WATCH
Water and Global Change

Water and global change

The WATCH Project Outreach Report

An introduction to the achievements of the EU WATCH Project. This report is aimed at policy makers and those with a stake in water resource management.

The Water and Global Change (WATCH) programme was an Integrated Project funded under the European Union's Sixth Framework Programme. It ran from February 2007 to July 2011. For the first time it brought together the hydrological, water resources and climate research communities at an international level. Together they analysed, quantified and predicted the components of the global water cycle and the related water resources – for the present and for the future. They also evaluated the associated uncertainties, and clarified the vulnerability of global water resources within key societal and economic sectors. The contacts and friendships that were made during the life of the project will benefit water research for many years to come.

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The WATCH Project Outreach Report

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This report is based on a series of interviews with participants. Extracts from these interviews can be viewed at www.eu-watch.tv and at www.youtube.com/user/euwatchtv

Foreword by Dr Bryson Bates

Dr Bryson Bates is an expert in climate impacts on water resources. He sits on the United Nations' World Water Assessment Programme Expert Group on Climate Change and Water, and the Expert Group on Scenarios. He has co-authored chapters and reports for the International Panel on Climate Change.

Dr Bates is the Leader for Pathways to Adaptation Theme in CSIRO's Climate Adaptation National Research Flagship in Western Australia. He leads a team of researchers who are providing sound scientific knowledge to underpin the development and implementation of effective options for adapting to climate change.

The impacts of climate change on the hydrological cycle display many different patterns. The effects on atmospheric water vapour content or on soil moisture, and changes in precipitation are examples. These effects have been linked to the global warming now observed over several decades. More specifically, higher water temperatures and changes in extremes are projected to affect water quality and exacerbate water pollution. This is likely to lead to negative impacts on ecosystems and human health, as well as on water system reliability and operating costs. In addition, sea-level rise is projected to extend areas of salinisation of groundwater and estuaries, resulting in a decrease of freshwater availability for people and ecosystems in coastal areas. Besides this, changes in water quantity and quality due to climate change are expected to affect food security, water access and utilisation, especially in arid and semi-arid areas, as well as the operation of water infrastructure - such as hydropower, flood defences, and irrigation systems.

Policy interventions for climate change mitigation and adaptation must be built on solid science. Yet, our understanding of the complex climate system is still inadequate, and our evaluations of the impacts of climate change are correspondingly uncertain. Creating more dependable impact assessments requires effective partnerships among research organisations and, importantly, partnerships between scientific disciplines. One critical partnership is that between climate scientists and hydrologists. Yet, in the past these groups have not worked effectively together. WATCH has changed that.

As one of the key projects funded by the European Union's Sixth Framework Programme, WATCH has gathered 25 partners from outstanding European organisations dealing with climate change studies and created an integrated project, which is now delivering new findings about climate change impacts on the global hydrological cycle.

The purpose of projects such as WATCH is to underpin evidence-based policy-making. This requires that the scientific results are presented in a straightforward, jargon-free way that can be readily understood by the non-specialist. This "Outreach Report" meets that requirement. The report describes how the project has brought together the hydrological and climate communities to analyse, quantify and predict the components of the current and future global water cycle. It shows how WATCH evaluated the attached uncertainties and clarified the overall vulnerability of global water resources related to the main societal and economic sectors.

Policy-makers and stakeholders will benefit from reading this Outreach Report. I am certain the results from WATCH will be a cornerstone of future action in this field.

Summary for policy makers

Water and Global Change (WATCH) was a €13M Integrated Project funded under the European Union's Sixth Framework Programme. It ran from February 2007 to July 2011. It brought together the international hydrological, climate, and water resources research communities to resolve the water cycle at the global scale so that studies of climate and hydrology become inseparable in the future.

The foundation of WATCH was built on understanding the water cycle in the recent past. In doing so, researchers were able to assess the ability of hydrological models – often developed at local and regional scales – to receive data from climate models and produce results at a global scale.

Key to this was the development of a consistent set of climate data for use as input. The WATCH Forcing Data covers the period 1901 – 2001 and is based on a global 0.5 degree x 0.5 degree (~ 50km x 50km) grid. It comprises eight essential climate variables. The 21st century data set – the WATCH Driving Data – covers the period 2001 – 2100. It was created using a novel bias-correction methodology applied to three well-established climate models, each running for two IPCC future emissions scenarios.

Both data sets are freely available to the world's research community, providing a significant new resource for future projects.

Using these data, WATCH completed an ambitious Water Model Inter-comparison Project. This led to the development of data and tools to provide a reliable multi-model approach to assessing impacts on the water cycle. The models were shown to be fit-for-purpose for estimating river flows at global, continental and regional scales. This has allowed the first steps to be taken towards a consistent assessment of water availability. This approach is similar to the one taken with climate studies – such as in IPCC Reports – and will reduce the need to rely on local hydrological studies that are unlikely to be representative at a global scale.

In looking at extremes, WATCH has compiled an exceptional pan-European set of observed river flow data from more than 400 stations. These data have contributed to the compiling of the Flood and Drought Atlases. These publications capture the characteristics of droughts and floods over the 20th century across Europe. They can be combined with other key data sets to produce figures for the human, economic and environmental consequences of individual historical events.

WATCH has made significant progress in understanding and recording hydrological extremes in the 20th century, and projections for the 21st. This provides the clearest evidence yet that it is possible to model these both on a European and global scale.

WATCH has highlighted the critical importance of evaporation within the water cycle. In response, it has produced a new global data set of evaporation from land for the period 1984 – 2007 that provides a unique breakdown of the components of evaporation. This breakthrough is due to the availability of high-quality satellite data, coupled with novel and innovative approaches taken by WATCH researchers.

Early analysis of the data appears to support the suggestion that total global land evaporation has reduced over the last ten years. This is contrary to the belief that increasing temperatures due to climate change should cause an increase in global evaporation. The data will allow future studies of global trends, of changes in regional evaporation, and across biomes.

WATCH has modelled changes in climate due to changing land use to understand the overall climate-impact of the wide-scale deforestation that has been a feature of the last century. Models agreed that in the key regions, changes to climate could be identified.

WATCH has also shown that some changes in land use can reduce evaporation and increase river flows, but that one type of land use – irrigation – has the opposite effect.

Overall, the models confirm the need for land-use change to be considered alongside climate change, and any predictions of future climate ought to include the impact of land-use and land-cover change.

Until WATCH, climate and impact models had been treated separately. WATCH has shown that these models can be coupled, and that they should be coupled routinely in the future. Only then will we be able to model feedbacks, and be able to estimate the effects of future planned changes.

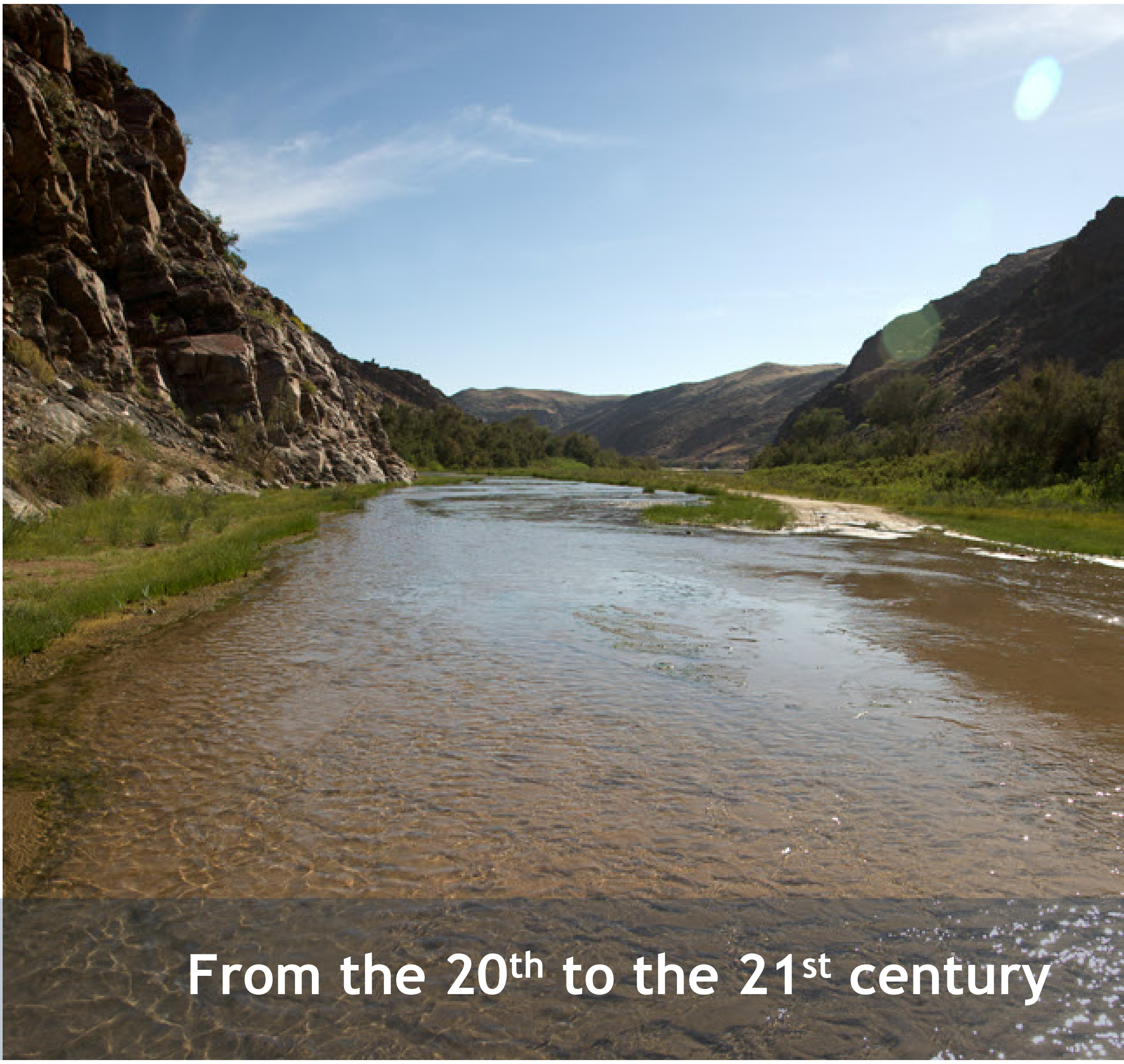
By combining data on water availability and water demand, WATCH has identified and quantified where there are deficits, and where water is more plentiful. Water scarcity occurs when there is not enough water available to meet the demands of agriculture, industry, and domestic use. WATCH quantified water use in these sectors and assessed the drivers that will influence usage in the future.

The WATCH approach to assessing water use by rainfed and irrigated agriculture makes a distinction between "blue" and "green" water; "blue" is water withdrawn from rivers, lakes, reservoirs and groundwater for use in irrigation schemes, and "green" is the moisture stored in the soil from rainfall.

This approach revealed that approximately half of the blue water that is withdrawn for use in irrigation schemes is from non-renewable or non-local water resources. Globally, the amount of water used in agriculture also far exceeds what was suggested in previous studies which considered blue water only.

The consistent methods used within WATCH to derive new data sets make it easier to link them and to consider them together rather than in isolation. This promotes better understanding of the total demands that are being placed on the world's resources.

WATCH leaves a clear legacy of an increased understanding of the water cycle in a time of global change. In addition, it has created an international group of knowledgeable and experienced modellers working at the interface between hydrology and climate science. These scientists will go on to influence international research projects for years to come, underpinning the development of evidence-based inter-governmental policy-making. And, they will take with them an awareness and an enthusiasm for what can be achieved by large research teams working in partnership.



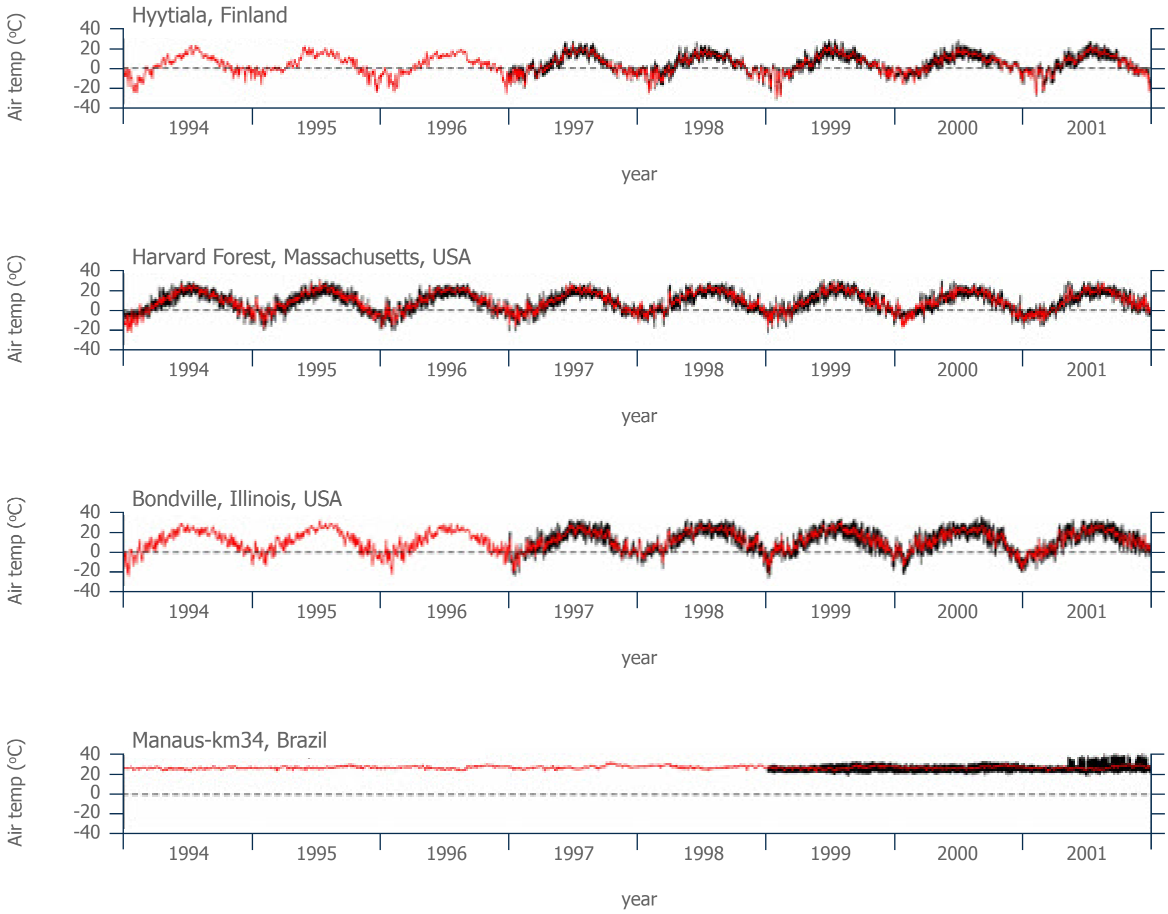
From the 20th to the 21st century

Key components of the water cycle such as rainfall, evaporation and river flow vary naturally over all time scales – from minutes to millennia. Man's activities are modifying them and this will continue as CO_2 levels rise and our use of water increases. If we are to respond to these changes successfully, we must first quantify both the amount of water that will be available and what the future demand will be. Most importantly, we must begin to consider availability and demand as a single issue.

WATCH has done this by bringing together climate, water cycle, and water resource experts. It has pooled their knowledge and skills, and has established effective frameworks for co-operation. For the first time, these communities have agreed common terminology and protocols for data exchange, providing a foundation for work at the global scale. What started-off as a scientific-handshake has developed into a movement with genuine momentum. It will benefit water management in the 21st century, and will influence international research projects for years to come, underpinning the development of evidence-based inter-governmental policy-making.

From basic physics we know that air temperature will increase with increasing concentrations of greenhouse gases. Higher temperatures over the oceans will increase evaporation and the humidity held in the atmosphere. This is likely to lead to higher rainfall over the whole globe and the further likelihood of more intense rainfall. Regionally, these changes in rainfall will depend on shifts in weather patterns, but there is already general agreement that Medi-

WATCH Forcing Data (daily) verses Flux Tower data (half-hourly)



Time series of half-hourly air temperature at selected flux tower sites (black) compared with daily average air temperature for corresponding half-degree grid boxes from the WATCH Forcing Data (red).

terranean climates. will become drier and the northern latitudes will be wetter.

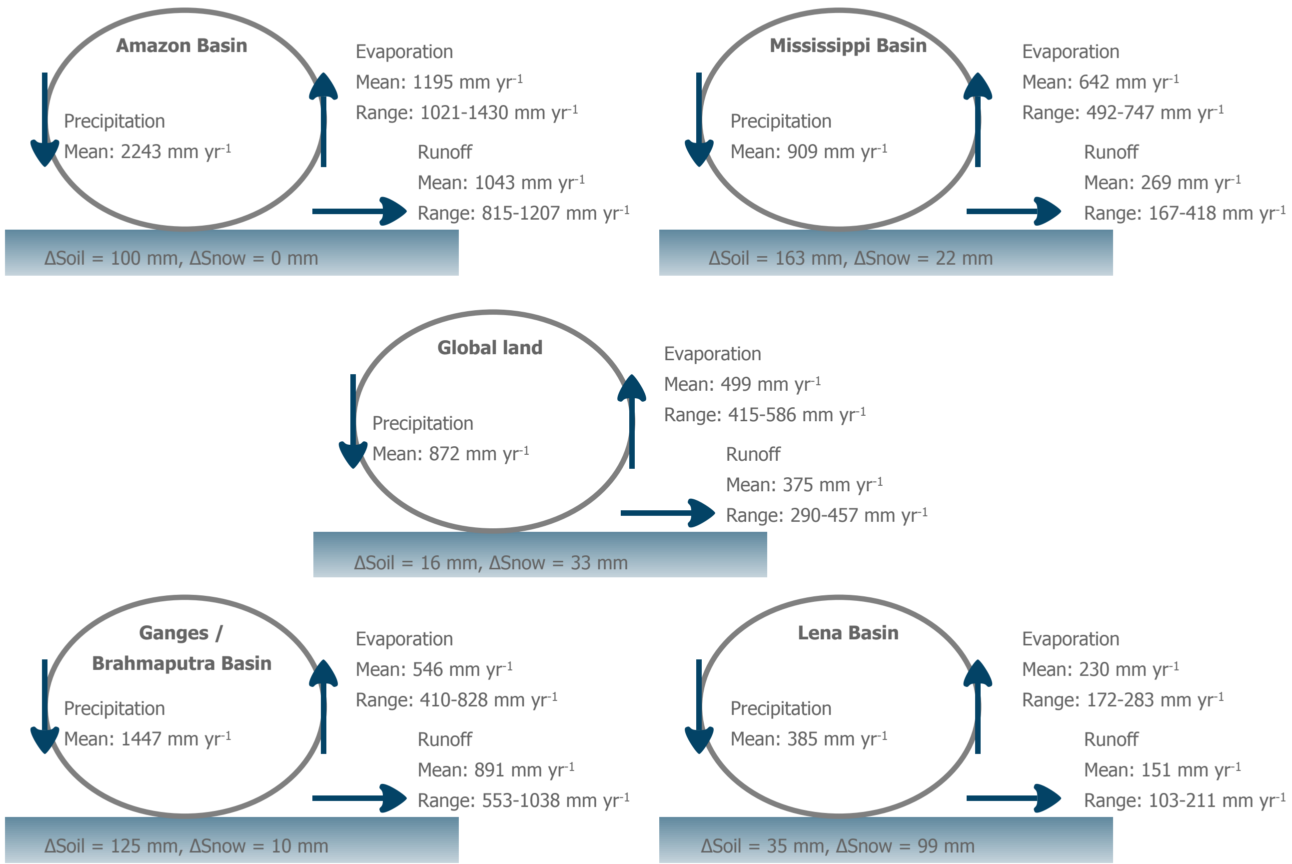
Such statements are highly significant. They are also incredibly broad. To manage their implications, we require more details of actual water availability in the future. This information can be provided by climate and hydrological models, but we must appreciate the uncertainty in model projections, and we must maintain a culture of on-going model improvement. As a starting point, WATCH recognised that we must develop a thorough understanding of the water cycle in the recent past.

Taking the output data from climate models to drive hydrological models on a global scale seems an obvious thing to do. However, up until now, the different space and time scales at which the two communities work has been a significant stumbling block.

Climate models have been working at the global scale for decades, dividing the Earth into conveniently sized grid cells, commonly 1 degree by 1 degree (~ 100km x 100km). By contrast, hydrological models were catchment-based (i.e. river-basin based), with grid cells as small as 50m x 50m. Even the fastest super-computers cannot run global climate models at these small scales, so a compromise was needed. To complicate matters further, the two communities had also developed their own terminologies, often with similar terms having quite different meanings. WATCH brought these groups together not just scientifically, but physically – in the same room – to discuss their different requirements, to agree terminology, and to promote mutual understanding so that they could move forward together.

Co-leader of WATCH, Pavel Kabat of WUR, said "The water cycle is complicated and cannot be understood fully by measurement or modelling alone; data are sparse, and models are not adequate. We need a combination of the two."

Components of water fluxes and storages



Components of water fluxes and storages for global terrestrial land surface (middle) and four major basins representing different climate regimes for the period 1985 – 1999. The numbers represent simulation results of eleven models participating in WaterMIP.

The first step in bringing data and models together was the production of the WATCH Forcing Data; a comprehensive and consistent global climate data set for the 20th century. These data are the result of merging a 3-hourly climate data set and monthly observational data sets which together cover the period 1901 – 2001. These widely used original data sets were known to have specific individual shortcomings which have previously precluded their direct use in hydrological modelling. WATCH reduced the potential effects of these by adopting the best published procedures for adjusting previously unused reanalysis climate data, based on monthly observational data, and then adding further novel observational-adjustment procedures.

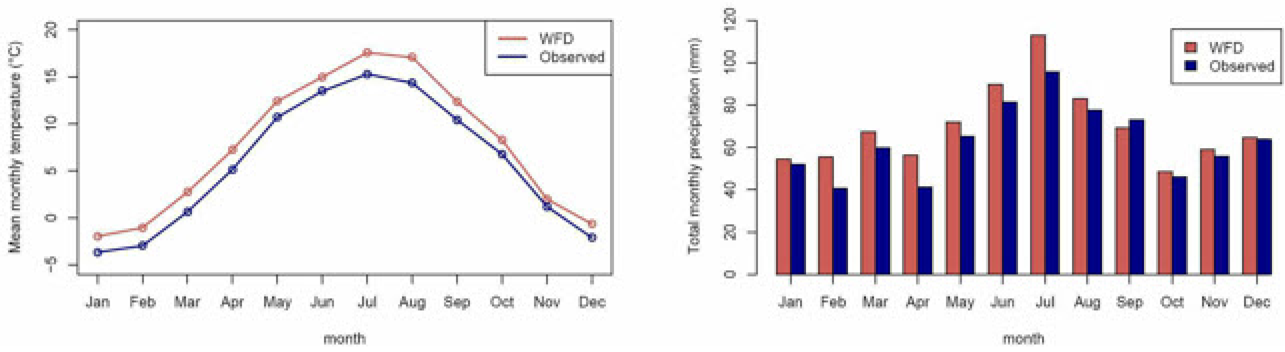
The WATCH Forcing Data is based on a global 0.5 degree x 0.5 degree (~ 50km x 50km) grid and comprises eight essential climate variables. Five of these are provided at 6-hourly intervals, and three at 3-hourly intervals.

The forcing data can be used as input to hydrological models to produce comprehensive global water cycle data sets, and they have been validated locally against observed hourly meteorological data. This provides a benchmark against which we can test our modelling ability in the early 21st century. The global water cycle data sets also provide invaluable historical data for areas of the world where little or no observed climate and hydrological data exist. The use of these data to drive hydrological models has been tested at a range of test basins across Europe with considerable success. This shows how valuable this data set will be in regional hydrological assessments worldwide.

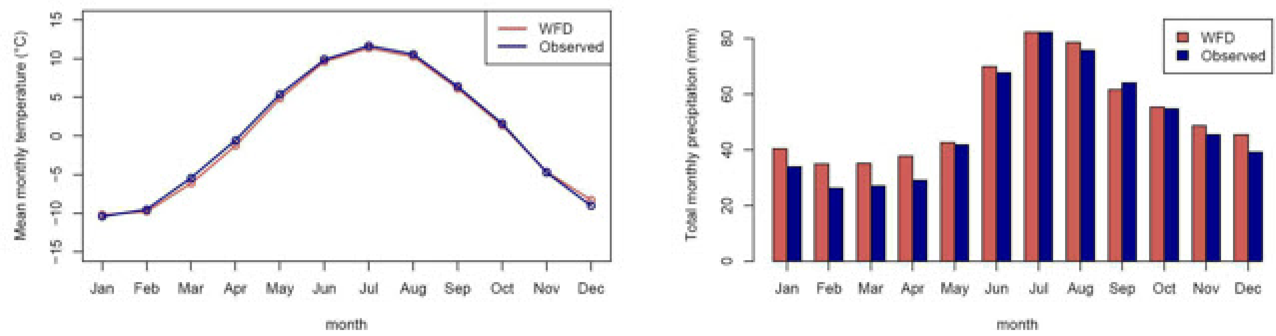
WATCH Forcing Data is freely available to the world's research community, providing a significant new resource for future research projects.

The 21st century data sets were created using a novel bias-correction methodology, trained on the 20th century WATCH Forcing Data. These data for 2001 – 2100 are known as the WATCH Driving Data. They provide the same climate variables as the WATCH Forcing Data, and use the same grid. They have been created from three well-established climate models, each running for two IPCC

Monthly temperature and precipitation regimes



Monthly temperature and precipitation regimes for local meteorological observations and WATCH Forcing Data in WATCH test basin Narsjø, Norway.



Monthly temperature and precipitation regimes for local meteorological observations and WATCH Forcing Data in WATCH test basin Upper-Metuje, Czech Republic.

future emissions scenarios. This provides six input options for the hydrological models.

This new methodology addressed the problem that climate models produce biases in their regional rainfall – they can be too dry or too wet and, generally, include too much light rain or drizzle. The rainfall to runoff process is highly non-linear – so, for example, river flows will respond strongly to heavy rainfall, but may not respond to light rainfall at all.

The range of results across the six options provides a constant reminder of the uncertainty in modelled data, and it will prevent us becoming too focused, and over-reliant on a single set of numbers.

WATCH – in association with the international Global Water System Project - completed its own Water Model Inter-comparison Project (Water MIP). This ran all the hydrological models using a common 20-year subset of the WATCH Forcing Data. Such studies in which models are compared are not rare, but Water MIP set new standards; not just in terms of the number of models involved, but also in terms of the spatial coverage and the timespan.

This unprecedented multi-model multi-scenario approach has produced an invaluable suite of hydrological data sets that provide a new picture of long-term behaviour of river flows and soil moisture, and how they may change in the future. The results from Water MIP and further details of how we link climate to river flows can be found in "From climate to river flows" starting on page 14.

The translation of changing rainfall patterns into river flows is not straightforward. It depends on the characteristics of the catchment – whether there is groundwater, what the land cover is, and the topography of the catchment. And, of course, human intervention in the catchments may have an overriding influence. Land-cover changes, dams, extractions and channelling can completely change the flow regime of a river.

Before WATCH, studies of the global water cycle had focused on seasonal or monthly river flows. Now, with the availability of sub-daily data (at 6- and 3-hourly intervals) WATCH has been able to go one step further: to analyse droughts and floods at finer time scales, and to explore how they have changed over time.

Using the forcing data and hydrological models, WATCH successfully reproduced known events in the 20th century, such as the European drought of 1976, and compared them with actual observed data that detail the extent and intensity of the events.

Droughts and floods have very different characteristics, both in timescale and extent, but WATCH has developed techniques that are applicable to both. Key outputs of this work are the European Flood and Drought Atlases for the 20th century. Both of these are covered within "Floods and droughts" starting on page 19.

The global climate and hydrological data sets are high-value outputs of WATCH, and they have great importance for the future. However, we also need to understand how new activities and practices will impinge on the water cycle. Irrigation, changing land cover, and changing agriculture all affect river flows and evaporation, as do large-scale changes in industrial and domestic use. In many areas of the world, these activities are already exploiting water resources at unsustainable levels. WATCH includes regional studies – particularly in Asia – where these activities and practices are prevalent. The outputs from these studies help to improve models, serving as a reality check on model performance. They also help to improve forecasts for these regions, and to identify management options to overcome water-related problems.

These findings are being built-in to models – irrigation is just one example – and a range of other data sets that complement the forcing and driving data are now available. These include global surface temperature, forest rainfall interception, dams and reservoirs, cropland area (irrigated and rainfed), open water on land, and a number of others. Further details on this work and the data sets can be found in "Feedbacks, evaporation and land use", and in "Reconciling supply and demand" starting on pages 24 and 29 respectively.

Whilst WATCH provides the best picture yet of the future water cycle and the demands that will be placed upon it, it is very much a first step. With its combination of data and models, WATCH has shown that the water cycle is clearly changing in response to a range of drivers. Richard Harding of CEH, co-leader of WATCH said "WATCH has shown that there is still substantial uncertainty in our modelling of the future water cycle. Yet, as we develop understanding of the driving processes, we will be able to make more confident assessments for the future. The next challenge is to communicate and apply these results within the wider user community."

WATCH forcing and driving data

The WATCH Forcing Data is a single data set of climate variables that covers the period 1901 – 2001. It has been produced by combining the Climatic Research Unit's monthly observations of temperature, "wet days" and cloud cover, plus the GPCCv4 monthly precipitation observations, and the ERA40 reanalysis products (with the addition of corrections for seasonal – and decadal – varying atmospheric aerosols needed to adjust the solar radiation components).

The WATCH Driving Data covers the period 2001 – 2100 and has been generated using three well-established climate models that have been downscaled and bias corrected. Each model was run for two different IPCC scenarios, giving six data subsets within the driving data.

All of the forcing and driving data sets cover the land surface of the Earth (excluding Antarctica) on a 0.5 degree x 0.5 degree (~ 50km x 50km) grid. This gives 67,420 data points. Each data set provides eight variables. These are –

- air temperature at 2m above ground;
- surface pressure at 10m above ground;
- specific humidity at 2m above ground;
- wind speed at 10m above ground;
- downwards long-wave (infra-red) radiation flux;
- downwards short-wave (solar) radiation flux;
- rainfall;
- snowfall.

The first five variables are provided at 6-hourly intervals, the remaining three variables are provided at 3-hourly intervals. The WATCH Forcing Data and WATCH Driving Data are freely available.

For further details visit www.eu-watch.org/

From climate to river flows

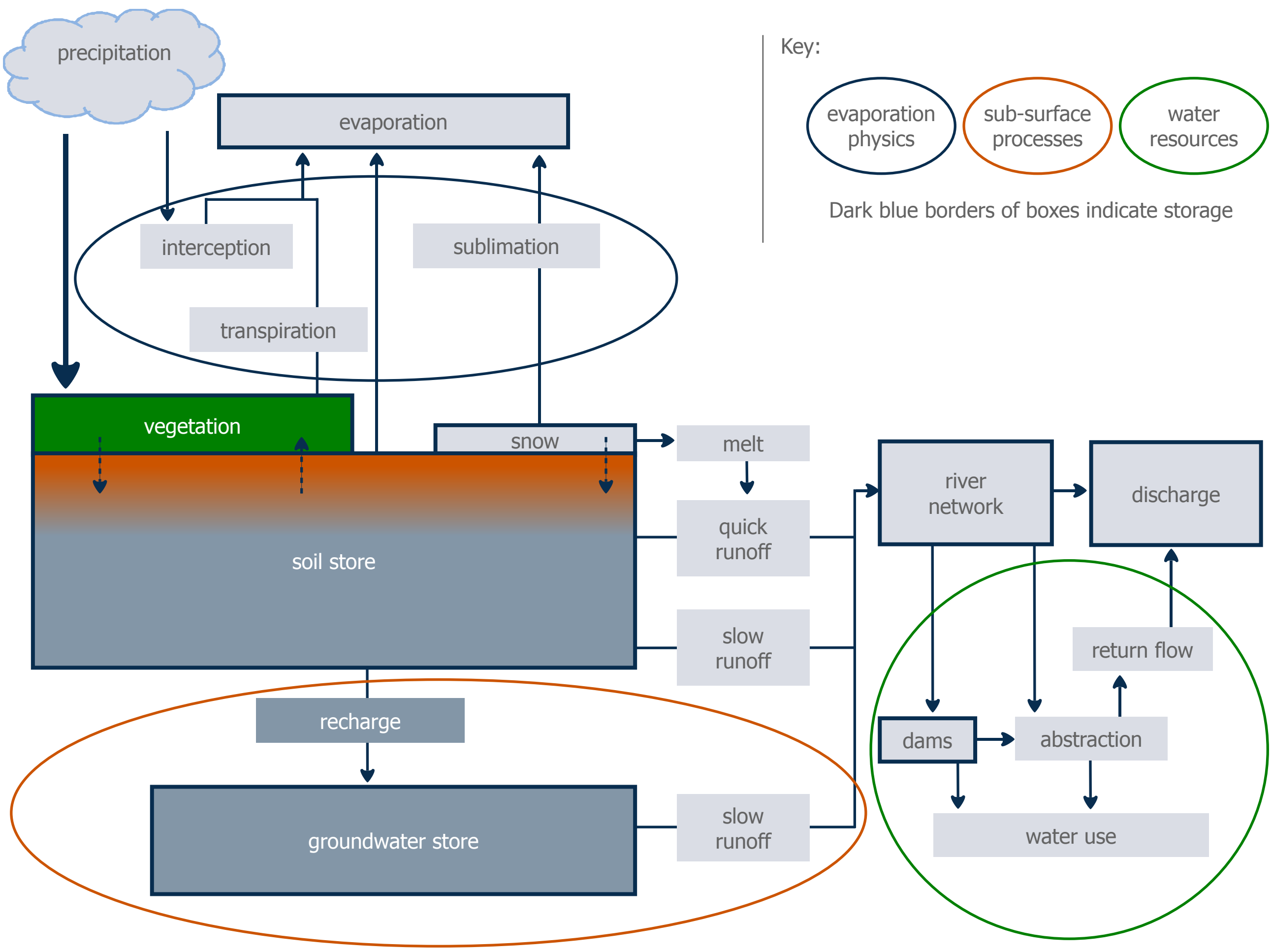
The science of climate change is now well-established. Yet, climate scientists continue to separate what is happening in the atmosphere from what is happening on the ground; particularly when water is involved. This is not realistic. WATCH was established to bridge the gap, and to resolve the water cycle at the global scale so that studies of climate and hydrology become inseparable.

Climate models can deliver figures for rainfall across the Earth's surface, but there is no simple formula to translate these into river flows. Every catchment is different and the proportion of rainfall that finds its way into rivers, and the delay in it doing so, is influenced by topography, soil type, land cover, geology, human activity, and other physical processes. To translate climate into river flow we need models that capture these influences. Numerous models exist, but they have been developed for a variety of purposes, many at the catchment scale, and often for areas as small as a few thousand square kilometres.

WATCH needed to establish whether it was possible to upscale these models and use them to produce meaningful results at a global scale.

The model inter-comparison project (Water MIP) was a relatively small component of the original WATCH plan. However, recognising its potential to improve models, to quantify uncertainty within them, and to provide a valuable framework for future global water-cycle work, it quickly became a major output of WATCH. Water MIP will benefit inter-governmental policy-making and large scale impact studies in the future.

Processes involved in moving from climate to river flows



The processes involved in moving from climate to river flows are complex and numerous. Each model will have strengths and weaknesses in the way that it represents these processes. The arrows indicate routing of water within a model.

Water MIP embraced two types of model: land-surface and hydrological. Both types take climate data – along with other variables – and are able to provide estimates of evaporation and river flows. However, the methods that they use to achieve this can be quite different. Land-surface models are concerned primarily with the physics of energy exchange at the land surface. Representation of hydrological features and processes within them tend to be simplified. Hydrological models tend to be more statistically based, and focus on hydrological features and processes. The physical processes within them, such as evaporation, are often simplified.

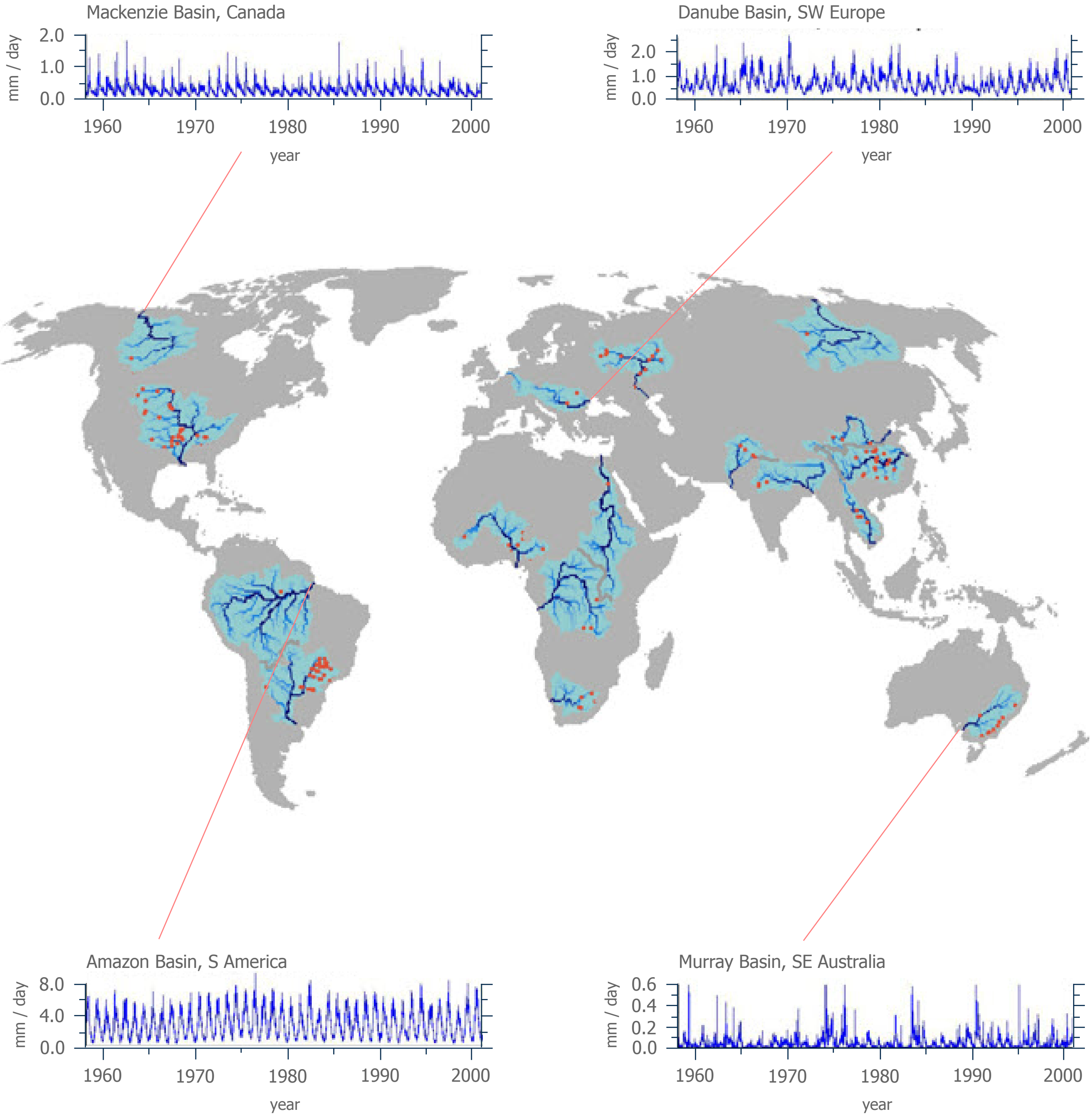
Seven models were included in the first phase of Water MIP. By the later phases, as global interest in the project grew, this number had increased to thirteen.

Running such a large number of models with daily data at a global scale, and for such long time periods had never been attempted before. For it to be successful it needed a strict framework. It is worth remembering that these models have evolved independently over a number of years and have been subject to different institutional (and national) influences. And, each has its own operational needs. The modelling groups came together to agree the framework, and during this they established links that would be of mutual benefit during and beyond the lifetime of WATCH.

The over-riding requirement of the framework was for all models to accept the same input data – namely the WATCH Forcing Data, and WATCH Driving Data - and also non-climatic data such as land cover and irrigation. This requirement underpinned our ability to perform true comparisons.

To comply, models needed to be adapted. The changes that were necessary included moving from monthly to daily time-steps, and introducing the capability to accept and utilise new data types.

The "land mask" and major drainage basins

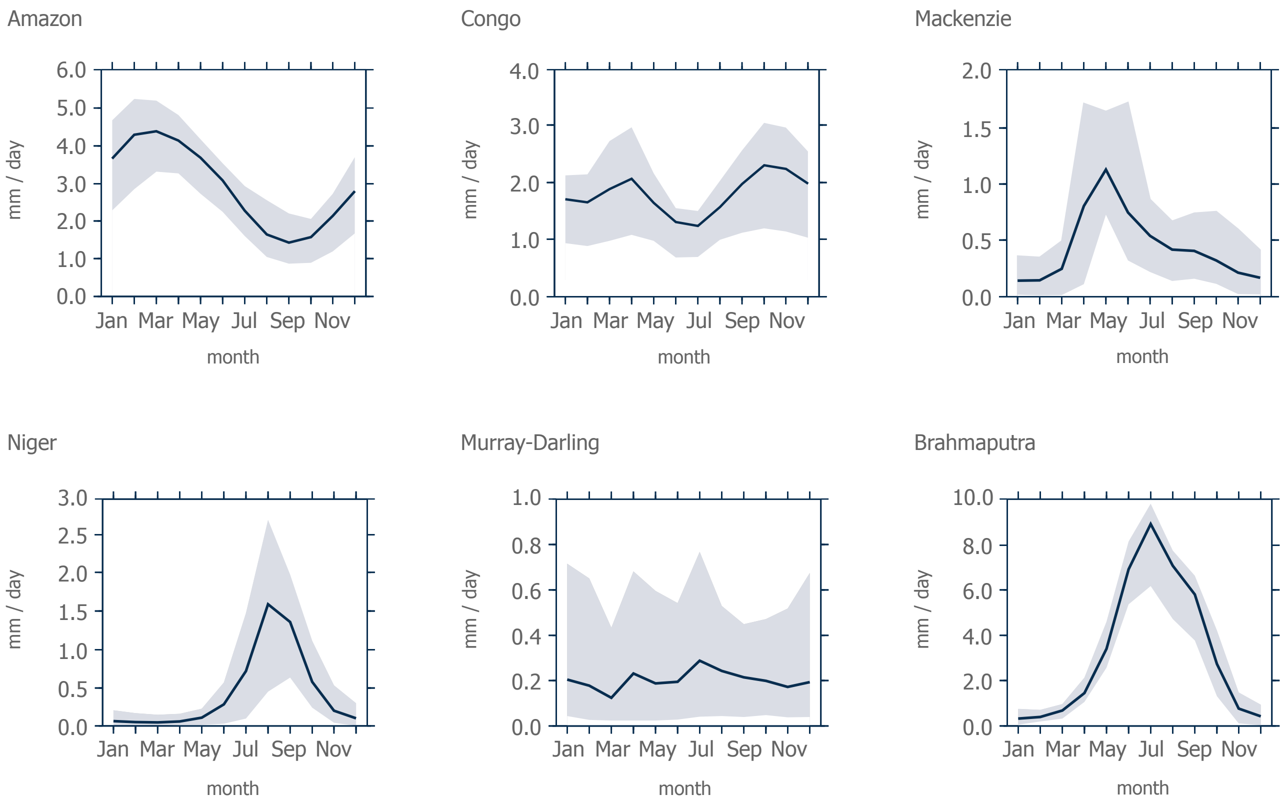


The river drainage network for 18 major global basins (light blue), including rivers (blue and black), and location of major dams (red). All models in WATCH used the same river routing scheme and land-sea mask for portioning land in every grid box. The time series data illustrate the daily average total runoff (i.e. surface plus subsurface) in mm per day for selected basins for 1958 – 2000. The time series are area-weighted averages for each basin from an ensemble of six hydrological model outputs run using the WATCH Forcing Data.

Other protocols were established within the framework, such as a standard agreement on the "land mask" (the grid cells describing the Earth's surface that were to be used in the study), and the paths that rivers should take over the landscape.

The changes to the models were completed before the WATCH Forcing Data was available, so the inter-comparison was trialled using alternative data sets containing the agreed variables for the periods 1961-1990 and 2071-2100. Later runs used the WATCH Forcing Data.

Multi-model total runoff



Multi-model total runoff monthly mean in mm per day for six of the world's major river basins for the period 1985 – 1999. The shaded area represents the range of the thirteen models. The continuous blue line is the ensemble mean.

A number of individual runs were completed. Ones that assumed natural pristine conditions were then compared with runs that included human influence. The final phase used the WATCH Driving Data, and looked at the 21st century, with the focus on the potential impacts of climate change.

The first phase revealed large disagreements between the modelled river flows. Interestingly – and a little unexpectedly – the two different types of models did not fall into two distinct camps of over-estimation and under-estimation. The exception to this was in areas where snow is a major influence on the hydrology.

The main root of the differences lay in the way that each model handled evaporation, with a number of models becoming unstable when evaporation rates changed significantly. This was a concern because changes in evaporation are an anticipated feature of climate change. Until now, the uncertainties attached to rainfall estimates have received great attention, but it was clear from the first results of Water MIP that equal attention needs to be paid to evaporation.

This issue highlights the fact that even if models have been calibrated for past or existing conditions, it does not mean that they are calibrated for all future scenarios. One approach to improve our understanding of what is required of the models is to calibrate them for a 20-year period, e.g. 1921 – 1940, and then to run them for successive 20-year periods, 1941 – 1960, 1961 – 1980, etc.. The models can be recalibrated after each run to better-understand a model's response to changes over time. This is a pragmatic approach, but it still provides no guarantee of a model's ability to model the future given that most predicted rates of change outstrip anything that we have seen in the 20th century.

The outputs of the models have been validated using discharge data from a set of large catchments such as the Amazon, the Danube and the Brahmaputra. The use of large catchments is a useful reminder of the scale for which the models are suited. We must remember that each gridded cell of the input data is 2,500km^2. A catchment the size of the Rhine contains fewer than 70 grid points which provides limited scope to capture the variety within it.

Despite the models not agreeing on absolute figures, there is encouraging agreement on the expected rates and level of change in river flows that are predicted for the future. And, with such a number of models available, it gives strength to an ensemble approach.

The first impressions from running the models for the 21st century with the WATCH Driving Data are that the results are highly suitable for analysing large-scale phenomena. Water MIP has developed the data and tools to provide a consistent multi-model approach to assessing impacts on the water cycle at a global scale, and it has taken the first steps towards a consistent assessment of water availability. This complements the approach taken with climate studies – such as in IPCC Reports – and reduces the need to rely on local hydrological studies that are unlikely to be representative at a global scale.

There are still large uncertainties attached to the models, and work will continue to identify and quantify these. In addition to the uncertainties, there are shortcomings with some of the input data that are available. Groundwater is a particular problem. It is not well-represented within models and it is very difficult to obtain daily abstraction data over large regions. Even if the data exist, there can be pressures not to make them available; some authorities are reluctant to reveal the extent of reserves, or perhaps to reveal the unsustainable way that reserves are being exploited. In addition, details of the proportion of pumped groundwater and river extraction used in irrigation schemes are very sparse.

Large scale groundwater use does lead to local imbalances within the models and this can cause them to highlight areas where the use of groundwater is likely to be unsustainable. What is not clear is the time scale over which the groundwater extraction is unsustainable. If it is over the short term, the groundwater may be rapidly exhausted. In these cases the only solutions are either engineering-intensive, such as bringing water from further afield, or else moving the scheme to another area.

The global approach of Water MIP provides estimates of river flows in areas where little or no historical river flow data exist. This is important for the future because it is possible to envisage large scale irrigation schemes being established in new areas – for example, in the Zambezi and Congo basins.

Whether it is moving existing irrigation systems to new locations or establishing new schemes in otherwise untouched areas, the potential effects of these can be quantified using the approaches developed within Water MIP.

The models have been developed and improved during the course of the project. They have shown that they are fit-for-purpose for estimating river flows at global, continental and regional scales. They have also shown themselves to be adaptable and able to utilise new data sets as these become available. And, whilst the running of the models takes time, computing power was not a constraint, so runs could be scheduled as required from time to time.

We are now more than ten years into the 21st century, and there is a strong argument to update the WATCH Forcing Data and the WATCH Driving Data. This will support regular multi-model runs to produce data for the assessment of the vulnerability of global water resources for the next 100 years, rather than for just the 21st century. This is pertinent given that there are many people who are alive now, who will still be alive in the 22nd century.

Water MIP – a community effort

One of the aims of establishing the modelling framework was to accelerate improvements to models. After each phase of Water MIP, the comparing of results provided opportunities for introspection: for modellers to assess how other models were performing, to understand the reasons for disagreement, and then to go away and to use the new understanding to improve their own models.

In addition to improvements, groups also introduced new modules to their models – for example, to accommodate water quality – and this also served to inspire and invigorate other groups.

Evidence of the desire to improve models was observed by Christel Prudhomme of CEH. She said, "At the beginning of Water MIP there were seven models, and whilst everyone was willing, there was some anxiety surrounding how models would perform against each other. Towards the end of the project, when we had thirteen models involved, one modeller had missed a deadline and had failed to make available his outputs for comparison. His extreme disappointment at his data not being included was symptomatic of the commitment and enthusiasm shown by all participants."

Floods and droughts

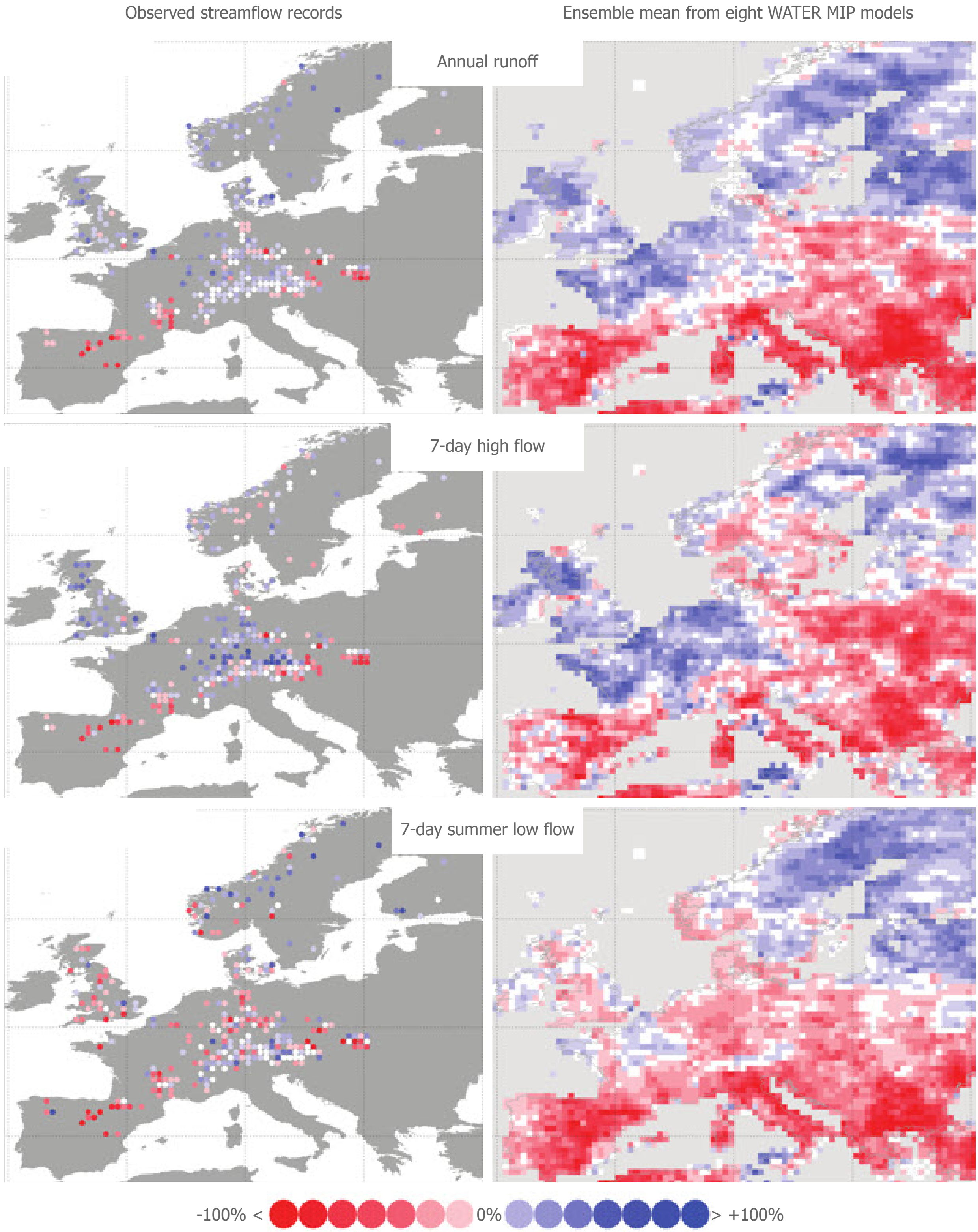
Extreme events in the water cycle cause damage, disruption and loss of life. A changing water cycle will include changing extremes. According to IPCC predictions, there will be increases in the length and severity of droughts, and more seasonal and regional changes in floods. Policy makers and planners need the information to deal with this. WATCH has developed methods and techniques to recognise and record the conditions that have caused floods and droughts in the past, so that we can analyse the likely effects of future changes.

Floods and droughts are the result of markedly different processes. Large-scale floods are usually generated by intense, and long-lasting rainfall, or by snowmelt. Droughts are characterised by persistent large-scale weather circulations causing low rainfall, often in combination with high rates of evaporation. Despite these differences, WATCH has looked at floods and droughts together to develop techniques and methods that allow consistent characterisation of extreme events at the European as well as the global scale.

As the name suggests, extreme events are rare. To make analysis meaningful, we need long data records of daily river flows for several decades or more. The WATCH approach of exploring trends at the pan-European scale means that the data set must also include enough measuring sites to capture the range of topography and climate across Europe.

WATCH has compiled an exceptional pan-European data set (the EWA/WATCH data set) of more than 400 stations with observed river flows covering the period 1962 – 2004. These data have contributed to the

Trends in European runoff



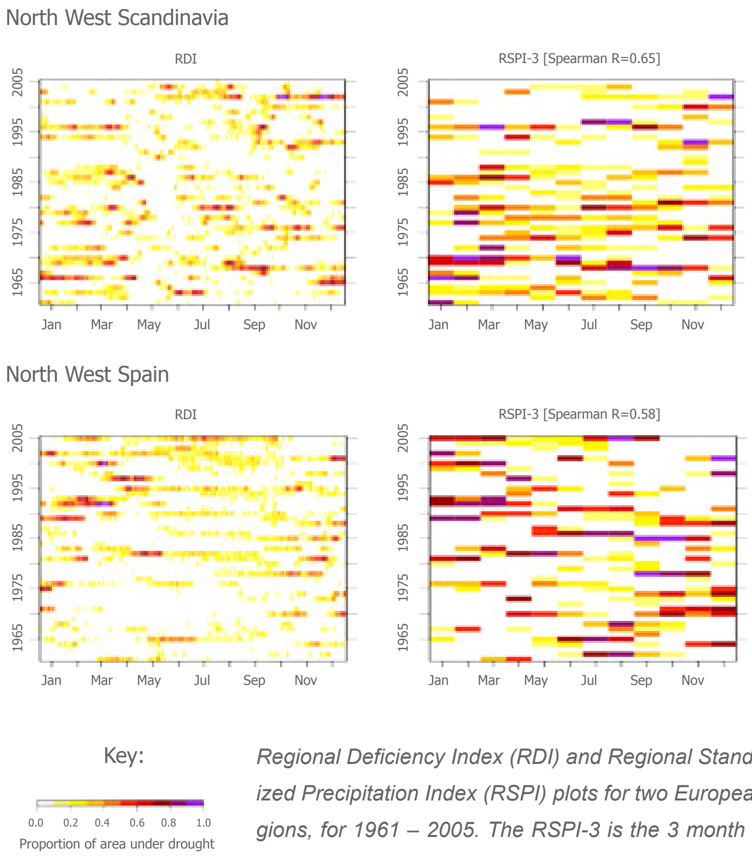
Trends in European annual runoff for 1963 – 2000. Trends are expressed in percentage of the mean over the time period. Correlation between trends in observations and multi-model mean in the respective grid cells are r=0.65 for annual runoff, r=0.6 for high flow, and r=0.45 for low flow.

production of flood and drought maps for Europe which can be combined with other key data sets to produce figures for the human, economic and environmental consequences of individual historical events.

The data set is also ideal for evaluating models that are being run using the WATCH Forcing Data. In the past, river flow data from global models has been validated using observed data from large continental-scale catchments such as the Danube or the Amazon. The EWA/WATCH data set is compiled from smaller, undisturbed catchments, and the network of measuring stations is dense enough to provide meaningful information over a large area. It is this denseness of data that has allowed WATCH to assess the ability of large-scale hydrological models to reproduce extremes at continental scale. This is a significant addition because, as a general rule, large scale models have focused on annual, seasonal and monthly means for large river basins.

The model intercomparison of extremes has helped to reveal the strengths and weaknesses of the individual models. This exercise provided invaluable feedback to the modellers and has improved our understanding of the water cycle.

Novel methods for depicting drought



Regional Deficiency Index (RDI) and Regional Standardized Precipitation Index (RSPI) plots for two European regions, for 1961 – 2005. The RSPI-3 is the 3 month SPI averaging interval. It is the one most correlated with RDI .

The ability to reproduce extremes will improve as this feedback is incorporated into revised models. This is highly encouraging as we look to model extremes using the WATCH Driving Data for the period to 2100.

Access to up-to-date data is essential when we are trying to identify trends over periods that include the immediate past. Unfortunately, access to hydrological data is not as easy as it should be, and our ability to make further progress will be hindered unless accessibility is improved.

Two highly visible outputs of WATCH are the Flood and Drought Atlases. They capture the characteristics of droughts and floods over the 20th century across Europe.

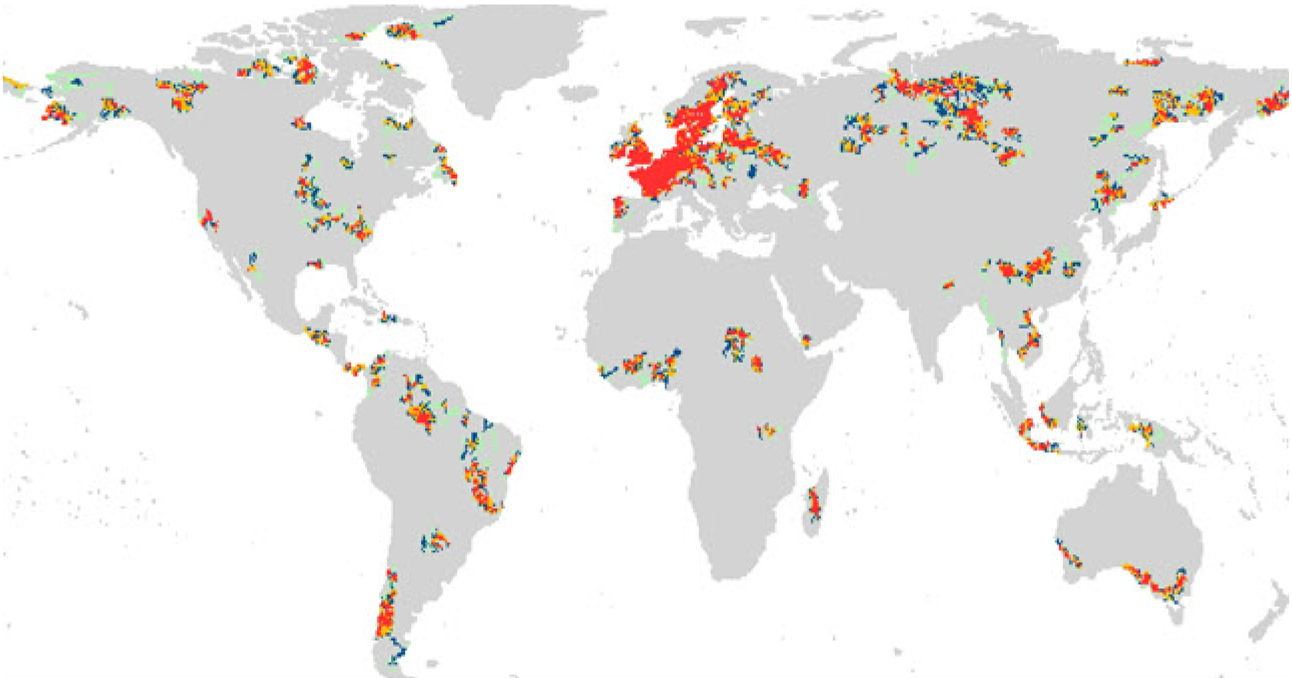
Similar work has been done in the past, but the WATCH atlases use newly developed, more visual, and more intuitive ways to present the timing and location of events, their duration and extent, plus their severity. The atlases are also very good at presenting rainfall and streamflow anomalies. For example, they can highlight when and where a particular amount of rainfall has triggered an unexpectedly severe flood. The reasons for this can then be investigated.

The atlases have established a comprehensive reference of historical European floods and droughts, viewed in a continental context rather than national or regional. This larger scale approach allows policy makers to see beyond their own region and to see how their responsibilities link to neighbouring areas that may be experiencing similar conditions, and to judge when coordinated management is needed. The atlases also provide a benchmark of extremes against which to compare future modelled data, and future observed events.

The EWA/WATCH data set has been used to detect changes in observed data over time. The analysis concurs with climate records for Europe, showing higher mean annual flows in the wetter north, and lower annual means in the drier south.

Analysis also revealed that in those regions that experience low flows during the summer, we are now seeing lower low flows. But in contrast, in regions that experience low flows during winter (due to freezing conditions) there are now higher low flows. This is because increased temperatures are causing winter snowmelt. Seasonal changes within years are also apparent. In northern Europe, the period December-February is becoming wetter, and there is a noticeable shift towards drier conditions in March and

Synchronicity of global drought



Synchronicity of global drought for August 1976. Red areas indicate where the simulated runoff is lower than 5 out of 100 yr runoff (95%), orange: runoff lower than 10 out of 100 yr runoff (90%), blue: runoff lower than 15 out of 100 yr runoff (85%) and light blue: runoff lower than 20 out of 100 yr runoff (80%)).

April. Further work will reveal whether this is the result of trends in temperature or rainfall. Our objective is for the models to reproduce subtleties such as these.

The outputs from nine hydrological models using the WATCH Forcing Data were assessed. The different data-needs of the climate and hydrological modellers are described in "From the 20th to the 21st century" starting on page 9.

WATCH has shown that these models can reproduce flow dynamics and high flows, but they are less capable of reproducing low flows using daily input data. There is a satisfactory spread of results either side of the observed data, with the mean of the modelled results coming closest to the observed. The annual patterns of maxima and minima are promising, but there are clear weaknesses in reproducing the seasonal and monthly flows, and low flows.

The models tend to perform better in wetter regions – because it is easier to model the response to rainfall when soil is moist. They are also good at capturing the start and the peak of droughts, but there is disagreement in how they show a drought developing and ending.

The location and extent of large-scale droughts are reproduced satisfactorily by the model ensemble, and so are trends in annual flows. Thus, the model ensemble provides a full coverage of Europe (beyond the observations), as shown in the figure on page 20 for the annual trends. A pronounced drying in southern and eastern Europe is observed, and this pattern of change agrees with future predictions based on climate change scenarios.

These first results are encouraging, and work is now looking at the internal processes of the models to identify why they produce different results.

Some of these differences will be down to the way that models represent the key drivers of high and low flows. One feature that can cause large differences between models is the representation of snow. The physical processes related to snow melt are complex, and models represent them in a wide variety of ways.

Groundwater is another feature that is not well-represented within models, and that has the capacity to influence both floods and droughts. A catchment with groundwater will be more resilient during periods of drought than one without. This can cause observed "patches" within maps of large-scale drought. These patches can be difficult to explain without access to river basin data or a model's ability to simulate stores in the river basins.

One approach in the future may be to identify the different drivers within regions and select the models that are best able to represent them.

A complementary study within WATCH looked at five small catchments across Europe. The objective of this study was to assess the ability of relatively large scale data to reproduce droughts in small catchments. It found that using the more coarse WATCH Forcing Data (rather than more detailed local forcing data) as input for the hydrological models did not lead to substantially different drought characteristics for the small catchments. This means that WATCH Forcing Data can be used in places where local forcing data are not available.

The catchment studies also showed that the ensemble mean of the large-scale models (running with the WATCH Forcing Data) reproduced drought characteristics similar to more detailed hydrological models that were using local forcing data.

The success of the large and small scale studies gives us confidence that the hydrological models will produce meaningful extremes of runoff when they are applied to the 21st century using the WATCH Driving Data. Comparing the outputs with the atlases will then reveal how the location, timing and severity of extremes will change in the future.

The detailed study of droughts such as those in 1976 and 2003 helps us to understand how they developed over an area, over time, and in intensity. Droughts are highly complex, but tools are being developed that will recognise historical patterns. This will allow us to forecast how large-scale droughts might spread in the future. Given the slow rate at which droughts develop, such tools would have operational applications. The tools will also allow us to anticipate the occurrence of simultaneous droughts across the world. Such occurrences, for example in the world's main food producing regions, would exert considerable strain on world food security.

WATCH has also identified the best methods for drought characterisation on a global scale and made recommendations for standardisation to allow inter-comparisons of drought characteristics across the world.

WATCH has made significant progress in understanding and recording hydrological extremes in the 20th century and has provided the clearest evidence yet that it is possible to model these both on a European and global scale. However, models need to be improved further, and WATCH has demonstrated that such improvements are accelerated by the availability of comprehensive and up-to-date observed data. Europe has a dense network of river flow measuring sites, but needs the data from these sites to be made more readily available, preferably through a single outlet. A system is already in place for flood warning at JRC in Ispra. This network could be expanded – an evenly spread network of 500 stations would be a starting point – to include sites that are suitable for drought studies. If the momentum of WATCH is to be maintained, then this matter needs to be addressed swiftly.

A pan-European data set of river flows

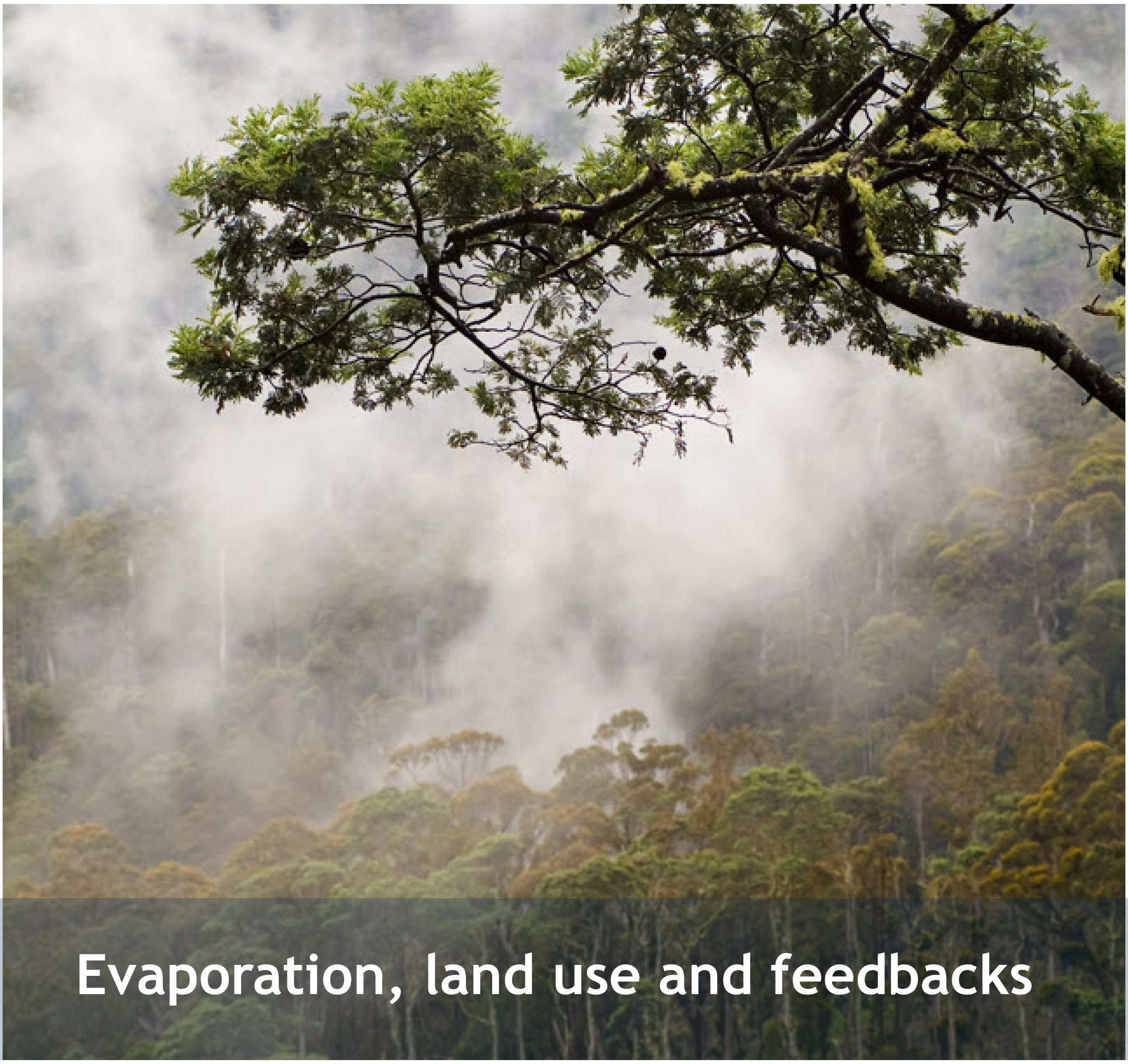
WATCH needed a pan-European data set of daily river flows from undisturbed catchments covering at least the last 40 years as an addition to the larger river basins included in the Global Runoff Data Centre. With no central data source, WATCH obtained permission to use data from the European Water Archive that had been collected as part of an earlier international project (UNESCO FRIEND). This ran until 1992 and had amassed data from stations dating back to 1962. To bring this up-to-date, WATCH contacted the measuring authorities – there is often more than one for each country. Responses provided data for 1993 – 2004 from over 400 sites in fifteen countries.

Unfortunately, there are still a number of areas on the map of Europe that have no representative data in the WATCH database. This is frustrating because we know that data *do exist* for these areas, but for a variety of reasons, they cannot be obtained through reasonable effort. The frustration is doubled because these areas – eastern and southern Europe – are the regions that are identified as being most sensitive to climate change.

The need for a more coordinated, centralised and accessible approach to river flow data from undisturbed catchments is highlighted by the fact that, for largely historical reasons, the majority of data have restrictions on their use. This means that projects that follow-on from WATCH may well have to go through the same labour intensive exercise to assemble quality data sets. This is an avoidable waste of resources.

This lack of accessibility of hydrological data contrasts strongly with the free availability of meteorological data. For example, all upper-air data that is collected is released according to WMO protocol in near-real-time and is then used by national weather forecasting centres throughout the world. Europe's leadership in initiating a similarly open system for key European hydrological data from undisturbed catchments complementing the data base at GRDC, would ensure that the database becomes and remains up–to-date.

Despite the EWA/WATCH data set being a "gold standard" for working on extremes, it is already seven years out-of-date. The additional data would complete a continuous 50-year record, and provide 15% more data. This may further confirm the trends that have been identified up to 2004.



Evaporation, land use and feedbacks

Climate change is only one of the drivers that will affect the water cycle in the future. Human activities – particularly deforestation – are changing large areas of the globe. This change – generally to shorter vegetation of crops and pasture – affects evaporation. This, in turn, has the potential to change not only river flows, but also large-scale weather patterns. Engineering projects such as hydro-electric and irrigation schemes cannot be ignored, and the scale of these will only increase in response to a growing and an increasingly wealthy world population.

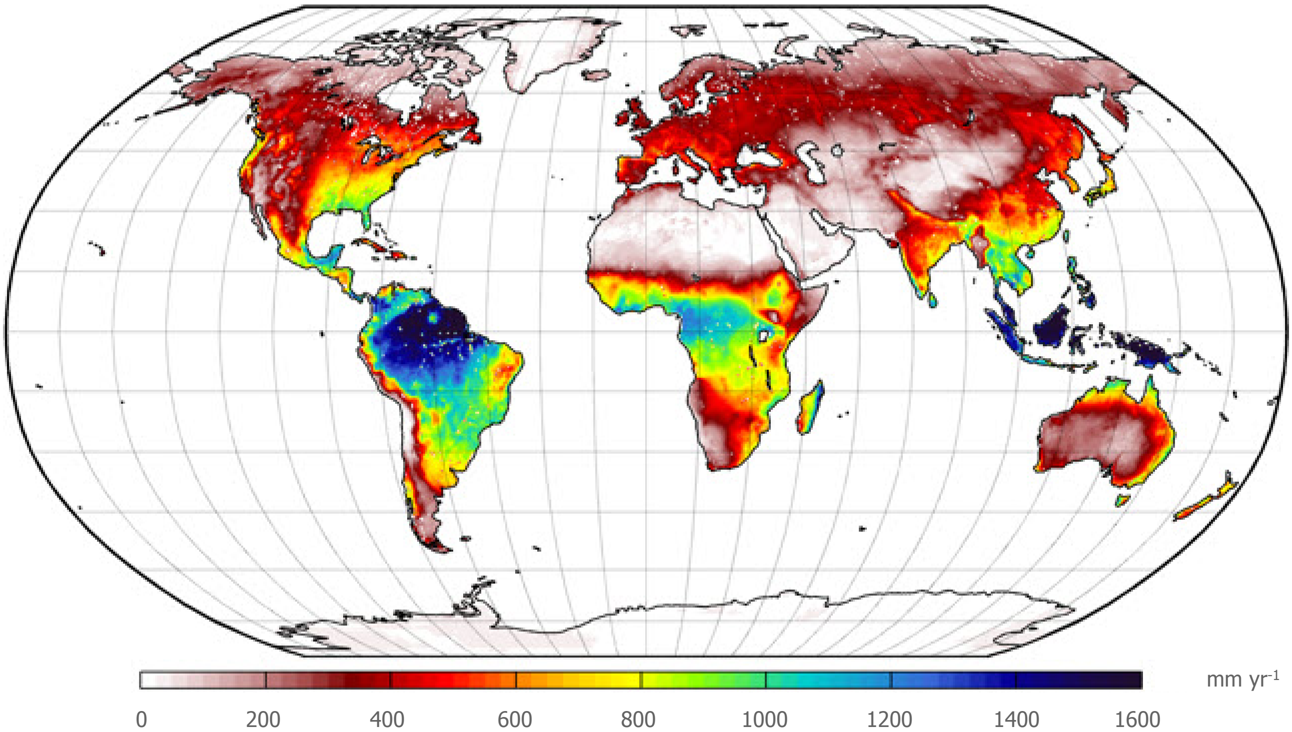
WATCH has made the first steps towards quantifying the effects of these changes at global and regional scales. Key to this is our understanding of evaporation.

WATCH has produced a new global data set of evaporation from land. This is on a 0.25 degree x 0.25 degree (~ 25km x 25km) grid, and has produced daily estimates for the period 1984 – 2007. This provides functionality beyond existing data sets in that it breaks down evaporation into separate components of transpiration through plant leaves, direct evaporation from the soil surface, forest rainfall interception, and snow sublimation.

This breakthrough has been made possible by the availability of high-quality satellite data, coupled with novel and innovative approaches taken by WATCH researchers.

The data set can be used itself for validating climate models, and it will help hydrological modellers to produce improved river discharge estimates at regional scales. And, data-sparse areas such as Africa will benefit greatly.

Land surface evaporation



Average Land Surface Evaporation for 1984 – 2007 in mm per year from the Global Land-surface Evaporation: the Amsterdam Methodology (GLEAM). This data set, derived as part of WATCH, completes the observed global water cycle over land for the first time. With these data we can make progress on understanding the role of the land surface on weather systems and on climate.

Analysis of the data set reveals how different variables affect evaporation at different times and in different places. It is, therefore, highly tempting to seek out trends, but this must be done with caution. Although the data go back to 1984 (when the input data from satellites first became available), we need at least another ten years of data before trend analysis becomes valid. However, the data do appear to support the suggestion that total global land evaporation has reduced over the last ten years.

This is contrary to expectation: increasing temperatures due to climate change should cause an increase in global evaporation. More data are needed and the effect of ocean oscillations needs to be quantified before more meaningful conclusions can be drawn. As Han Dolman of the Vrije Universiteit commented, "WATCH has brought climate science and hydrology together. The next step is to bring in the ocean science. We expect sea surface temperature to have a strong influence on evaporation from the land and we shouldn't consider the oceans and land as existing separately – we need to treat them as parts of a single system."

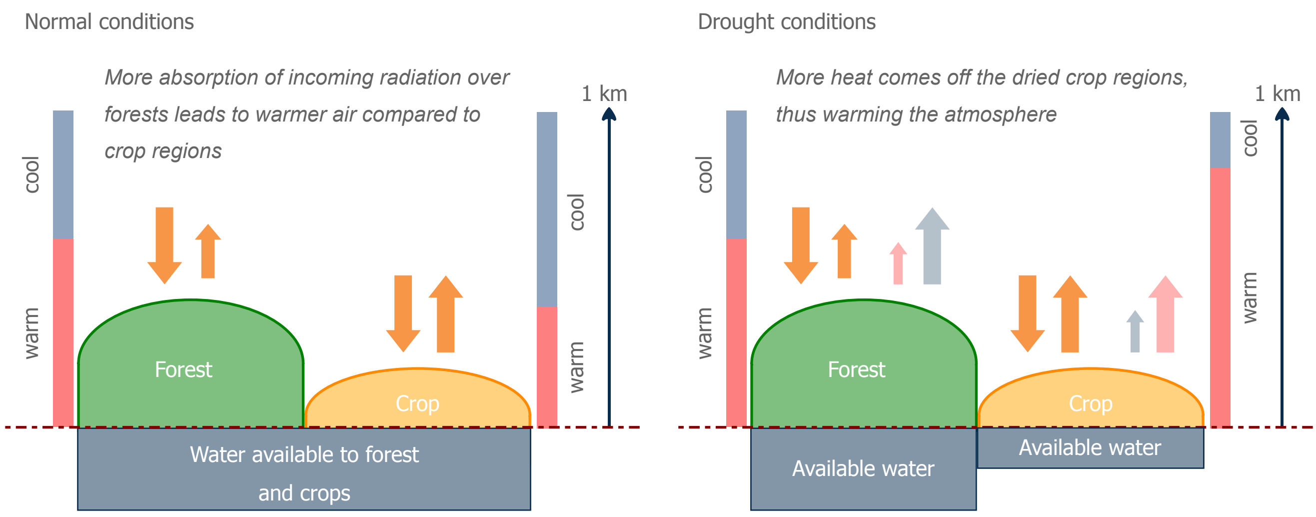
It may be too early to use the data set for trend analysis, but it does reveal the dynamics of evaporation. For example, during summer in Europe and North America there is high correlation between net solar-radiation and evaporation. By contrast, in the Sahara, the Middle East, and central Australia, it is soil moisture (or lack of it) that controls evaporation.

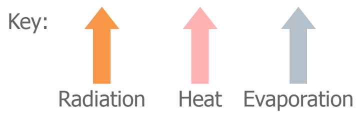
By overlaying the evaporation data set on land cover data, we can see that 30% of global land evaporation comes from tropical forests. If you add savanna to this, the figure rises to over 50%. We can also look at how components differ from continent to continent and region to region. This means that when the data-record is suitably long, not only will we be able to look at global trends, but also changes in regional evaporation, and across biomes.

It is clear that land use and land cover influence evaporation. Hence, changes to land use will cause changes to evaporation rates, and changes to the climate and the water cycle. WATCH has produced a map of land cover change over the 20th century and produced estimates and scenarios for what might happen in the 21st century.

WATCH has modelled changes in climate due to changing land use over

Schematic of water use during normal conditions and during droughts





In times of drought, the deeper roots of forest trees can access water. In addition, forest trees can also conserve water whilst crops use it up. This is a vital consideration when land use change is planned.

the last century to understand the overall climate-impact of the wide-scale deforestation that has been a feature of that period. The aim of this was to determine how man-made changes to the landscape have influenced regional weather.

Models agreed that in the two key regions of largest land-use change – mid-United States and western Russia – changes to climate could be identified. The removal of forest and replacement with shorter vegetation of crops or pasture is likely to have cooled temperatures by about 1°C in these areas over the last century.

Despite this identifiable change, the models did not agree on the impact on evaporation and rainfall; with some suggesting an increase, and others a decrease. Some of this disagreement can be attributed to the different ways that the models handle the land-use data. Methods are being developed to make this more consistent.

A further reason for disagreement is that there are conflicting reasons for the evaporation and rainfall to vary.

When forests are replaced by crops and pasture, it alters the available moisture in the soil, notably its capacity to absorb energy, and the efficiency of exchange of surface heat and moisture between land and the atmosphere. Some of these changes are likely to increase evaporation, whilst others are likely to cause a decrease. The models treat the processes differently. One way to deal with this is through an ensemble approach – taking the mean of the collective results and using the range of estimates to derive the uncertainty.

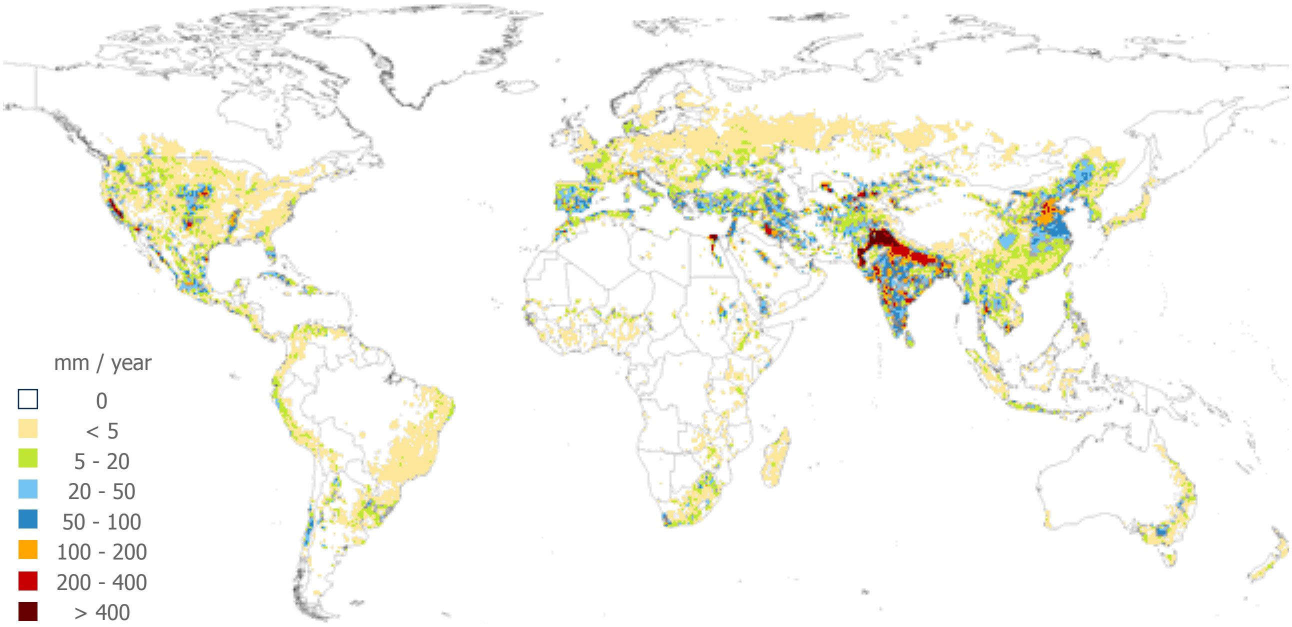
Overall, the models confirm the need for land-use change to be considered as a driver of climate change, and any predictions of future climate ought to include the impact of land-use and land-cover change.

So far, we have talked only of land-surface processes. Changing rainfall patterns and evaporation, and changing vegetation cover affects the rate at which groundwater reserves – on which large proportions of the world's population rely – are replenished. It is only when we obtain a better understanding of the surface impacts and feedbacks of these changes that we can begin to assess the impact on groundwater. Until now, river flow and groundwater models have developed independently. WATCH has striven to achieve better representation of groundwater within hydrological models, and better representation of evaporation within groundwater models.

In addition to exploring land-cover effects on weather systems (using climate models), WATCH has used hydrological models to explore how land cover can influence the proportion of rainfall that enters rivers. WATCH has shown that some changes in land use can reduce evaporation and increase river flows, but that one type of land use – irrigation – has the opposite effect; it increases evaporation and reduces river discharges.

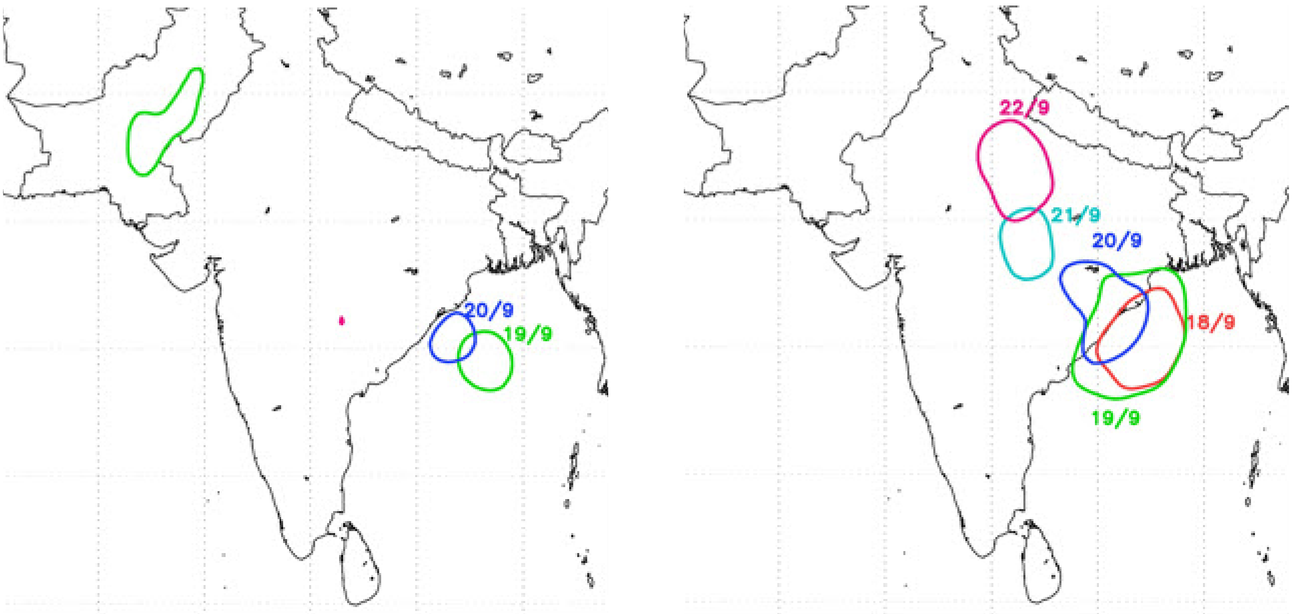
This brings into focus the issue of feedbacks. WATCH has looked in detail at two areas that are vulnerable to man-made change: the Niger Inland Delta, and the Indus and Ganges basins.

Areal extent of irrigated land



The LPJmL model simulated annual net irrigation requirements in mm per year averaged over the period 1971 – 2000. Values per grid cell (incl. non-irrigated areas) highlighting the areal extent of irrigated areas.

Modelling monsoon depressions



Monsoon depression development and movement simulated by the REMO model: 18-22 September 1991 at 999 hPa Mean Sea Level Pressure. The map on the left shows results that do not take into account irrigation schemes in the area. The map on the right shows output from a model run that has included data for irrigation schemes. The results on the right are in-keeping with ground observations. This work is highlighted on the following page.

The Niger Inland Delta in Mali floods every year late in the wet season as a result of rainfall many hundreds of kilometres upstream. Once flooded, the sudden availability of water for evaporation within the wetland contrasts with the strongly moisture-limited sparse vegetation in the surrounding region. This causes a greater than 50% increase (compared to when the region is dry) in the daytime initiation of new convective storms in the region of the wetland. This leads to cloud cover and thunderstorms hundreds of kilometres westwards.

The inland delta study provides observational evidence of a remote hydrological feedback with the wetland affecting both local and regional rainfall. This feedback raises the possibility that changes in upstream water use, for example through large-scale hydroelectric schemes, could have an impact on the climate over a wide area.

The Indus and Ganges basins contain the largest continuous area of irrigation in the world. For the first time, WATCH has quantified and mapped the sensitivity of the onset of the monsoon to irrigation patterns in the region.

A new data set for evaporation

Previous approaches to estimating evaporation at a global scale have used atmospheric conditions to calculate the potential evaporation from a particular type of land cover. This does not take into account the amount of water in the soil, and overlooks the fact that as the soil dries out the actual evaporation dips below this.

WATCH took a data-driven approach, assessing the range of data that were available and devising new optimised algorithms to use them. Soil moisture data was the starting point as it provides an indication of the water that is available to the system.

Like the WATCH Forcing Data, the evaporation data set is now freely available to the research community at -

ftp site 130.37.78.12 (user: adaguest, pwd: downloader) .

The data set has been validated using an existing global network of observation sites. There is strong correlation between the observed and modelled data. However, it is important to remember the limitations of this type of validation. The network of observations is relatively sparse, and each measurement point has a small footprint compared to the model grid which are over 500km^2.

As well as being sparse, the observation network is not evenly spread across the Earth's surface. Large gaps exist which make it impossible to check anomalies in the modelled data – such as in the Congo Basin.

Despite this, the strong correlation with the observed data has inspired confidence in the modelled data.

The ability to provide separate figures for the components of evaporation is a unique feature of the data set. "The explicit calculation of forest rainfall interception at a global scale is totally new," explained Richard de Jeu of the Vrije Universiteit. "When rainfall is intercepted by forest canopies, some evaporates without ever reaching the ground. This interception occurs at much higher rates than the other evaporation components, making it critical that we estimate it separately."

Researchers used the novel approach of applying a "lightning frequency" data set to identify the locations and timings of intense rainfall. This helped them to develop more accurate methods for calculating interception that could then be applied globally.

The monsoons in this area are driven by the seasonal changes in temperature contrast between ocean and land. Evaporation cools the land, so large scale irrigation changes this contrast. Climate models can only recreate this if they include the effect of large-scale irrigation. This is highlighted by the modelling of depressions over the Bay of Bengal. These depressions are observed to develop over the bay and then head inland. Climate models did not capture this movement until the influence of irrigation was included (see figure on previous page).

The effects of changing the use of large areas of the Earth are highly complex. Within regions it can be unclear as to the overall effect they are having, but WATCH has demonstrated that these changes should not be ignored.

Climate models need to develop methods to represent the changes in land use, and they need to include activities such as irrigation.

Until now we have treated climate and impact models separately. Climate models have been the providers of input data to the impact modellers. We must now aim to couple the models routinely. Impact models must not just receive data from the climate models, but also provide data to them in return. Only then will we be able to model feedbacks, and be able to estimate the effects of future planned changes.

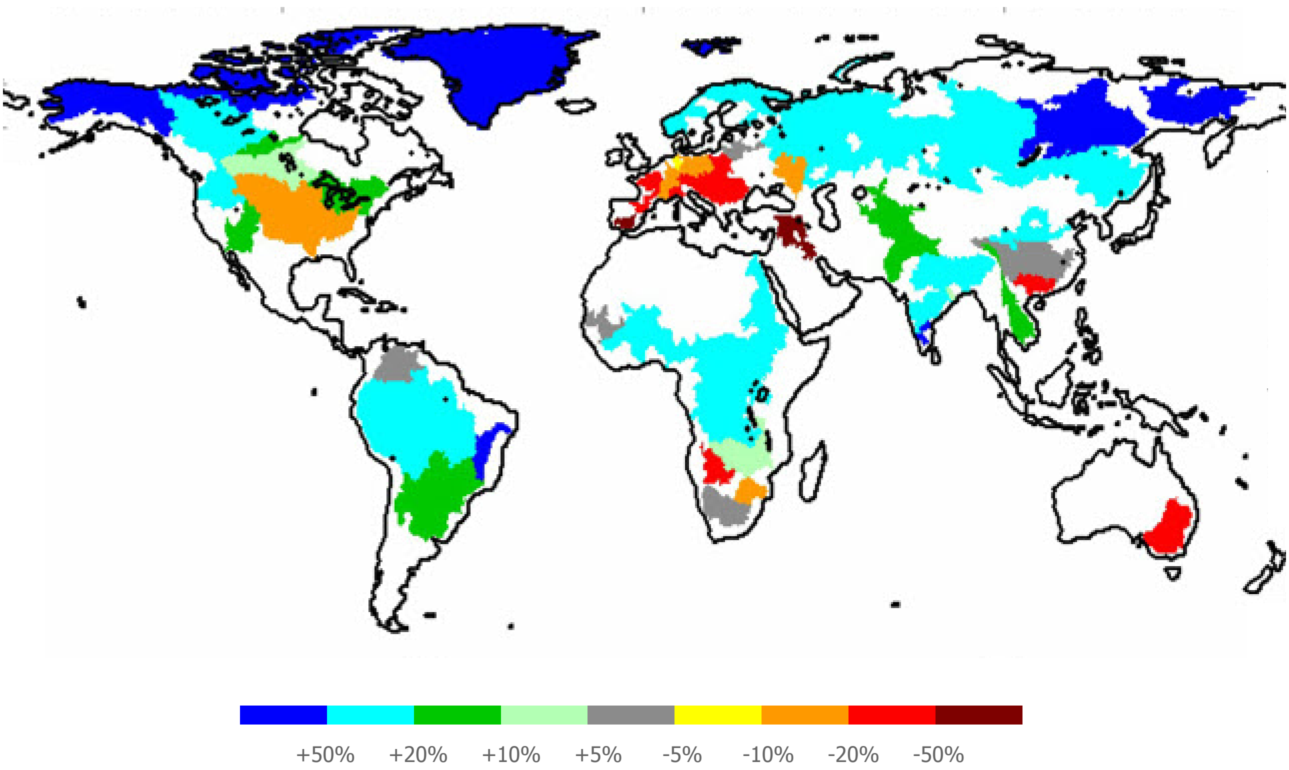
Reconciling availability and demand

The methods and data sets developed in WATCH allow us to make estimates of past and future global water availability. But, it is only when we bring this together with the demand for water that we can begin to identify and quantify where there are deficits – where water scarcity is a problem – and areas where water might be more plentiful. Water scarcity occurs when there is not enough water available to meet the demands of agriculture, industry, and domestic use. To identify such areas, WATCH has quantified water use in these sectors and has assessed the drivers that will influence usage in the future.

The work goes beyond the climatic causes of change in the water cycle by also looking at the socio-economic influences that impinge on water availability and scarcity. For example, in many regions, population is set to increase at a rate that will put far greater demands on water resources than any of the changes that are associated with climate change. The outputs of WATCH will help policy makers to take informed decisions; to identify water-rich areas that have the potential to produce and export more food, and to anticipate where intervention may be needed in the future.

The WATCH approach to assessing water use by rainfed and irrigated agriculture makes a distinction between "blue" and "green" water. The blue part is water that has been withdrawn from rivers, lakes, reservoirs and groundwater for use in irrigation schemes. The green water is the moisture stored in the soil from rainfall. It has been demonstrated that about two thirds of global crop production relies on green water, which

Changes in available water resources at the end of the 21st century



Changes (2071 – 2100 compared to 1971 – 2000) in available water resources projected by an ensemble of eight global hydrology models using data from three global climate models. The available water resources were derived by taking into account the total runoff for selected large-scale river basins minus an estimate of the environmental flow requirements in the respective basins.

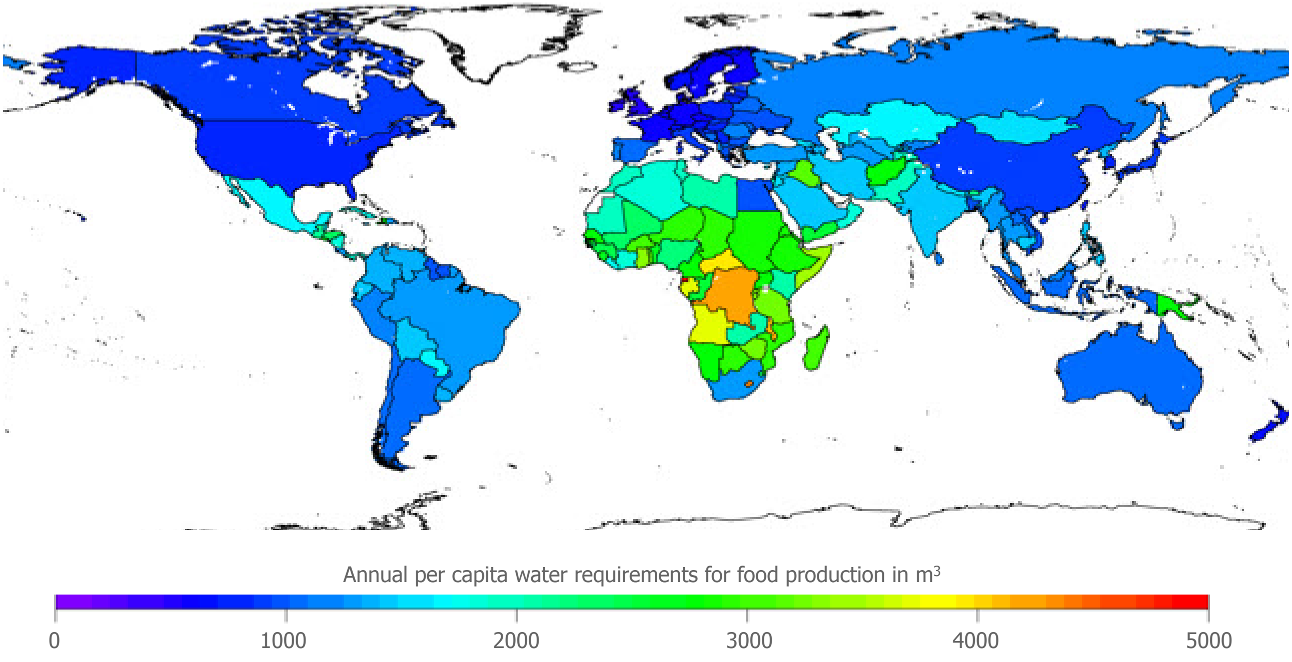
constitutes about 90% of the total agricultural water consumption.

A WATCH study using results from 17 climate models has quantified current and future green and blue agricultural water use and water scarcity. It is the first time that blue and green water use in agriculture have been calculated at a scale of 0.5 degree x 0.5 degree and over such long time periods (up to 2100). WATCH has also compared water availability with the water needed to produce a balanced diet for a country's inhabitants (3,000 kcal per person per day – the hunger alleviation target – with an assumed 20% share of animal products). A key result is that climate change alone is likely to decrease the availability of both green and blue water in a number of countries, while at the same time, in some regions more water will be required for growing each unit of food. Thus, more areas will be affected by water scarcity in the future, and some countries will lose their capacity to produce the food needed to feed their population. If population growth is considered in addition to climate change, even more countries are at risk of losing food self-sufficiency.

WATCH results reveal that approximately half of the blue water that is withdrawn for use in irrigation schemes is from non-renewable or non-local water resources. Globally, the amount of water used in agriculture also far exceeds what was suggested in previous studies that considered blue water only. The use of green water by rainfed and irrigated agriculture is significantly higher than blue water use. These outcomes underline the importance of green water, and they demonstrate that green water flows must be included in global water-resource calculations and in water scarcity studies.

In addition, WATCH has shown that green water flow should feature in all future calculations of virtual water trade. The term "virtual water" describes water used in the production of goods or services. For example, if the production of one tonne of wheat requires over a million litres of water (most of which evaporates from the crop), then that is the virtual water content of the wheat. And, if a country sells that tonne of wheat to another, the virtual water is traded internationally. Until now, water trade

“Green” and “blue” water demand



Green and blue water demand (cubic meters per person and year, 1971 – 2000 average) of countries for producing a daily diet of 3000 kcal per inhabitant per day, assuming that the diet is composed of 80% vegetable- and 20% animal-based products.

figures have been based primarily on blue water.

Clearly, food production must increase to meet the demands of a growing world population. But, the growth in population will not be uniform across the globe. This, together with worsening water scarcity, will increase the need for inter-regional trade.

In response to this, WATCH considered eleven of the world’s major crop types, and produced data sets on a 0.5 degree x 0.5 degree grid, based on calculations of the underlying processes. These data sets show the virtual water trade among countries.

As a result of this analysis, we can now quantify the agricultural water footprints for all countries at the start of this millennium. The agricultural water footprint of a country is the total volume of freshwater used to produce crops that are consumed and/or produced in that country. The footprints were sub-divided into internal and external footprints. The external component is the virtual water that is imported with goods. The blue and green contributions to both internal and external footprints were also calculated. For further information, see the inlay on page 33.

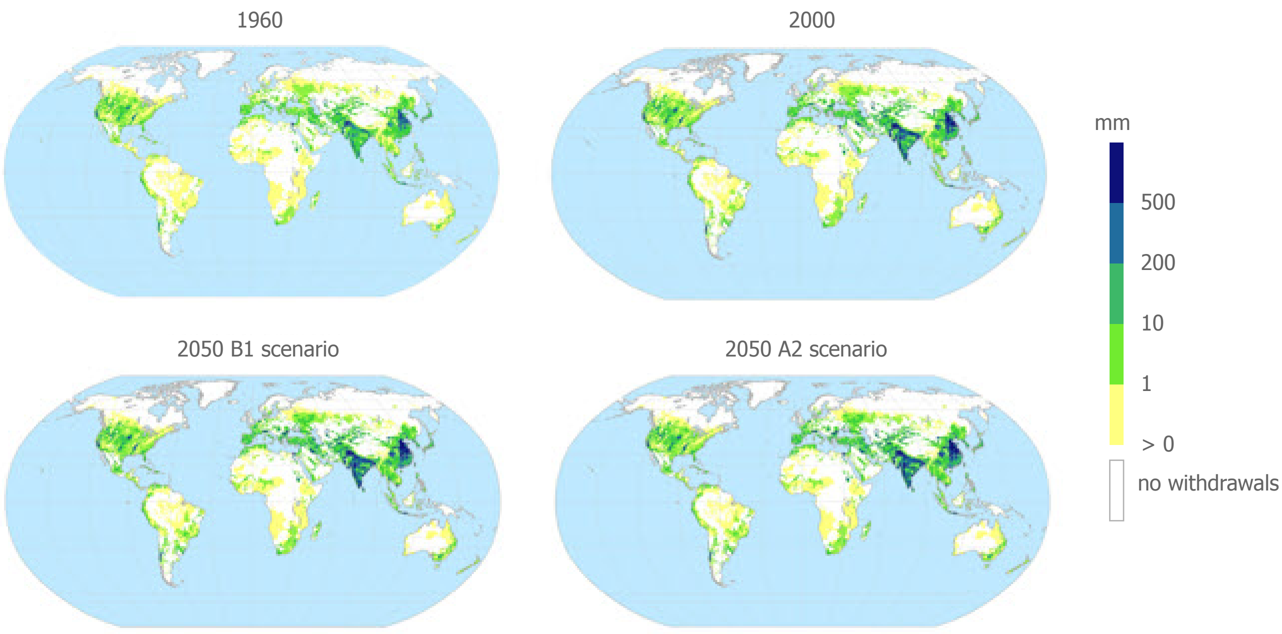
Water demand for industrial use – for manufacturing and energy production – is also increasing, and it already takes a significant volume of the Earth’s freshwater resources. WATCH has produced data sets of water usage that take into account economic growth, water saving technologies, and electricity production by thermal power stations. The methods that have been developed to produce these data sets also provide us with the tools to assess and plan for change in the future.

The amount of water used in manufacturing is calculated as the difference between water that is withdrawn (from rivers, reservoirs, lakes or groundwater) and water that is returned to the system as waste. The water “used” is either lost as evaporation during production, or else is stored in the end-product.

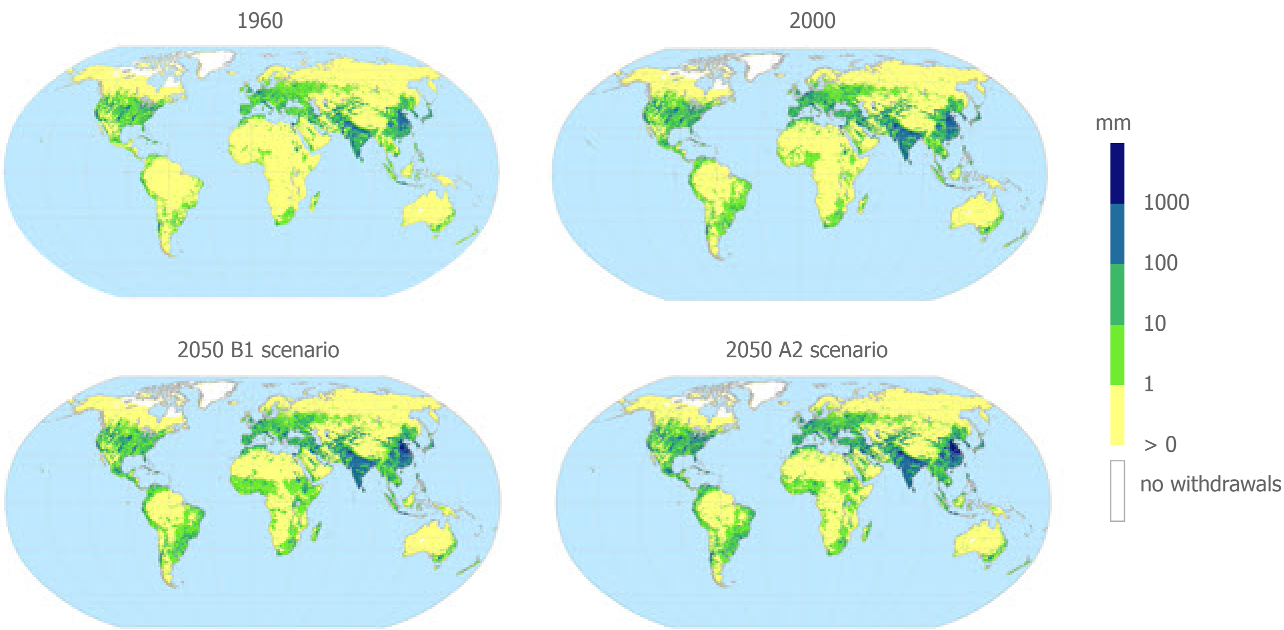
Overall, water use for manufacturing at the end of the 20th century was fifteen times higher than at the start, with a sharp increase from the 1950s. Furthermore, the range in withdrawal and use at the end of the 20th century is increasing; for example, in North America, only 9% of what is withdrawn is actually used, while in Europe this figure is 57%. Despite the massive difference in productivity, North America uses less water for manufacturing than Africa.

Water usage in energy production is dependent on the cooling method employed by the power station – tower cooling, pond cooling or once-through systems. Whilst the amounts differ for each type of cooling system, the relationship between water use and energy production is straightforward, with withdrawal and water use

Water withdrawals - past and future



Water withdrawal for irrigation - in 1960 and 2000, and for two climate scenarios in 2050.



Total water withdrawal in 1960 and in 2000, and for two climate scenarios in 2050.

increasing at the same rate as energy production.

In Asia and the South Pacific, where energy production is increasing at the fastest rate, three quarters of production is generated using tower cooling. Whilst this method requires less water to be withdrawn, it uses more water than non-tower systems because of the high losses through evaporation.

The issue of cooling has been highlighted by another data set created by WATCH. These data provide estimates of global river water temperatures for the 21st century. Nuclear power stations require cooling water at temperatures below 23°C. There have been occasions in the recent past when river water temperatures have exceeded this for very short periods. Alarmingly, the new data set suggests that in the future, river water temperatures could be above 23°C for up to three months of the year in areas where nuclear power stations operate.

This is just one example of the complex links between man and the water cycle, and it captures the ethos of WATCH; that all aspects of the water cycle and the activities that rely on it are interconnected and must be viewed as a whole.

Domestic water use is significantly smaller than agricultural or industrial use. It accounts for only 10% of global water use. Socio-economic developments such as population and economic growth cause increases in demand, whilst technological developments have the capacity to reduce waste and increase efficiency. WATCH has shown how these drivers have affected domestic usage over the 20th century.

The swiftest change has come since the 1960s. This period coincides with a doubling of population, and a doubling or tripling of economies across regions. Economic development has a clear effect on water usage. This peaks when average individual wealth reaches a certain level. After this, technology and conservation initiatives help the demand to plateau or reduce. This link to economic development means that the influence and rate of technological change differs from country to country.

Overall, the demand for domestic water use is five times greater at the end of the 20th century than at the start. All regions – with the exception of Europe – show increasing domestic water use over the last 50 years, with increases in Asia, Africa and Latin America being driven by a growing population. Europe's relatively stable population and improvements in technology have led to a small decrease in use. WATCH has considered future population scenarios, and policies that will influence water use and economic growth in order to produce estimates of domestic water use in the 21st century.

These studies of agricultural, industrial and domestic use establish baselines from which we can measure future change. The consistent methods used to derive new data sets make it easier to link them and to consider them together rather than in isolation. This promotes better understanding of the total demands that are being placed on resources. Additionally, when using the newly derived methods to assess future climate and socio-economic scenarios, we must expect to see limiting factors emerge.

Co-leader of WATCH, Pavel Kabat of WUR, said "This may be unpopular or unwanted science. Policy makers will need to make political choices about how water is used. There will come a time soon when we cannot have everything, and decisions will have to be made, otherwise food shortages will become a reality."

The methods developed within WATCH should allow us to look ahead and to calculate the volumes of water needed to cultivate sufficient food. It is then that the key question must be answered; what do we sacrifice – manufacturing, energy production or ecosystems – in order to provide it?

Water footprints

The data set of agricultural water footprints shows where countries are saving and losing water through trade and, for the first time, where land is being saved and lost through trade. For example, a country that imports a crop is saving its own internal blue and/or green water, and is also saving on land that would otherwise be used to produce the same or an alternative crop.

The distinction between blue and green water is important because they characterise different sources and consequently there are different opportunity costs attached to each. The data reveal that green water dominates both the internal (84%) and external (95%) footprints.

The method used to grow a crop dictates the blue/green balance of its virtual water content, so countries that mainly export rainfed crops are exporting mainly green water, whereas exporters of irrigated crops are exporting blue water. Recognising this distinction is a key step in water resource planning as it identifies the strengths and weaknesses associated with certain crop production methods, and points to potential improvements in agricultural water management and international trade policies.

Overall, the total external footprint of countries is small – just 6% of the total global blue-water footprint, and 16% of the total green-water footprint. Whilst it is small, this trade still saves significant water volumes and land areas for the importers, and it may become much more important in the future given that water scarcity is likely to increase in many regions.

The legacy of WATCH

WATCH leaves the clear legacy of an increased understanding of the water cycle in a time of global change. In addition, it has created an international group of knowledgeable and experienced modellers working at the interface between hydrology and climate science. These scientists will go on to make valuable contributions to future global science. And, they will take with them an awareness and an enthusiasm for what can be achieved by large research teams working in partnership. This enthusiasm was particularly apparent amongst those in the early stage of their careers who were interviewed during the writing of this report. One of the reasons was summed up by Fulco Ludwig; "All those involved in WATCH have benefited because the scale of the project has allowed people to spend significant and meaningful amounts of time on it. And, the level of senior involvement has been exceptional."

Closer working between research communities

The culture of closer working that was nurtured during WATCH has led to a step-change in the level of mutual understanding between climate and water scientists. The dividends of this are clear, and they should provide the incentive – and give groups the confidence – to develop the now-necessary future links with other groups such as oceanographic modellers.

A new appreciation of the relationships between the drivers of past and future change in river flows and water resources

Climate change, demographic and land-use change, and changing patterns of consumption all drive chang-

Hydrologists and climate scientists discuss the early results from WATCH at the Annual Assembly in Bratislava in 2008. These meetings were highly effective in promoting mutual understanding and forging partnerships that will last long after the completion of WATCH.

es in river flows and water resources. WATCH has provided a new appreciation of the relative importance of these individually, and also of how they interact.

New consolidated global and regional data sets to provide for a systematic analysis of the terrestrial water cycle

Not only have these new WATCH data sets for the 20th and 21st centuries underpinned the research within the project, but they are now readily available to a worldwide research community for use in future regional and global studies.

Improved and tested models of the terrestrial hydrological cycle and water resource assessment

A project the size of WATCH brings managerial challenges, but it also brings considerable opportunities, as Han Dolman explained. "With large projects you can take greater risks, and these are the areas with the most potential for high benefit breakthroughs. Smaller projects have much tighter deadlines and deliverables; they are safe science. WATCH allowed an element of risk, and the benefits are there."

WATER MIP is a prime example of this. It started out as a relatively small component of WATCH but was able to expand once the importance and potential benefits were recognised. To run 13 models side-by-side at a global scale, and to compare and analyse the results has accelerated model development far beyond what was originally anticipated.

A quantification of the uncertainties in modelling of the global hydrological cycle

The quantification of uncertainty will lead to new ways of assessing impact and adaptation studies, and should provide an agenda for integrated model development in coming years. Ronald Hutjes said, "The different

The timing and duration of scenes such as this in the Upper Guardiana in south central Spain will change as a result of a changing hydrological cycle. Work within WATCH will assist in planning ways to deal with this.

groups are working much better together and this is leading to better estimations of the future water resources – and even better appreciation of the uncertainty of the estimations."

New global and regional analyses of major floods and droughts of the 20th century, and an outlook for the 21st century

WATCH has demonstrated that extremes – both floods and droughts – can be analysed regionally and globally using 0.5 degree x 0.5 degree data. The availability of the WATCH data sets should give groups the confidence to undertake further studies at these scales, and to utilise the novel methods of presentation that have been pioneered in producing the flood and drought atlases.

WATCH has developed methods to identify water scarce areas in the present, and to predict where water scarcity will become an issue in the future.

WATCH has brought together the climate and hydrological modelling communities so that land surface / atmosphere feedbacks can be accommodated within each community's models.

A global analysis of water scarcity in the 20th and 21st centuries

In many ways this analysis and the resulting data sets epitomise the original ambitions of WATCH; to go beyond climate and river flows, and to integrate these with current and future human demands and drivers. The outputs should be an invitation and incentive for further more ambitious studies in the future.

An improved understanding and quantification of the feedbacks between the land surface and the atmosphere in the Earth system

WATCH has modelled land surface / atmosphere feedbacks using a range of models. "WATCH has shown the benefits of using a multi-model approach, and it is of particular importance when modelling feedbacks," said Ronald Hutjes. "By using a range of models you are more likely to detect an effect that may not have been considered or foreseen. This is because the water cycle is complex, and man is adding to the complexity. Multi-models are an insurance policy."

Putting the legacy into action

WATCH is now complete. Its outputs, summarised in this document, can now be applied to the task of formulating evidence-based policy with a foundation of sound science.

"WATCH has confirmed that the hydrological cycle is changing," said Han Dolman, "And, the components are changing at different speeds and at different locations around the world. If you are planning to manage water over the next 5-10 years, then you need to start making changes now. The results from WATCH will make this easier."

If you wish to discuss the legacy of WATCH, or ways that its outputs can be used in the future, contact Richard Harding.

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Further information

The websites listed below provide further information about WATCH and the issues that it addressed.

www.eu-watch.org - the project website providing information on partners, work blocks and publications.

www.eu-watch.tv - the online version of this report with video and audio supplements from those involved.

www.waterandclimatechange.eu - an introduction to the global water cycle and its links with climate change.

www.ipcc.ch - the Intergovernmental Panel on Climate Change.

www.ileaps.org - the Integrated Land Ecosystem - Atmosphere Processes Study.

www.gewex.org - the Global Energy and Water Cycle Experiment.

www.gwsp.org - the Global Water System Project.

www.ec.europa.eu/research/fp6 - the European Union's Sixth Framework Programme.

SIXTH FRAMEWORK PROGRAMME

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