SPACE SCIENCES SERIES OF ISSI

Remote Sensing and Water Resources

A. Cazenave · N. Champollion · J. Benveniste
J. Chen *Editors*

Springer

INTERNATIONAL SPACE SCIENCE INSTITUTE

Space Sciences Series of ISSI

Volume 55

More information about this series at http://www.springer.com/series/6592

A. Cazenave · N. Champollion
J. Benveniste · J. Chen
Editors

Remote Sensing and Water Resources

Previously published in *Surveys in Geophysics*, Volume 37, Issue 2, 2016

Springer

Editors
A. Cazenave
International Space Science Institute
Bern
Switzerland

and

LEGOS-CNES
Toulouse
France

N. Champollion
International Space Science Institute
Bern
Switzerland

J. Benveniste
European Space Agency
European Space Research Institute
Frascati
Italy

J. Chen
Center for Space Research
University of Texas at Austin
Austin, TX
USA

ISSN 1385-7525
Space Sciences Series of ISSI
ISBN 978-3-319-32448-7 ISBN 978-3-319-32449-4 (eBook)
DOI 10.1007/978-3-319-32449-4

Library of Congress Control Number: 2016935393

Cover illustration: Lake Balkhash, Kazakhstan. Image of the lake was taken by the NASA Space Shuttle Discovery on Mission STS039 in April 1991 (*Source* NASA). Image amended by A. Fisher, ISSI, Bern, Switzerland.

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG Switzerland

Contents

DOI 10.1007/978-3-319-32449-4_1
Reprinted from *Surveys in Geophysics* Journal, DOI 10.1007/s10712-016-9356-4

Foreword: International Space Science Institute (ISSI) Workshop on Remote Sensing and Water Resources

A. Cazenave[1,2] · **N. Champollion**[2] · **J. Benveniste**[3] ·
J. Chen[4]

Received: 3 January 2016 / Accepted: 4 January 2016 / Published online: 22 January 2016

About 97 % of the total amount of water on Earth is found in the oceans and 2 % is stored in the Greenland and Antarctic ice sheets. It is only the remaining 1 % that is the amount of water available for the biospheric processes and for all human needs. This fresh water component is stored in both surface and subsurface reservoirs. On the surface, the storage volumes consist of rivers, lakes, man-made reservoirs, wetlands and inundated areas. Subsurface reservoirs include root zones (the uppermost few metres of the soil), as well as confined and unconfined aquifers and other geological formations. Except for the deep aquifers that evolve on thousand-year timescales, terrestrial waters are continuously exchanged with the atmosphere and oceans through vertical and horizontal mass fluxes (i.e. precipitation, evaporation, transpiration of the vegetation and surface and underground runoff). These exchanges as well as the associated storage of water in the different components of the climate system characterize the global water cycle.

On land, changes in the global water storage result from climate variations, from direct human interventions in the water cycle and from human modifications of the physical characteristics of the land surface. Climate variations (which are due to both natural and

---

✉ A. Cazenave
anny.cazenave@issibern.ch; anny.cazenave@legos.obs-mip.fr

N. Champollion
champollion@issibern.ch

J. Benveniste
Jerome.benveniste@esa.int

J. Chen
chen@csr.utexas.edu

[1] LEGOS, CNES, 18 Avenue Edouard Belin, 31401 Toulouse Cedex 9, France

[2] ISSI, Hallerstrasse 6, 3012 Bern, Switzerland

[3] ESA-ESRIN, Via Galileo Galilei, 0044 Frascati, Italy

[4] CSR, University of Texas at Austin, Austin, TX, USA

anthropogenic causes) produce changes in the land water balance, leading to either an increase or a decrease in water storage. For example, cold and wet climatic conditions have the tendency to increase water storage, while a warm and dry climate has the opposite effect. Many human activities directly affect land water storage; examples are groundwater pumping in aquifers, the construction of dams on rivers to form artificial man-made reservoirs and irrigation for improved agricultural production. Anthropogenic changes in land surfaces such as urbanization, agriculture and deforestation also lead to water storage changes.

Being an integral part of the climate system, terrestrial waters have important links to, and feedbacks with and from, the atmosphere and oceans via energy and moisture fluxes. Gaining a better understanding of the global hydrological cycle, in particular its terrestrial component, is thus a key issue in climate research today. It is also of significant importance for creating an inventory of water resources and for managing them.

In the last two to three decades, global estimates of the spatio-temporal changes in land water storage (surface, soil and underground waters, as well as snow packs) have relied on hydrological models, either coupled with atmosphere–ocean global circulation models or forced by meteorological observations. However, hydrological phenomena are so complex that it is very difficult to represent the hydrological system in such a simple way. What is needed is the acquisition of a huge amount of observations and their assimilation into complex models.

In situ gauging networks have been installed for several decades in many lakes and river basins. However, they are distributed non-uniformly throughout the world, and they often suffer from intermittent operation. In situ measurements provide time series of water levels and discharge rates, which are used for studies of regional climate variability, as well as for socio-economic applications (e.g., water resources inventory, navigation, land use, planning infrastructures, hydroelectric energy, flood hazards) and environmental studies (rivers, lakes, wetlands and floodplains hydroecology). However, for more than two decades, ground-based gauge networks have declined in many regions (Alsdorf and Lettenmaier 2003), because of economic pressures or for political reasons. For example, over 20 % of the freshwater discharge to the Arctic Ocean is ungauged; surface water across much of Africa and portions of the Arctic is either not measured at all or has experienced the loss of over two-thirds of the gauges (Shiklomanov et al. 2002). The physical removal of gauges from many lakes and river basins is, unfortunately, a common situation in many parts of the world. Besides, the distribution of collected data is often restricted, because water-related data are often considered to be sensitive national information. Therefore, to accurately measure, monitor and forecast global supplies of fresh water using in situ methods is almost impossible because of the lack of access to an adequate amount of in situ measurements worldwide.

For the past 10–15 years, remote sensing techniques have demonstrated their excellent capability to monitor several components of the water balance of large rivers, lakes and reservoirs, on timescales ranging from months to decades (e.g., Alsdorf and Lettenmaier 2003; Alsdorf et al. 2007; Famiglietti et al. 2015). For example, radar and laser satellite altimetry are routinely used for systematic monitoring of the water levels of large rivers, lakes, reservoirs and floodplains. If combined with satellite imagery, satellite altimeter observations also enable the variations of surface water volumes to be estimated. Passive and active microwave sensors offer important information on soil moisture (e.g., the SMOS mission) as well as on wetlands and snowpacks. Space gravity missions (in particular the GRACE mission) directly measure the spatio-temporal variations of vertically integrated terrestrial water storage. When combined with hydrological model estimates or other observations of surface waters and soil moisture made from space (e.g., from satellite altimetry and SMOS), satellite gravity data can be used to study groundwater storage variations. Synthetic Aperture Radar Interferometry (InSAR) can be also used to estimate river flow.

In the very near future, the Surface Water Ocean Topography (SWOT) mission will provide frequently updated two-dimensional maps of surface water levels and river discharges, with global coverage and with unprecedented resolution (~ 100 m globally on land). All these observations, as well as those planned in the near future (e.g., the European Sentinel missions), will become increasingly important in improving our understanding of hydrological processes at work in large river basins and their links with climate variability and socio-economic activities. Significant new information can be expected by combining models and surface observations with space observations, which offer global geographical coverage, good spatio-temporal sampling, continuously repeated monitoring and the capability of measuring water mass changes occurring at or below the Earth's surface.

The scientific papers presented in this volume represent the outcome of a workshop on 'Remote Sensing and Water Resources' held in October 2014, in Bern, Switzerland, as part of the International Space Science Institute (ISSI) Earth Observation Programme. The objective of the workshop was to bring together leading scientists involved in the global water cycle, land hydrology and water resources research, either processing observations or running hydrological models or combining both. Two main issues were addressed during the workshop: (1) promoting the synergistic use of space observations for monitoring water storage changes in river basins worldwide, and (2) using the space data in hydrological models either by data assimilation or as external constraints. Participants in the workshop were experts in different disciplines, including remote sensing, hydrological modelling, meteorology, geophysics and climate science.

The first two articles address hydrological modelling, at the global scale ('Modelling fresh water resources at the global scale; challenges and prospects' by Döll et al.) and at the regional scale in a river basin that has been highly modified by human activities ('Hydrological modelling in highly anthropized river basins; example from the Garonne Basin' by Martin et al.). The paper by Zhang et al. 'On creating global gridded terrestrial water budget estimates from satellite remote sensing' investigates the reliability of global remote sensing products in closing estimates of the global water budget.

Three papers deal with the use of satellite altimetry and other remote sensing techniques to study surface waters. The paper by Crétaux et al. is an overview of lake monitoring from space. Biancamaria et al. demonstrate the high potential of the future SWOT mission to study surface waters with a precision, spatial resolution and temporal sampling that was previously unavailable. The issue of monitoring wetlands is addressed by Prigent et al. in an overview article entitled 'Towards high resolution monitoring of continental surface water extent and dynamics at global scale; from GIEMS (Global Inundation Extent from Multi-Satellites) to SWOT'.

The next three papers deal with the GRACE-based space gravimetry technique and its capability to measure total terrestrial water storage, accessing groundwater storage by removing model-predicted surface water storage change. The paper by Humphrey et al. 'Assessing global water storage variability from GRACE: trends, seasonal cycle, intra-annual anomalies and extremes' focuses on short-term water storage anomalies, as well as on extreme events such as droughts. The recovery of estimates of groundwater depletion in aquifers from GRACE measurements is discussed by Chen et al. in a paper entitled 'Groundwater storage changes: present status from GRACE observations'. The paper by Wada et al. 'Modelling global groundwater depletion: present state and future prospects' evaluates the recent advances which modelling approaches bring to enable groundwater depletion to be estimated at a global scale.

The capability of future space gravity missions with new on-board interferometric laser systems to improve both the precision and resolution of water storage measurements is evaluated in Flechtner et al. ‘What can we expect from the GRACE-FO Laser ranging interferometer for Earth sciences applications?’. The next paper by Lopez et al. ‘Subsurface hydrology in the Lake Chad Basin from space-based and hydrogeological data’ investigates how space radiometry combined with hydrogeological data and modelling can provide constraints on groundwater circulation in semi-arid regions. Finally, an overview of the significant issue of the provision for human beings of ‘Water and Food in the 21st century’ is given by de Marsily and Abarca Del Rio.

This Special Issue includes the majority of the lectures presented at the workshop, in some instances grouped into a single article in order to reflect a broader view of the subject. This volume focuses on terrestrial waters and, as such, complements the book published as the outcome of a previous ISSI workshop which was mostly devoted to the atmospheric water cycle (Bengtsson et al. 2014).

Clearly, studying the global water cycle is a very complex problem as many Earth processes are at play, and we recognize that several other volumes would be necessary to fully cover the ongoing research in this domain. However, we hope that the present issue will contribute to

1. fostering the interests of the science community around future spaceborne missions,
2. supporting the exploitation of past, present and future invaluable spaceborne measurements, and
3. gathering multidisciplinary teams working together on satellite observations, in situ data, modelling and data assimilation techniques.

We thank ISSI and the European Space Agency for providing an inspiring framework which made such a fruitful workshop possible.

References

Alsdorf DE, Lettenmaier DP (2003) Tracking fresh water from space. Science 301:1492–1494

Alsdorf D, Fu LL, Mognard N, Cazenave A, Rodriguez E, Chelton D, Lettemaier D (2007) Measuring global oceans and terrestrial fresh water from space. EOS Trans AGU 88(24):253

Bengtsson L, Bonnet R-M, Calisto M, Destouni G, Gurney R, Johannessen J, Kerr Y, Lahoz WA, Rast M (eds) (2014) The Earth’s hydrological cycle. Space sciences series of ISSI vol 46. ISBN 978-94-017-8788-8

Famiglietti J, Cazenave A, Eicker A, Reager JT, Rodell M, Velicogna I (2015) Satellites provide the ‘big picture’ for global hydrology. Science 349(6249):684–685

Shiklomanov AI et al (2002) Widespread decline in hydrological monitoring threatens Pan-Arctic research. EOS Trans AGU 83:13–16

DOI 10.1007/978-3-319-32449-4_2
Reprinted from *Surveys in Geophysics* Journal, DOI 10.1007/s10712-015-9343-1

Modelling Freshwater Resources at the Global Scale: Challenges and Prospects

Petra Döll[1] · Hervé Douville[2] · Andreas Güntner[3] · Hannes Müller Schmied[1] · Yoshihide Wada[4,5,6]

Received: 12 March 2015 / Accepted: 26 September 2015 /

Abstract Quantification of spatially and temporally resolved water flows and water storage variations for all land areas of the globe is required to assess water resources, water scarcity and flood hazards, and to understand the Earth system. This quantification is done with the help of global hydrological models (GHMs). What are the challenges and prospects in the development and application of GHMs? Seven important challenges are presented. (1) Data scarcity makes quantification of human water use difficult even though significant progress has been achieved in the last decade. (2) Uncertainty of meteorological input data strongly affects model outputs. (3) The reaction of vegetation to changing climate and CO_2 concentrations is uncertain and not taken into account in most GHMs that serve to estimate climate change impacts. (4) Reasons for discrepant responses of GHMs to changing climate have yet to be identified. (5) More accurate estimates of monthly time

---

✉ Petra Döll
p.doell@em.uni-frankfurt.de

Hervé Douville
herve.douville@meteo.fr

Andreas Güntner
guentner@gfz-potsdam.de

Yoshihide Wada
y.wada@uu.nl

[1] Institute of Physical Geography, Goethe University Frankfurt, 60629 Frankfurt, Germany

[2] Centre National de Recherches Météorologiques, Météo-France, 42 av. Coriolis, 31057 Toulouse, France

[3] Helmholtz Centre Potsdam, German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany

[4] Center for Climate Systems Research, Columbia University, 2880 Broadway, New York, NY 10025, USA

[5] NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025, USA

[6] Department of Physical Geography, Faculty of Geosciences, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands

series of water availability and use are needed to provide good indicators of water scarcity. (6) Integration of gradient-based groundwater modelling into GHMs is necessary for a better simulation of groundwater–surface water interactions and capillary rise. (7) Detection and attribution of human interference with freshwater systems by using GHMs are constrained by data of insufficient quality but also GHM uncertainty itself. Regarding prospects for progress, we propose to decrease the uncertainty of GHM output by making better use of in situ and remotely sensed observations of output variables such as river discharge or total water storage variations by multi-criteria validation, calibration or data assimilation. Finally, we present an initiative that works towards the vision of hyperresolution global hydrological modelling where GHM outputs would be provided at a 1-km resolution with reasonable accuracy.

Keywords Global hydrological model · Climate data · Water abstraction · Model uncertainty · Calibration · Remote sensing data

1 Introduction

Water flows as well as water storage at and below the land surface of the Earth affect water availability for humans and ecosystems, result in hazards such as floods and affect atmospheric processes, sea level and global biogeochemical cycles. They have been increasingly altered by human actions including emissions of greenhouse gases, land use, water abstractions and the construction of dams and dykes (e.g., Vörösmarty and Sahagian 2000; Sterling et al. 2013). Ecosystems suffer from these alterations and, in many regions, human development is constrained by water scarcity. Freshwater systems including their natural and human components need to be characterized regarding both water quantity and quality to support a sustainable land and water management and a better understanding of the Earth system. Global-scale quantification of water flows and storage in freshwater systems under current and future conditions is of particular interest in a globalized world and can support the wise development of global-scale water management and governance (Vörösmarty et al. 2015).

Quantification is best achieved by combining in situ and remote sensing data with physical modelling. Global hydrological modelling serves to estimate water flows on the land areas of the globe such as evapotranspiration, river discharge or groundwater recharge as well as water storage (or only water storage variations) in different compartments, e.g., in soil or in groundwater and surface water bodies. It uses data on precipitation and other climate variables over land areas as input and computes water flows from the land areas to the oceans (or into internal sinks on the continents), thus covering the terrestrial part of the global water cycle. While global hydrological modelling has been refined and extended with respect to modelled processes (in particular regarding human impacts on natural water flows and storages) and computed indicators in the last decade, modelling uncertainties have not become less albeit better known. These uncertainties are generally categorized into uncertainties due to model inputs (e.g., climate variables or soil properties), parameter values and model structure, but uncertainty of observations used for model validation or calibration also has to be considered (Sood and Smakhtin 2015). Different models compute contradictory estimates of, for example, mean annual evapotranspiration and low, mean and high flows in river basins (Gudmundsson et al. 2012) or groundwater depletion (Döll et al. 2014a). They result in strongly varying projected impacts of climate change on river discharge (Schewe et al. 2014) or irrigation water requirements (Wada et al. 2013). Even global mean annual evaporation estimates as derived from global hydrological modelling (or satellite observations) differ by almost a factor of 2 (Jiménez et al. 2011), which is an important obstacle for the detection and attribution of changes in evapotranspiration due to global warming (Douville et al. 2012). Reasons for the discrepant model output have not been sufficiently analysed.

With this paper, the authors wish to share their perspectives on important challenges of and prospects for modelling continental water flows and storages at the global scale. In the next section, we briefly present existing modelling approaches. In Sect. 3, we discuss seven challenges and illustrate them with results of two global hydrological models (GHMs), WaterGAP (Döll et al. 2003; Müller Schmied et al. 2014) and PCR-GLOBWB (Wada et al. 2014). In Sect. 4, we present three advancements that may help to better characterize freshwater flows and storages at the global scale in the future. Finally, we draw our conclusions.

2 Approaches for Modelling Global Hydrology

To understand and quantify natural and human-induced water flows and storage changes across large scales, a number of models that simulate the continental part of the hydrological cycle on a regional to global scale have been developed in recent decades. Models developed to simulate global hydrology can be roughly classified into GHMs, land surface models (LSMs) and dynamic global vegetation models (DGVMs). Most DGVMs, however, do not include lateral water flows or surface water bodies, and can therefore only be used to assess runoff but not discharge. GHMs focus on simulation of water resources; they have a comprehensive representation of continental hydrological processes and often take into account human water use as well as man-made reservoirs. LSMs serve as a module of global climate models (GCMs) and therefore model both water and energy balances at the land surface. Due to this, they often represent the soil with a higher vertical resolution than GHMs and represent evapotranspiration and snow melt in a less conceptual manner than GHMs. LSMs often lack a groundwater reservoir, lateral routing or consideration of surface water bodies, and in most cases, they do not model the impact of human water use or man-made reservoirs. Finally, some LSMs are able to also model vegetation dynamics, or DGVMs have been extended to simulate global hydrology including not only vertical but lateral water flows as well as human water use and man-made reservoirs. In addition, simulation of irrigation water use is not only done by some GHMs, LSMs and DGVMs but also by global crop models (e.g., Elliott et al. 2014).

In the following, we do not distinguish between GHMs, LSMs and DVGMs but summarily refer to all of them as GHMs (like Schewe et al. 2014 or Hagemann et al. 2013 did) because existing models cannot be strictly classified into the three categories and because we focus on their ability to simulate terrestrial water flows and storages. GHMs typically simulate the dynamics of soil moisture storage due to precipitation and evapotranspiration, the generation of runoff and the discharge through the river network. The majority of these models are based on the water balance concept and track the transfer of water through a number of storage compartments with time steps ranging from a month to less than 1 day. Conceptual models are chosen as they are deemed to be more robust than empirical models and more parsimonious in their data requirements than fully physically based models, while they maintain the ability to translate the effects of global change on water flows and storages in a consistent manner. Over time process descriptions have become more physically based. Few models simulate human water use that is essential to quantify river discharge, water availability and water stress, and even fewer models represent groundwater including groundwater recharge and abstractions, which is crucial to assess groundwater resources. Sood and Smakhtin (2015) presented an overview over 12 GHMs, and Bierkens et al. (2015) provided a table that describes the main features of GHMs and regional-scale hydrological models.

3 Challenges

Aiming at an improved representation of freshwater systems at the global scale, global hydrological modelling faces diverse challenges. We select some of the most important challenges that have been identified by the scientific community, i.e. constraints that lead to uncertain model output and thus limit the usefulness of global hydrological modelling for understanding freshwater systems.

3.1 Modelling Human Water Use

Human water use leads to anthropogenic water flows in the form of water abstractions from and return flows to surface water or groundwater bodies (Döll et al. 2012; Wada et al. 2011). Quantification of these flows is important for two reasons. On the one hand, water abstractions, consumptive water use (the part of the withdrawn water that evapotranspires during use) or net water abstractions (water abstractions minus return flows) are used in combination with estimates of water availability to compute indicators of water stress (or water scarcity). On the other hand, these anthropogenic water flows alter natural groundwater and surface water flows and storages (Döll et al. 2014a, b; Wada et al. 2012). It was estimated that around the year 2000, mean annual river discharge had been decreased due to water abstractions and man-made reservoirs by more than 10 % on one-sixth of the global land area (excluding Greenland and Antarctica), as compared to natural discharge (Döll et al. 2009). The strongest alterations, with, e.g., both decreases and increases of mean annual water storage (Döll et al. 2012), are found in semi-arid and arid areas of the globe, where irrigation is the dominant water use and alterations of river flow regimes by water abstractions are more important than alterations due to man-made reservoirs (Döll et al. 2009).

In global hydrological modelling, water abstractions and return flows are mostly estimated at a spatial resolution of 0.5° by 0.5° (55 km by 55 km at the equator) or 5′ by 5′ (9 km by 9 km). While water use for domestic and industrial purposes is assumed to vary negligibly throughout the year, monthly estimates of irrigation water use are required due to the often high seasonal variation of irrigation requirements. Modelling of water use for households and manufacturing strongly relies on statistical water abstraction data provided by countries, but data generally exist for a few years only. To derive annual time series by country, abstractions are modelled taking into account structural and technological change (Flörke et al. 2013). In addition, downscaling to the grid cell level is required and is mainly done based on urban and rural population in grid cells (Flörke et al. 2013; Vassolo and Döll 2005). Cooling water requirements for thermoelectric power plants are computed for each