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ANNEXE II

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Addressing the challenge of water scarcity and droughts in the European Union

Impact Assessment

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ANNEX 2

Droughts and climate change[1]

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1. Introduction

Drought is a sustained and regionally extensive occurrence of below average natural water availability. It is mainly caused by low precipitation and high evaporation rates, but in regions with a cold climate, temperatures below zero can also give rise to a winter drought. Drought can be characterized as a deviation from normal conditions in the physical system (climate and hydrology), which is reflected in variables such as precipitation, soil water, groundwater and streamflow. Drought is a recurring and worldwide phenomenon having spatial and temporal characteristics that vary significantly from one region to another (Tallaksen & van Lanen, 2004). Drought should not be confused with aridity, which is a long-term average feature of a dry climate, or with water scarcity, which reflects conditions of long-term imbalances between available water resources and demands (Tallaksen & van Lanen, 2004; Working Group on Water Scarcity and Drought, 2006). It is important, however, to note that the most severe human consequences of drought are often found in arid or semi-arid regions where water availability is already low under normal conditions (aridity), demand is close to, or exceeds, natural availability and society seldom lacks the capacity to mitigate or adapt to drought.

Climate change is expected to primarily affect precipitation, temperature and potential evapotranspiration, and, thus, is likely to effect the occurrence and severity of meteorological droughts. An important question for the assessment of future impacts (i.e. socio-economic and environmental) is how changes in meteorological drought will affect soil water drought and hydrological drought, i.e. groundwater and streamflow droughts. Soil water drought is, for example, relevant for agriculture, terrestrial ecosystems, and health through the occurrence of heat waves, whereas hydrological drought has significance for among others water resources (agriculture, domestic and industrial water use), aquatic ecosystems, power generation, and navigation.

Sections 2 and 3 describe changes in the physical system (climate and hydrology) with emphasis on hydrological changes for past and future conditions, respectively. Elaboration of possible changes of environmental and socio-economic impacts due to altered drought development is beyond the scope of this annex. The annex concludes with thoughts on how to move forward, in particular about the role the EC Integrated Project WATCH (WATer and global CHange) can play.

2. Droughts and climate change (past climate)

Over the last decade, numerous studies have been published about climate change and drought-related issues, although it is hard to discriminate from other human influences. Moreover it is difficult to distinguish between effects of climate change and multi-decadal climate variability (e.g. Berdowski *et al.*, 2001). Different approaches can be followed to assess the possible change of the past climate and its impact on drought. Commonly, physically-based, process-oriented models are applied to simulate time series of hydrometerological data. Following types of models have been used:

1. GCMs and RCMs (e.g. Gedney & Cox, 2003; Huntingford *et. al.*, 2003; Kabat *et. al.*, 2004) that simulate the atmosphere including a more or less simple land surface scheme. These models generate gridded time-series of hydrometeorological variables at a large scale (10-50 km);
2. Land Surface Hydrological models (LSHMs)(e.g. Hagemann & Dümenil Gates, 2003), which are off-line modules of GCMs and RCMs, and Global Hydrological Models (GHMs)(e.g. WBM, Vörösmarty *et al.*, 1998; LaDWorld, Milly *et al.*, 2002; WaterGap, Alcamo *et al.*, 2003 and Döll *et al.*, 2003; GUAVA, Meigh *et al.*, 2005). The GHMs have a more detailed representation of the hydrology than the GCMs, RCMs or LSHMs. The LSHMs and GHMs use climate forcing data as boundary condition and also produce gridded time-series of hydrological variables at a large scale (10-50 km);
3. River Basin Hydrological Models (RBHMs)(e.g. Gottschalk *et al.*, 2001; van Lanen *et al.*, 2004b; Bell *et al.*, 2006). These models also use climate forcing data (preferably RCM output) as boundary condition and generate time series of hydrological data at a detailed scale (~1 km).

The models are calibrated and validated with rather short time series of observed data, as far as possible. The modelling is supported by analysis of preferably long time series of observed hydrometeorological data to detect trends[2] (e.g. Hisdal *et al.*, 2001; Pekarova *et al.*, 2006).

The 4th Assessment Reports of the IPCC (Alley *et al.*, 2007; Adger *et al.*, 2007) provide a recent summary of observed changes in hydroclimatological variables. Records of global surface temperature show that the eleven years from the period 1995–2006 rank among the 12 warmest years in the record of the last 150 years. The total temperature increase from 1850-99 to 2001-05 is 0.76°C [range 0.57°C to 0.95°C]. Widespread changes in extreme temperatures have been observed over the last 50 years. Colder conditions have become less frequent, while hot days and heat waves have happened to be more frequent. Furthermore the IPCC report states that mountain glaciers and snow cover have declined on average both in the Northern and Southern hemispheres. The number of glacial lakes has been increased and their areas have been grown. The IPCC authors report increased run-off and earlier spring peak discharge in many glacier- and snow-fed rivers, indicating a regime shift for some rivers. Although not consistent for all assessed regions due to the highly spatial and temporal nature of precipitation, a long-term trend (1900-2005) could be observed, showing a significant precipitation increase for Northern Europe and a decrease for the Mediterranean region. More intense and longer droughts have been observed over wider

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[2] In addition paleoclimatic studies are carried out (for more information see, e.g. Stahl & Hisdal, 2004; Alley et al., 2007).

areas since the 1970s, in particular in the tropics and subtropics. Such droughts have been linked to higher temperatures and decreased precipitation, which are considered to be the result of large scale changes in atmospheric circulation in response to changing sea surface temperatures, wind patterns and decreased snow pack and cover.

Alley *et al.* (2007) state that the observed widespread warming, together with ice mass loss, supports the conclusion that it is extremely unlikely that global climate change of the past 50 years can be explained by known natural causes alone. Difficulties remain in reliably attributing observed temperature changes at smaller scales because natural variability is relatively large. It is likely that the area affected by droughts has increased in many regions and it is more likely that it has a human cause. This also holds for the frequency of heat waves. The increased demand for water has worsened the consequences of drought in many cases.

Many IPCC conclusions are based on regional-scale studies. For example, Klein Tank *et al.* (2002) report that the observed annual precipitation (1946-99) in 34 European countries show a positive trend mainly for northern stations, whereas negative trends concentrate in the south. At 45% of the stations a significant decrease in frost days occurred. The Europe-averaged increase in number of warm days is similar to the decrease in cold days.

Becker *et al.* (2004), van Lanen *et al.* (2004a) and Schulze (2004) give a detailed description of the response of hydrological processes to among others climate variability and change at scales from the small catchment to the river basin. Van Lanen *et al.* (2004b) and Demuth *et al.*, (2006) provide a comprehensive overview of the possible observed effects of climate change on hydrological droughts, even though detection of trends is cumbersome because long time series are needed (e.g. Stahl & Hisdal, 2004; Kundezewicz & Robson, 2004; Dixon *et al.*, 2006) and differences in catchment response might influence the regional patterns. Measurements for several decades to over a century are required to detect climate change with high confidence (Ziegler *et al.*, 2002). Pekarova *et al.* (2006) have analyzed annual river flow from 18 major European rivers over the period 1850-1997. The investigation shows neither significant long-term increase nor decrease. Lang *et al.* (2006) report on an ongoing comprehensive study that uses time series of river flow from about 200 French gauging stations. The first results show that there is no conclusive proof that climate change has a significant effect on drought regimes. Majerčáková *et al.* (1997) show a remarkable decrease in the annual streamflow since 1980 for 64 Slovak rivers covering a range of hydrological regimes. The decrease is most prominent in autumn and winter months. The highest decrease in streamflow is in the southeast (30 – 40%) and the lowest in the west, northwest and northeast (5–10%) of Slovakia. Analysis of spring yields gives similar results, although the decreasing trend strongly varies over the country. The decrease seems to be related to a change in precipitation and temperature. In the United States streamflow from catchments without evident anthropogenic influence shows an increasing trend in 16 out of 20 water regions over the period 1929–1988 (Hubbard *et al.*, 1997). It is likely that external climatic forcing causes the increase.

Global warming may also results in a regime shift particular in regions with snow and ice, where higher temperatures lead to earlier snowmelt and longer growing season. This trend is confirmed by observations showing that the beginning of the growing season in mid-latitudes has clearly advanced since 1989 (Chmielewski & Rötzer, 2002). Subsequently, this might lead to an increase in the frequency and severity of summer drought in these regions. The higher temperatures also cause more intensive melting and retreat of glaciers (e.g. Berdowski *et al.*, 2001). For example, Chalise *et al.* (2006) report on an increasing number of glacier lakes, glacier lake outburst, and higher discharge at high elevation in the Himalayas. The increase can be related to a temperature rise. A study for the Nordic countries (Hisdal *et al.*, 2006) reports that the increased temperature has caused both an earlier snowmelt and a higher evapotranspiration. In Southeast Norway this has led to longer summer droughts in about 60% of the river basins.

There are, however, large regional variations in trends due to the high natural variability in climate as well as catchment properties as demonstrated by Hisdal *et al.* (2001) for hydrological drought conditions in Europe. The study showed that there were no significant changes for most stations in the period 1962-90, however, distinct regional differences were found. Trends towards more severe droughts in Spain, the western part of Eastern Europe and in large parts of the UK, whereas trends towards less severe droughts occurred in large parts of Central Europe. (Fig. 1). The study further illustrates that the use of time-series with a length of 30 years (e.g. the WMO standard periods are 1931-60 and 61-90) can lead to erroneous conclusion about long-term trends. Periods of 30 consecutive years were selected from a 100 year dataset with daily streamflow. Depending on the selected subperiod, trends towards both more or less severe hydrological droughts were found over the period 1901-2000 with no clear development over the century.

Drought severity and frequency studies have to consider the full range of climate variability. Several studies, that have used long records, point at the large temporal variability, which makes it difficult to draw firm conclusions on the influence of climate change on hydrological drought. Based on an analysis of the discharge of the River Meuse over the period 1911–1998, it is impossible to conclude that drought has become more severe or frequent (Uijlenhoet *et al.*, 2001; De Wit *et al.*, 2001). No trend can be identified, although the River Meuse regularly suffers from drought (10 out of 100 years the river cannot meet the minimum supply criteria for some time of the year). Cole & Marsh (2006) and Marsh *et al.* (2007) have analyzed hydrometeorological data and other documents for England and Wales

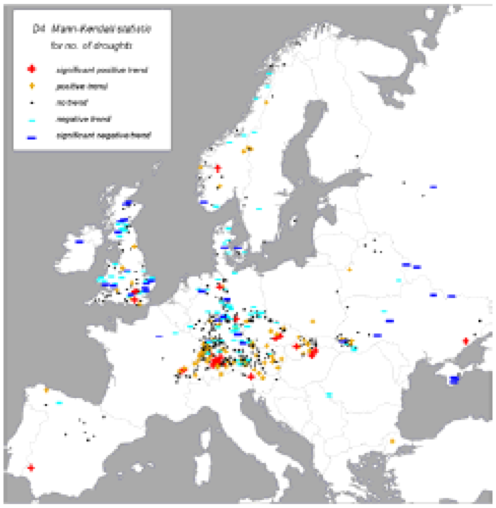

Figure 1. Trend in number of droughts over the period 1962-1990, red - significant positive trend (towards drier conditions) and blue - significant negative trend (towards wetter conditions)(source: Hisdal *et al.*, 2001).

from the period 1800-2006. They report that the historical period contains many multi-year droughts, in particular the 1940s experienced repeated periods of significant rainfall deficiencies. Extreme droughts occurred in 1798-1808 and 1890-1910 (so-called "long-drought"). The authors show that the annual rainfall totals for England and Wales do not exhibit a clear change over time, as derived from the frequency of drought episodes, indexed by exceptional 12-month (non-overlapping) rainfall deficiencies. However, they illustrate that since the latter stages of the Little Ice Age in the early 19th century, the hydrometeorological time series exhibit a number of changes which have important implications for droughts. There has been an increasing tendency, notwithstanding some recent droughts in the 1990s and 2000s, towards a more distinct seasonal partitioning of annual rainfall totals resulting in wetter winters and dryer summer, which commensurate with most climate change scenarios. This means a modest increase in winter run-off in flashy catchments, which is beneficial for reservoir refilling, and an increase of recharge in groundwater catchments leading to a higher storage and increased groundwater discharge that sustains summer streamflow.

In summary, it is still hard to detect changes in hydrological drought (streamflow and groundwater) in the 20th century and, if occurring, to attribute to climate change. Most studies do not show clear trends in time and over extended areas.

3. Projected droughts (future climate)

Clearly, projections of future changes in climate and associated drought development can only be simulated with a suite of models as mentioned in the previous section. On the basis of these modelling experiences the 4th Assessment Reports of the IPCC (Alley *et al.*, 2007; Adger *et al.*, 2007) provide the following key findings that are relevant for changes in drought. Until 2020 a warming of about 0.2°C per decade is projected for a range of scenarios. The projected globally average surface air warming (2090–99 relative to 1980–99) for 6 emissions ranges from a best estimate for the low scenario (B1) of 1.8°C (likely range: 1.1-2.9°C) and for the best estimate for the high scenario (A1FI) of 4.0°C (likely range: 2.4-6.4°C). Schär *et al.* (2004) and Seneviratne *et al.* (2006) also point at a regime with an increased variability of summer temperatures (in addition to increases in mean temperature).

In 2050, IPCC expects that the annual average river flow will have increased by 10-40% at high latitudes[3], and decreased by 10-30% over some dry regions at mid-latitudes and semi-arid low latitudes, some of which are presently already water-stressed areas. Drought-prone areas and regions affected by heat waves are considered likely to increase in extent. Water stored in glaciers and snow cover is projected to continue to decline, initially increasing, but eventually reducing streamflow during summer in downstream regions supplied by melt water from major mountain ranges. In Southern Europe especially climate change is projected to worsen conditions (high temperatures and drought) in a region that already faces water scarcity and heat waves in a substantial number of areas. In Central and Eastern Europe, summer precipitation is projected to decrease, causing higher water stress.

GHMs and RBHMs with climate forcing data as boundary condition (Section 2) have been applied to explore the effect of climate change in the 21st century on hydrological drought. In a global-scale assessment Arnell (1999) uses a GHM to simulate streamflow across the world. The results show that the patterns in change of annual river flows are generally similar to the change in annual precipitation. According to his study, the annual

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[3] Please note that the partitioning over winter and summer seasons is also relevant. In some river basins a higher annual precipitation still will lead to more severe summer drought (see below).

flow is expected to increase in high latitudes and many equatorial regions, but it is anticipated to decrease in mid-latitudes and some subtropical regions. He illustrates that the change in the minimum annual flow with a return period of 10 years (indicator for hydrological drought) alters in a similar way to the average annual streamflow. However, the proportional change tends to be larger. This conclusion is also supported by assessments at the catchment scale, e.g. Dvorak *et al.* (1997) show that changes in low flow characteristics tend to be proportionately larger than changes in annual, seasonal or monthly flows. The RBHM study in a Dutch catchment (van Lanen *et al.*, 2004b) confirms Arnell's conclusion for the high latitudes, meaning that droughts become less severe.

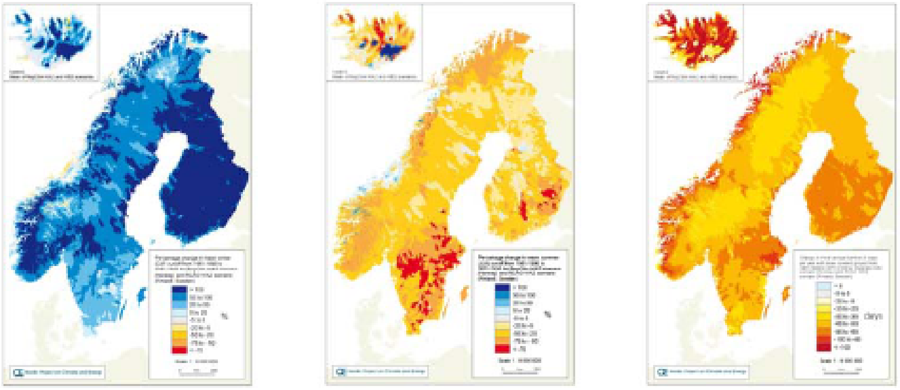

Figure 2 Simulated effects of climate change for the HadAM3H/A2 scenario in the Nordic countries (2071–2100 relative to 1961–90); left: percentage change in mean winter (DJF) run-off, middle: percentage change in mean summer winter (JJA) run-off, and right: change in mean annual number of days per year with snow covered ground (source: Beldring *et al.*, 2006).

However, in some high-latitude regions the annual streamflow will reduce because of a general increase in evaporation that counteracts the increase in precipitation. For example, catchments on the Belgium-Dutch border show this trend in simulated series (Querner *et al.*, 1997; Peters & van Lanen, 2001).

At the mid-latitudes, e.g. in many areas in the Mediterranean, the effects of climate change will be often overwhelmed by the effects of land use. Cruces *et al.* (2000) illustrate this for the Upper-Guadiana catchment (Spain), where more water-demanding agriculture has been implemented under semi-arid conditions and groundwater is heavily exploited since the 1960-70s.

In snow-affected climates the temperature increase can lead to a high portion of quick shallow subsurface flow which does not feed the aquifer or to a shift in the timing of the snowmelt from spring to winter implying a reduction in the summer low flow and higher drought risk (e.g. van Lanen *et al.*, 2004b). This is confirmed by modelling results from Eckhardt & Ulbrich (2003), who found a reduction of mean monthly groundwater recharge and streamflow of up to 50% for a catchment located in the central European low mountain range. In the Nordic countries a comprehensive study has been carried out to investigate the influence of climate change on hydrology with the main objective to provide information for hydropower generation (Beldring *et al.*, 2006). In Figure 2 the difference in winter and summer run-off and number of snow days for a particular scenario are shown. Climate change leads to substantial effects. The study shows that in general, the available water resources for hydropower increase, but in some areas dryer conditions are projected. In the summer season water shortage may occur at some locations. Hence, despite the projected increase in annual discharges at high latitudes, the RBHMs still predict more severe summer drought in some regions when account is taken for the change in precipitation distribution over the seasons, the earlier snowmelt and the higher evapotranspiration and longer growing season (Hisdal et al., 2006). This holds in particular for catchments with low storages.

Several studies illustrate that the effect of climate change on low flow is significantly affected by the stores in the catchment, e.g. soils, aquifers, lakes, bogs, snow pack, glaciers (van Lanen et al., 2004a). Results, for example, of low flow changes simulated for several Belgian catchments by using GCM scenarios show how the same scenario could produce rather different changes in different catchments, depending largely on the catchment geological conditions (Gellens & Roulin, 1998). Catchments with greater groundwater storage capacity tend to have higher summer flows under the climate change scenarios considered because additional winter rainfall tends to lead to larger groundwater replenishment. Low flows in catchments with low storage capacity tend to be reduced because these catchments cannot take advantage of increased winter recharge

In summary, the mid-latitudes, e.g. the water-scarce regions around the Mediterranean, are projected to be worse off in the future (higher number and more severe droughts). In addition, more heat waves are expected in South and Central Europe, which is a major health concern. For North and West Europe, the IPCC projects higher temperatures and associated evapotranspiration and an increase of annual river flow. Generally, this will lead fewer and less severe droughts, especially winter droughts. However, the physical structure of the river basin, in particular the stores, the seasonal distribution of precipitation and increased evapotranspiration will determine if more and more severe summer droughts will occur. Rivers draining snow-covered mountains may suffer more summer droughts from a reduced snow cover at the long run as these mountains provides important meltwater. Initially river flow will be higher (e.g. Chalise *et al.*, 2006). The larger summer temperature variability that has been expected by Schär *et al.* (2004) and Seneviratne *et al.* (2006) will likely lead to more droughts in many European regions.

Regions located in the transition zone between major climate zones, e.g. from the temperate to the dry climates, are particular susceptible to drought and thus to potential changes in climate (Stahl & Hisdal, 2004). A shift in climate may create a new transitional climate zone with unknown feedback mechanisms. In Europe a northward shift is observed influencing summer climate variability in Central and East Europe due to strong land-atmosphere coupling. This may potentially cause more droughts and heat waves in this and other mid-latitude regions (Seneviratne *et al.*, 2006).

There are many uncertainties in our understanding of the current water cycle (oceans, atmosphere and land) and how it will develop in the future (e.g. Prudhomme, 2006; Prudhomme & Davies, 2006).

4. Role of EC Integrated Project WATCH

The Integrated Project (WATCH: WATer and climate CHange) will advance our knowledge and skills to predict the effect of climate change on drought. It analyses and describes the current global water cycle (20th century), especially causal chains in the physical system (climate-hydrology) leading to observable changes in extremes (e.g. droughts). It will evaluate how the global water cycle and in particular droughts (21st century) respond to future drivers of global change (including greenhouse gas release and land cover change) and will contribute to a clarification of the overall vulnerability of global water resources. WATCH will assess the uncertainties in the predictions of climate-hydrological-water resources model chains using a combination of model ensembles and observations.

WATCH brings together hydrologists, water cycle experts and climate modelers. There has been a historical, disciplinary "disconnect" between communities: (1) developing integrated water cycle and water resources assessment and modeling frameworks, (2) estimating hydrological extremes, and (3) developing climate modeling frameworks. This has resulted in many conceptual and data-related inconsistencies in the studies and in projections of the state of future water cycle, including its extremes – both globally and in the regions. The different approaches are, however, gradually converging. Process representation in the models is becoming more comprehensive, the grid size of climate models is approaching that needed to resolve large basins and methods to use statistical information from climate models are being developed.

Our understanding of the global water cycle, including the characteristics of past droughts (Section 2) and how they might change in future (Section 3), is very fragmented and highly uncertain. There are many sources of information, which have a wide range of space and time scales and also come from different scientific communities. There has been no systematic collection and analysis of the observations globally. Hence, WATCH will develop a new consolidated dataset.

The current generation of global and regional climate models (GCMs and RCMs) is expected to unsatisfactory reproduce historical hydrological extremes, with considerable variability in the prediction of rainfall patterns, with differences between climate models and between different ensemble members of the same climate model. The issue of the inaccuracies in climate model output (in particular the rainfall, high temperatures and persistent dry periods) will be addressed by investigating the best method of transferring and validating information about extreme events between climate and hydrological models at different scales. WATCH will develop a new, highly consistent modeling framework for water resources, hydrology (incl. extremes) and climate studies. This framework, however, will not be attempting to fully link individual model segments into a fully coupled modeling system. Instead, WATCH analyses, data consolidation and modeling efforts will focus on building a new generation of interfaces between water resources, hydrological and climate models, attempting a maximum possible consistency in spatial and time scales involved, and in related process descriptions.

It is essential to know the uncertainty in any assessment of possible future changes in hydrological extremes and water availability. Uncertainty can come from a large range of sources: errors in our current "baseline" assessment, uncertainty in future development scenarios, the spread in climate model predictions, uncertainties in our hydrological models etc. It is essential to combine these uncertainties to produce a realistic assessment of the total uncertainty. The outputs from this merging of climate and hydrological models will be a full uncertainty analysis of the spatial and temporal scaling techniques available and recommended methodologies to transfer gridded climate model output to the basin scale.

Another crucial issue is the attribution of changes in the hydrological cycle (incl. the extremes), discriminating between external drivers, both natural and anthropogenic, and internal variability. There is considerable public and political interest in issues of attribution and it has significant practical implications as well. Attribution studies to date have focused overwhelmingly on large-scale temperature changes. Attribution of changes in hydrological variables and extreme weather events received much less attention, but is more relevant to many practical water management and policy decisions.

The WATCH project has identified one Work Block that investigates the frequency, severity and scale of the extremes, with emphasis on drought for past and future conditions. The overall objective of the work block is to advance knowledge on the impact of global change on hydrological extremes, i.e. spatial and temporal scale of droughts and large-scale floods.

The following specific objectives have been defined:

- to estimate the likely frequency, severity and scale of hydrological extremes (droughts and large-scale floods) globally in the 20th century;
- to advance our understanding of drought and large-scale flood generating processes and spatial and temporal development (scale) at the global, regional and river basin scale;
- to identify possible links between large-scale climate drivers and the temporal and spatial dynamics of hydrological extremes, including teleconnections and synchronicity of extremes at the regional and global level;
- to identify and develop physical indicators for various types of droughts and large-scale floods considering different spatial scales and hydrological regimes;
- to develop statistical methods to detect hydrological extremes at different scales, including the coarse-gridded scale typical of global models;
- to attribute the impact of climate and anthropogenic changes to hydrological extremes by comparing trends in observed time series and simulated time series obtained from climate forcing models combined with land surface hydrological and river basin models;
- to predict the likely frequency, severity and scale of future hydrological extremes (21st century) considering the sensitivity in hydrological extremes to changes in predicted climate and anthropogenic influences, and
- to analyse the uncertainty in predicted hydrological extremes at different scales including the propagation of uncertainties within linked modeling studies.

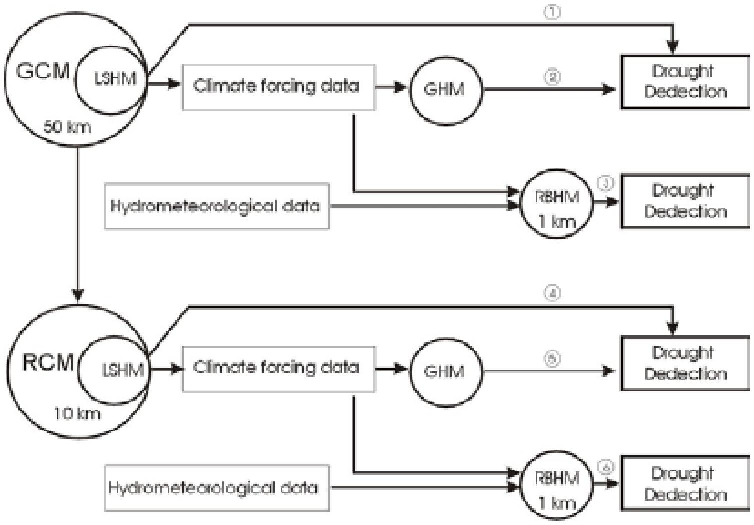

Figure 3 Flow chart showing how droughts are derived by using different models.

Different climatological and hydrological models and combinations are used to detect droughts (Fig. 3). Droughts are directly derived from the gridded outcome simulated by Land Surface Hydrological Models (LHSMs) linked to a GCM (1) or RCM (4). Droughts are also obtained from the gridded output generated by Global Hydrological Models (GHMs) that use climate forcing data from GCMs (2) or RCMs (4). For a few river basins (e.g. Glomma, Elbe, Upper-Guadiana), River Basin Hydrological Models (RBHMs) will be applied to detect droughts. These models are driven by climate forcing data from GCMs (3) and RCMs (6).

The <u>main outcomes</u> of the work block are:

- frequency, severity and scale of historical extremes (droughts and large-scale floods in the 20th century), including possible causes for observed trends/changes in the extremes (detection and attribution); and
- frequency, severity and scale of future extremes (droughts and large-scale floods in the 21st century), including an assessment of the sensitivity in the extremes due to climate change and anthropogenic influences.

The WATCH project has started in February 2007 and will last 4 years and the outcome will gradually become available in the coming years. It will make a significant contribution to climate change impact research, including assessing droughts, by bringing together different research communities, thus emphasizing the need to corporate between disciplines to move forward in this field.

Clearly, WATCH will not address all aspects relevant for droughts and climate change. For example, knowledge on the physical system (climate and hydrology) still need to be enhanced, especially on the propagation (space-time) of meteorological drought in soil water and hydrological drought, to be used as basic elements for early warning systems, forecasting of drought conditions that also considers climate change. Additionally, assessing impacts (environmental, socio-economic) of drought need more research. It is expected that these aspects will be covered by studies in the framework of the 7th Framework Programme.

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