Climatic Change, Kluwer Academic Press, 47: 91-115.

Semadeni-Davies, A., Hernebring, C., Svensson, G., Gustafsson, L.G. (2008). “The impact of climate change and urbanisation on drainage in Helsingborg, Sweden: Combined sewer system”. *Journal of Hydrology*, Elsevier, 350: 100-113.

Semenov, M.A., Barrow, E.M. (1997). “Use of stochastic weather generator in the development of climate change scenarios”. *Climatic Change*, Springer, 35: 397-414.

Steele-Dunne, S., Linch, P., McGrath, R., Semmier, T., Wang, S., Hanafin, J., Nolan, P. (2008). “The impacts of climate change on hydrology in Ireland”. *Journal of Hydrology*, Elsevier, 356: 28-45.

Stehlík, J, Bardóssy, A. (2002). “Multivariate stochastic downscaling model for generating daily precipitation series based on atmospheric circulation”. *Journal of Hydrology*, Elsevier, 256 (1-2): 120-141.

Vogel, R.M., Wilson, I., Daly, C. (1999). “Regional regression models of annual streamflow for the United States”. Journal of Irrigation and Drainage Engineering”. ASCE, 125: 148– 157.

Vörösmarty C.J., Green, P., Salisbury, J., Lammers, R. B. (2000). “Global water resources: Vulnerability from climate change acid population growth.”. *Science*, 289: 284-288.

Wang, S., McGrath, R., Semmler, T., Sweeney, C., Nolan, P. (2006). “The impact of the climate change on discharge of Suir River Catchment (Ireland) under different climate scenarios”. *Natural Hazards and Earth System Sciences*, 6: 387-395.

Wang, S.F., Kang, S.Z., Zhang, L., Li, F.S. (2008). “Modelling hydrological response to different land-use and climate change scenarios in the Zamu River basin of northwest China”. *Hydrological Processes*, Wiley, 22: 2502-2510.

Wigley, T.M.L, Jones, P.D., Briffa, K.R., Smith, G. (1990). “Obtaining subgrid scale information from coarse resolution general circulation model output”. *Journal of Geophysical Research*, 95: 1943-1953.

Wilby, R.L., Dawson, C.W., Barrow, E.M. (2002). “A decision support tool for the assessment of regional climate change impacts”. *Environmental Modelling & Software*, 17(2): 145-157.

Wilby, R.L., Tomlinson, O.J., Dawson, C.W. (2003). “Multi-site simulation of precipitation by conditional resampling”. *Climate Research*, 23: 183-194.

Wilby, R.H.L. (2005). “Uncertainty in water resource model parameters used for climate change impact assessment”. *Hydrological Processes*, Wiley , 19: 3201–3219.

Wilby, R.L., Harris, I. (2006). “A framework for assessing uncertainties in climate change impacts: lowflow scenarios for the River Thames, UK”. *Water Resources Research,* 42: W02419.1–10.

Wilby, R.L., Beven, K.J., Reynard, N.S. (2008). "Climate change and fluvial flood risk in the UK: more of the same?". *Hydrological Processes*, Wiley, 22: 2511-2523.

Wood, A. W., Leung, L. R., Sridhar, V., Lettenmaier, D. P. (2004). "Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs". *Climatic Change*, Springer, 62(1-2): 189-216

Zheng, H., Zhang, L., Zhu, R., Liu, C., Sato, Y., Fukushima, Y. (2009). "Responses of streamflow to climate and land surface change in the headwaters of the Yellow River Basin". *Water Resources Research*, 45: W00A19.