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TIME VARIATION IN HYDROLOGY AND GRAVITY

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Abstract. In view of the pivotal role that continental water storage plays in the Earth's water, energy and biogeochemical cycles, the temporal and spatial variations of water storage for large areas are presently not known with satisfactory accuracy. Estimates of the seasonal storage change vary between less than 50 mm water equivalent in areas with uniform climatic conditions to 450 mm water equivalent in tropical river basins with a strong seasonality of the climate. Due to the lack of adequate ground-based measurements of water storage changes, the evapotranspiration rate, which depends on the actual climatic and environmental conditions, is only an approximation for large areas until now, or it is based on the assumption that storage changes level out for long time periods. Furthermore, the partitioning of the water storage changes among different storage components is insufficiently known for large scales. The direct measurement of water storage changes for large areas by satellite-based gravity field measurements is thus of uttermost importance in the field of hydrology in order to close the water balance at different scales in space and time, and to validate and improve the predictive capacity of large-scale hydrological models. Due to the high spatial variability of hydrological processes temporal and spatial resolutions beyond that of GRACE are essential for a spatial differentiation in evapotranspiration and water storage partitioning.

Keywords: continental water balance, satellite gravity missions, large scale water storage, large scale evapotranspiration, sea level change, ungauged catchments

1. Introduction

The system of water redistribution within the global water cycle is the main driving force for life on the land masses. By transformation and transport processes in the hydrological cycle, water is changing its phase from liquid or ice to vapour and back. Water fluxes within and between the compartments land and ice masses, oceans and atmosphere are closely coupled to each other. In the form of a complex system of nested cycles from local up to global scales (Figure 1), mass and energy is transported over large distances. Atmospheric water vapour originating from evaporation at the ocean surface returns as precipitation on the oceans and, after vapour transport, on the

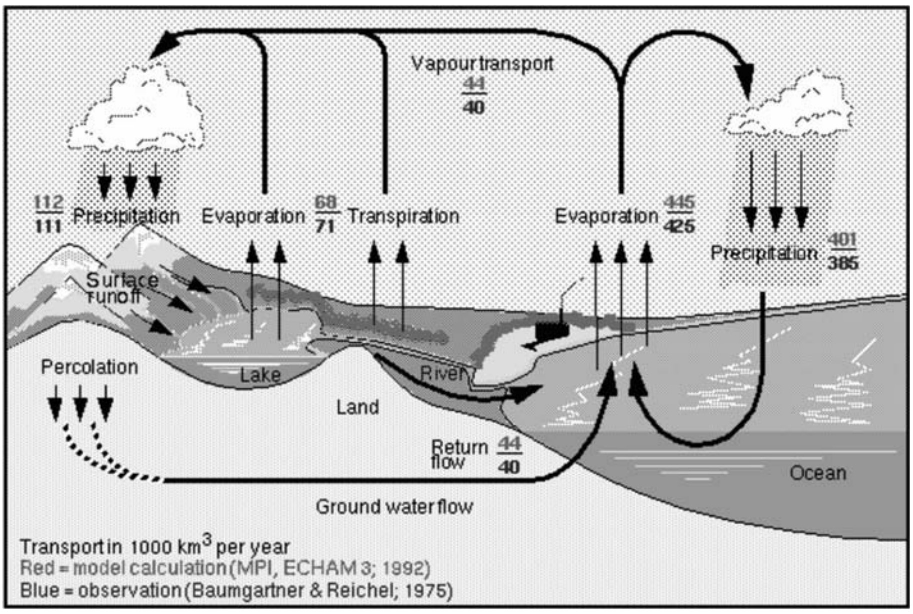

Figure 1. The global hydrological cycle (Max-Planck-Institute for Meteorology, Hamburg).

land masses. On the continents, water is recycled locally to the atmosphere by ongoing evaporation from open water surfaces or soils and by transpiration from plants and is returned by precipitation as rain or snow. These evapotranspiration processes are complex and vary considerably in time and space. They depend on the type of land use, i.e., the vegetation type, its vegetation period and leaf area, on the available soil moisture and on the local atmospheric conditions.

After withdrawal of water volumes by evapotranspiration, the remaining rain or snow melt is split up into a surface runoff component, a fast inter-flow component in the shallow soil zone and into percolation to deeper sub-surface zones resulting in a slow groundwater flow component. The relative contribution of the different flow components to total runoff is governed by topography, vegetation, soil characteristics, underlying hydrogeological conditions and the actual status of the related storages. In other words, these factors determine the relative contribution and the residence time of water masses in the different soil and rock storage compartments and, thus, the time-variable soil moisture and groundwater storage volumes. Runoff from the landscape is concentrated into the river drainage system. River runoff as well as groundwater flow at large spatial scales passes various intermediate storages, such as retention in the river network itself, in lakes or wetlands. There, it is partly subject to evaporation or extraction for human consumption, before being fed back into the oceans.

For a catchment area, being the basic spatial unit of hydrological analysis and water management issues, the water balance can be written as:

$$h_P = h_Q + h_{ET} + \Delta h_S \quad (1)$$

with h_P is the precipitation height, h_Q, the discharge height, h_{ET}, the evapotranspiration height, Δh_S, the storage change in units of water column per time interval.

However, the rates of water fluxes between the different components of the hydrological cycle vary considerably and show a specific temporal behaviour due to the different storage characteristics. These storages in the form of snow or ice cover, vegetation interception, surface water, soil moisture and groundwater all exhibit individual residence times, maximum storage levels and paths for water input and output. Characteristic average residence times of terrestrial water storages, for instance, range from a few days for the biomass or upper soil layers to several hundreds or thousands of years for deep groundwater storages (Figure 2).

Although making up only about 3.5% of total water in the hydrologic cycle, terrestrial water storage and related mass redistribution processes have a huge importance for the dynamic Earth system. Soil moisture, for instance,

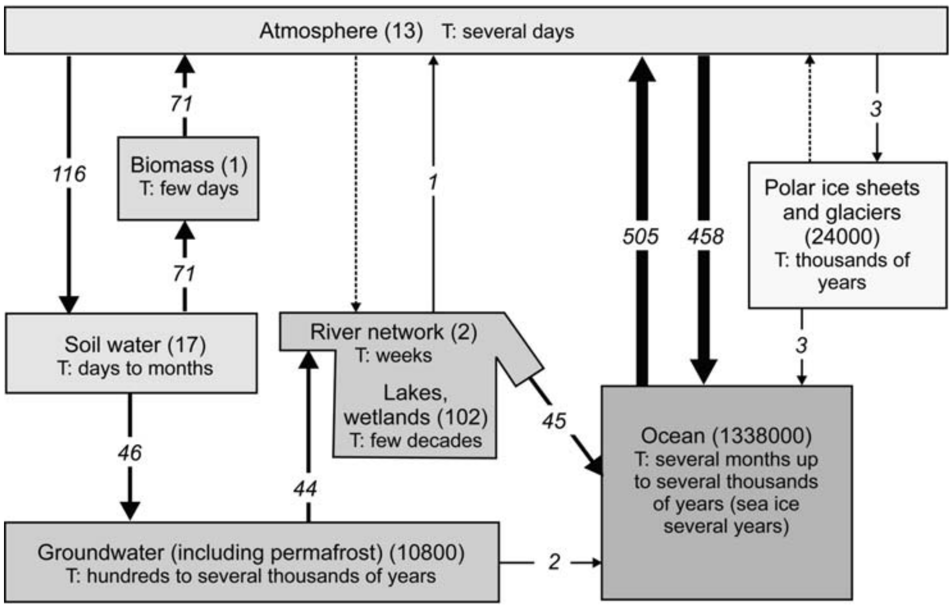

Figure 2. Storages in the global hydrological cylce. Storage volumes (1000 km^3, in brackets), fluxes (1000 km^3/year, in italics) and order of magnitude of mean water residence times (T) (after WBGU, 1997).

has frequently shown to be a key parameter as it links the water and energy cycles and, in addition, the biogeochemical cycle by transport of solutes and suspended load being associated with water mass redistribution.

Furthermore, terrestrial water storage is of highest importance for civilization on Earth. The replenishment of surface and groundwater storages provides the basis for water supply to a wide range of uses in the domestic, industrial and agricultural sectors. Soil moisture is essential for plant growth, including agricultural crops and thus food supply. About two-third of global water use is attributed to irrigation in agriculture. Population growth and economic development lead to an increasing water demand and rising extractions from terrestrial water storages. However, the physiographic settings of many regions in the world together with climate variability often constrain water availability to amounts being below the actual demand. About two-third of the population of the world live at least temporarily in such a condition of water stress.

Global climate change associated with a projected increase of global surface temperature in the range of 1.5–5.8 °C between 1990 and 2100 (IPCC, 2001) provides an increase of available energy for evapotranspiration and is expected to change volumes and flux rates between the storages of the hydrological cycle. Within a general tendency of increasing variability, global atmospheric water vapour and precipitation is expected to increase, although effects at the regional scale may deviate from the global tendency and are highly uncertain (IPCC, 2001). These changes, together with other aspects of global change such as land use changes which directly affect evapotranspiration and mass transport at the land surface, affect water availability in surface and groundwater water storages being essential for human use.

Thus, the knowledge and understanding of temporal and spatial variations in terrestrial water storage is of crucial environmental and economic importance. It forms the basis for a reasonable description of mass redistribution processes in the hydrological cycle for current conditions and consequently also for reliable estimates of the future development by scenario simulations. This, in turn, is essential for the implementation of adequate long-ranging water management strategies at the regional scale of river basins in view of both changing water availability and water demand. Going even beyond the regional scale, a global scale analysis is required due the close interaction of changes in the terrestrial water storages and the climate system and its feedback on future climate conditions.

Before the launch of the GRACE satellites, a large-scale monitoring system of changes in terrestrial water storage, however, did not exist. Ground-based observations of soil moisture or groundwater levels give only point estimates of the water storage and are hard to be interpolated to larger areas in view of the sparse measurement network and the multitude of influencing factors. Observations for large areas by remote sensing exist for the parameters snow cover and soil moisture, but are limited to the uppermost centimeters of the soil and do not capture the important deeper soil water and groundwater storage. While adequate measurements of precipitation and runoff may be available in some cases at the basin scale, a calculation of storage changes by use of the water balance equation (see Equation (1)) usually is not feasible as no reliable estimates of evapotranspiration are available for large scales. The shortage of adequate data (for model input and validation) also limits the applicability of hydrological simulation models to quantify water storage components for large areas.

Gravitational measurements by satellite missions are expected to be of extraordinary importance to overcome the lack of direct measurements of changes in the terrestrial water storage at large scales (e.g., Dickey et al., 1999). In the following chapters an overview is given on present open questions in hydrology and on the perspectives which are opened up by the use of gravitational measurements.

2. Global Water Balance

Until present, the global and continental water balance is not known with sufficient accuracy neither in its temporal variation nor for its mean annual values. Values differ considerably for different data sources (see Figures 1 and 3). This uncertainty is due to the difficulty of direct measurements of the climatic components of the water cycle (precipitation and evaporation) at the land surface in terms of the spatial coverage and density of measurement points. Problems also arise with the accurate measurement of river discharge on the global scale, especially for the main contributing river systems of the world with large discharge volumes. Estimates of total continental discharge into the oceans vary by about 20% (Figure 3).

Even more uncertain is the quantification of the considerably smaller net flux between oceans and land masses. It is defined by the imbalance between water vapour transport to the land masses and total runoff, and is required as a contribution to estimates of sea level change. Similar problems exist for the mass balance of ice masses (here the Antarctic and Greenland ice sheets), for which the mass output cannot be determined better than ±20% of the mass input (see Flury, 2005). However, these mass balances and the resulting net mass fluxes are essential for the determination of changes in the oceanic mass storage.

Observations of gravity changes allow a direct determination of mass variations and, thus, of net fluxes between the three compartments land masses, oceans and ice (Figure 2). However, an additional flow path has to be considered: the exchange with the atmosphere. Mass losses on land and ice masses are not only due to a loss of liquid water but also due to a release of

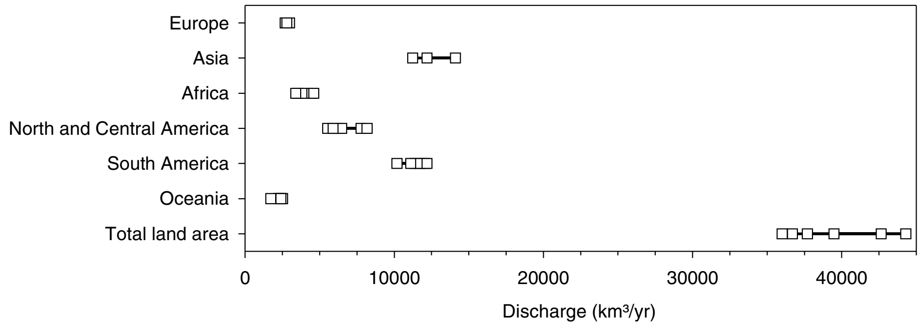

Figure 3. Long-term average annual continental discharge into oceans (estimations of six observation-based and model-based studies compared in Döll et al., 2003).

water vapour to the atmosphere. Thus, these four compartments of global water storage are closely coupled.

3. Atmospheric Mass Variations

As the gravitational measurements integrate terrestrial water and atmospheric mass variations, the effect of air mass redistributions has to be eliminated from the total signal prior to its use for hydrological analyses. The accuracy of these atmospheric corrections is of fundamental importance, as it determines the accuracy of mass variations determined for all the residual components, especially on short time scales. Local atmospheric mass per unit area is determined by the surface level pressure. In addition, the centre of gravity of each atmospheric column should be determined for signal separation. The pressure fields will usually be derived from atmospheric models such as by ECMWF (European Centre for Medium-Range Weather Forecasts) and by NCEP (National Centers for Environmental Predictions, USA) or of the respective reanalysis data. Their accuracy has to be assessed by means of a comparison with measured barometric data. It has been shown that pressure fields from operational analyses were usually adequate to remove the atmospheric contribution from GRACE gravity signals for hydrological applications with an accuracy of few millimeters of equivalent water thickness (Velicogna et al., 2001). Similarly, a pressure field derived from barometric measurements alone might be adequate if the station density is large enough. As the uncertainty in the hydrological signals due to atmospheric corrections varies with time and location, the error has to be assessed for each hydrological analysis of the gravity field measurements, depending on the area of investigation.

A direct check of the consistency of atmospheric mass changes derived from gravitational signals with that derived from surface pressure and thus a quantification of the resulting accuracy of atmospheric corrections is feasible in areas where all other fluxes causing mass changes are known or negligible. This may apply to arid zones, where after long periods without rainfall any mass redistribution by evaporation or runoff can be excluded and changes in the gravity signal are due to atmospheric mass fluxes only. Another possibility for a consistency check is to take advantage of characteristic response times of different components of the water cycle that contribute to mass variations. This may allow to separate the atmospheric signal with a high-frequency temporal behaviour from slower mass changes like groundwater storage variations.

4. Large-Scale Variations of the Terrestrial Water Storage in River Basins

Intra-annual and inter-annual dynamics of continental water storages vary substantially between environments of different physiographic and climatic conditions. For example, the intra-annual variation between maximum and minimum water storage amounts to about 50 mm of water column in river basins with rather uniform climatic conditions, whereas it is up to 450 mm in tropical river basins with a strong seasonal variation of climatic forcing, in particular precipitation input (Figure 4). These mass variations turn continental hydrology into one of the strongest signal components of time-variable gravity fields.

However, the spatial and temporal variability of water storage changes is not sufficiently known until now (e.g., singh and Frevert, 2002, for an overview). Observations of variations in continental water storages such as soil moisture or groundwater are rarely available even on small scales of sub-areas of river basins due to the limitations of the measurement methods with regard to sample density, spatial coverage or soil penetration depth as in the case of radar remote sensing of soil moisture. Yet even more difficult than to assess water storage is to quantify the water fluxes between the storages which often include complex interactions. A complementary way to quantify hydrological processes that influence water storage and fluxes is by using hydrological models. A wide range of hydrological models exists (e.g., singh and Frevert, 2002, for an overview), reaching from detailed physically-based process models to simplified models which make use of interrelated conceptual storages to represent water fluxes (e.g., evapotranspiration, percolation, runoff generation, river network routing). More comprehensive models of water management (Riegger et al., 2001) also address anthropogenic, time variant influences on water storages, such as pumping from groundwater or withdrawal from surface reservoirs for irrigation or other uses (cf. Figure 5).

The applicability of a specific model type depends, among others, on the spatial scale and the available information on soils, hydrogeology, land use

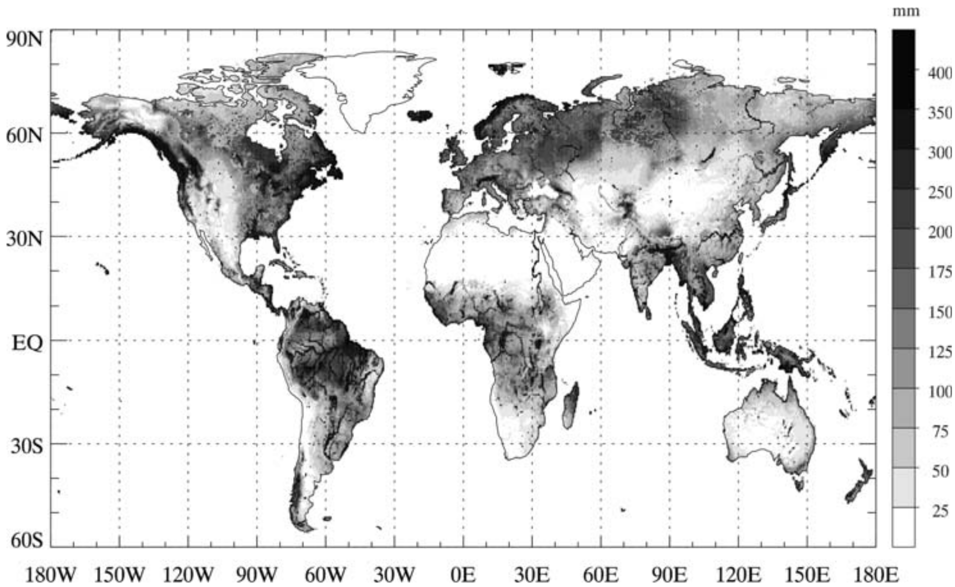

Figure 4. Average seasonal changes (changes between the months of maximum and minimum storage) of the total continental water storage (composed of the storage components snow, soil water, groundwater, river, lakes and wetlands), simulated on a 0.5° global grid with the model WGHM (Döll et al., 2003), period 1961–1995.

and climate. On small scales with detailed spatially distributed information, models can address a complex system of various interacting hydrological processes. These models often use a spatial discretization based either on a grid representation of all relevant parameters or on a sub-division of the river basin into areas of similar hydrological response.

With an increase in scale and a related decrease of detail in the available data, the actual landscape heterogeneity can no longer be explicitly represented in the model. Thus, scaling approaches are used to describe the sub-scale variability, e.g., by means of average parameters, distribution functions or simplifying lumped process formulations. In general, the capability of hydrological models to represent the hydrological cycle and, thus, their predictive power to quantify current and future variations in continental water storage, is dependent on the accuracy of input data, on the appropriateness of process formulations and on the availability of data for model calibration and validation. Large differences between regions of different climate or physiography in terms of hydrological processes and storage dynamics prevent hydrological models from being easily transferred from one region to another. In particular for large-scale applications, the only available variable for model validation usually is river discharge. Although satisfactory results may be obtained when comparing mean simulated and observed river discharge, the temporal variability and the state of soil, groundwater and surface water storage volumes may be unsatisfactorily

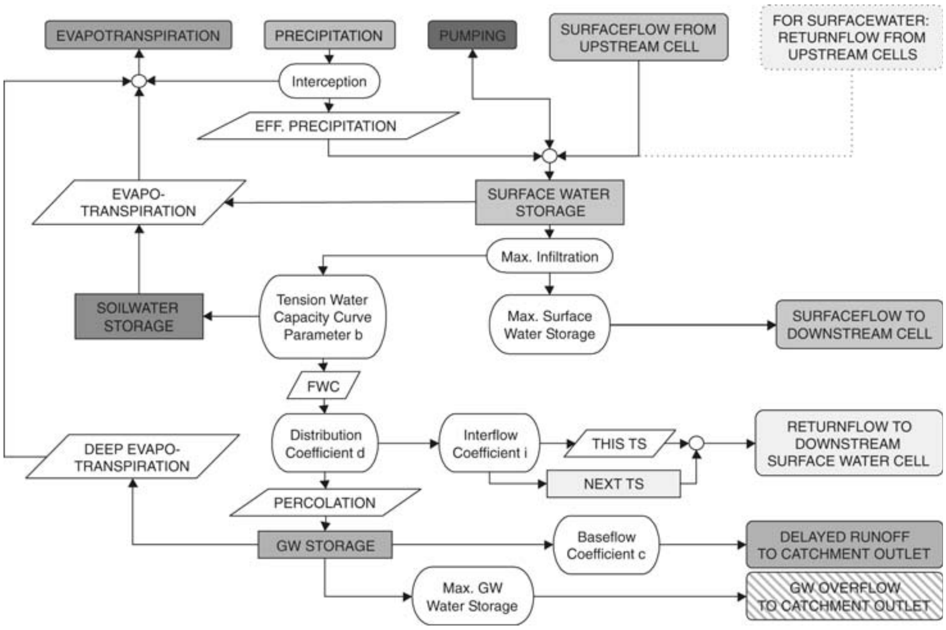

Figure 5. Flow chart of the Stuttgart–Hohai water balance model SHM (Riegger et al., 2001).

simulated in the model. As an example, current limitations of hydrological models to accurately quantify continental storage changes are shown in Figure 6 in terms of large differences in temporal storage variations between model results and water balance studies for large river basins.

In view of the existing uncertainties mentioned above, a multi-variable validation of hydrological models going beyond river discharge as validation variable has often been called for. In this respect, measurements of continental water storage changes by gravity missions can provide a unique additional data source for model validation.

First results from GRACE time-variable gravity fields reduced to the hydrological signal component clearly show a seasonal continental-scale pattern of water storage changes that corresponds to estimates by global hydrological models (Tapley et al., 2004; Wahr et al., 2004; Schmidt et al., 2005). Also at the scale of large river basins, first GRACE results allow to represent the characteristic temporal dynamics of storage change of basins in different environments. Discrepancies between water storage variations from GRACE and from hydrological models highlight, on the one hand, residual errors in the GRACE solutions (e.g., errors in reducing other than hydrological mass signals), and, on the other hand, limitations of the hydrological models.

Of course the use of satellite-based measurements as a fundamental additional information for large catchment areas has to be cross-checked

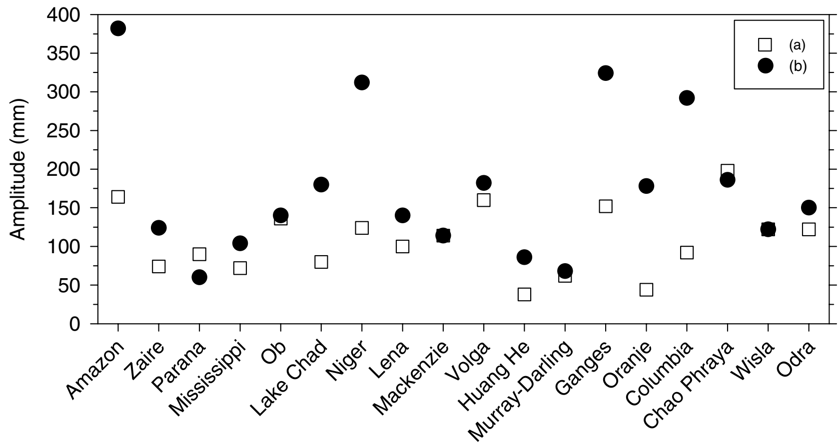

Figure 6. Mean difference between annual maximum and minimum terrestrial water storage for large river basins, (a) median value of 10 global land-surface models, years 1987–1988, (b) value derived from a water balance study, years 1989–1992 (data summarized in Rodell and Famiglietti, 1999).

with measurements from well observed catchments. Thus the validation of satellite-based gravity field measurements of continental water storage variations by ground-based measurements and the quantification of related uncertainties is of fundamental importance for hydrological modelling and forecasting and, as a consequence, for the separation of other contributions to gravity signals like the earth's mantle and crust dynamics (see Vermeersen, 2005). In principle, it consists of an investigation of the consistency between climatic and hydrological data on the one hand, and observed mass changes from satellite-based measurements on the other hand. For this comparison catchments are to be selected where ground-based measurements of soil moisture, groundwater levels, surface water storage and possibly snow cover exist with sufficient density and for which the processes are understood and reliable model estimates of water storage variations are available. An example for such a well observed and modelled catchment is the Rhine catchment (Figure 7; Hundecha and Bárdossy, 2004). With dimensions of 200×600 km and an area of 185,000 km^2 it is at or below the limit of the spatial resolution of gravity changes measured by the GRACE mission. Rodell and Famiglietti (1999) have studied water storage changes for a number of drainage basins. They find that for basins larger than about 200,000 km^2 reasonable changes in groundwater storage on monthly and annual time scales should be detectable by GRACE.

However, Figure 7 demonstrates that water storage variations show high temporal variability (in the order of decimeters up to 1 m of water column for this example) at much shorter spatial scales, at 100 km and less. These are certainly not detectable by GRACE. *Hydrology would benefit considerably*

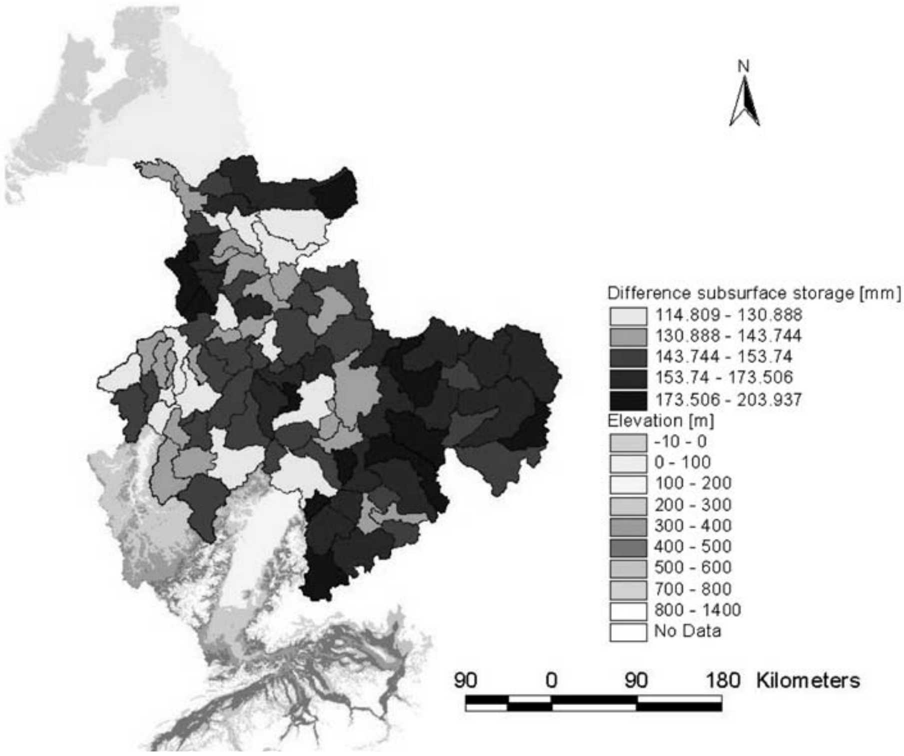

Figure 7. Spatial distribution of seasonal sub-surface water storage changes in the Rhine catchment between months of maximum and minimum storage according to the HBV model.

from future gravity missions resolving temporal variations down to small spatial scales of 100 km or less.

Gravity-based observations of terrestrial mass variations deliver integral values of storage changes of the components groundwater, soil moisture, snow water, and surface reservoir storage. Nevertheless, the characteristic temporal response of fluxes from different storages (Figure 8) – sufficient spatial resolution of 100 km or less provided – might allow a disaggregation of the gravity signal into individual components, which can be verified by ground-based measurements. This might finally allow a separation of storages even for catchments with insufficient ground-based measurements. For example, groundwater aquifers could be monitored with help of the gravity signal where a dense ground-based network does not exist, but where an increasing water demand may endanger the sustainability of groundwater resources.

The knowledge of continental water storage variations measured by satellite-based gravity field measurements is expected to considerably improve

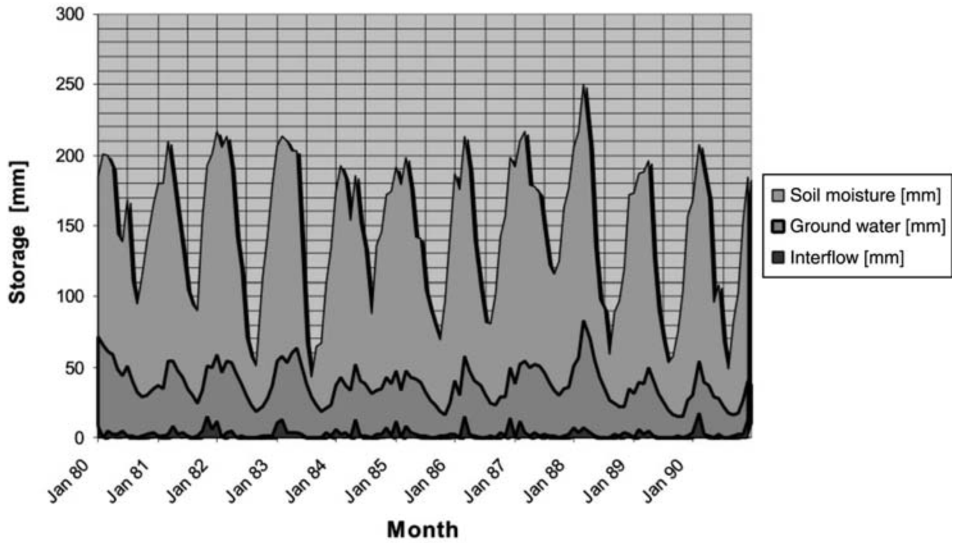

Figure 8. Time series of continental water storage averaged over 90,525 km^2 of the Rhine catchment for soil moisture, inter-flow and groundwater.

the understanding of hydrological processes and their dependencies on climate or physiography. The investigation of a large number of different environments and river basins will allow to cover the maximum diversity in basin characteristics and storage responses, ranging from humid tropical, arid and semi-arid, humid temperate to snow- and ice-dominated regions. In this way, relationships between storage variations and climate variability can be quantified for different basin characteristics and used to improve model transferability and to reduce related uncertainty. This is of particular importance for model transfer to ungauged catchments, where no calibration and validation with discharge data is possible.

5. Large-Scale Evapotranspiration

Evapotranspiration fluxes and their temporal distribution, depending on climatic conditions, actual soil moisture or the vegetation period, are poorly known on large scales. Different modelling approaches may deliver substantially dissimilar results at the monthly, seasonal or even annual time scale. Water storage changes derived from gravity variations, however, will enable to close the water balance and resolve the water balance equation for evapotranspiration (see Equation 1) (see Rodell et al., 2004, for a first application with GRACE data). This will allow for an evaluation and improvement of evapotranspiration models with respect to a realistic description under different hydrological situations (different climate zones, soil and vegetation conditions). Thus, observations of the temporal variability of continental water storages by gravity missions should be suitable for the validation of existing evapotranspiration modules in hydrological models. This reduces the degree of freedom in conceptional models and considerably enhances the quality of parameter estimations and the prognostic power of the models. The transfer of this knowledge to ungauged catchments will then allow a calculation of discharge on the basis of known water storage changes from gravity variations and climatic data and thus deliver an essential input to the assessment of the global water balance.

6. Trends and Anomalies in Continental Water Storage

Processes of environmental change may cause gradual changes in terrestrial water fluxes and storage volumes, which are of high importance for ecosystems and human water and food supply. Similarly, large-scale modifications of the oceanic and atmospheric circulation patterns such as in the course of El-Nino Southern Oscillation (ENSO) also have marked effects on the continental hydrology at inter-annual scales in terms of anomalies of precipitation, soil moisture and runoff. Inter-annual changes in the hydrological contribution to the gravity field measured by satellite missions will allow to investigate slowly changing storages, i.e. of groundwater or continental ice masses, and thus contribute to the direct detection of long-term trends for large spatial scales. New signals of climate change may become observable. In high latitudes, for instance, increasing temperature is expected to lead to a thinning or disappearance of permafrost. A long-term storage decrease will contribute to continental net discharge and thus to sea level rise. In arid to sub-humid areas, climate change is likely to decrease soil moisture, causing runoff changes, land degradation or desertification. The gravity-based observations of inter-annual water storage changes will also help to better understand the impact and persistence of global ENSO-type of circulation anomalies on continental hydrology.

Large scale anthropogenic impacts on water storage are expected to become observable by changes in the gravity field. Direct impacts by water management like withdrawal use of groundwater and surface water for irrigation as well as indirect impacts via changes in land use like deforestation or drainage of wetlands could be detected in areas where these data are not available by other means. As on large spatial scales different hydrological storages (ice, groundwater, soilwater) are coexisting, these components have to be separated by means of auxiliary data from ground measurements or hydrological models for a differentiated description of trends. Ground-based measurements of mass changes in glaciers or long-term variations in the groundwater table are therefore indispensable in order to quantify the consistency with the gravity signal and separate different storages by means of signal dynamics in well observed areas.

The dependency of the observed terrestrial storage changes on changing environmental boundary conditions in the context of climate change or human impacts is not only important for the investigation of hydrological processes and the evaluation of hydrological models, but also for the separation of geophysical contributions (by earth's mantle and crust dynamics) on this long-term time scale. In hydrologically insufficiently observed areas it is indispenible to determine long-term changes in water storage from climatic data on the basis of models. Only after the separation of hydrological gravity changes based on hydrological models, a separate analysis of geophysical components is possible.

Long-term environmental change is not only expressed by changes in the mean, but also by changes in the temporal distribution or variability. In this respect, another potential to detect gradual changes in the hydrological cycle by gravity measurements is via the analysis of changes in the intra-annual regime of storage variations on a monthly basis. Particularly, temporal shifts in the soil moisture regime due to an increasing fraction of rainfall relative to snow in the course of global warming can be analysed. Long-term changes in water storage due to changing frequencies of different atmospheric circulation patterns can potentially be detected. These analyses help to quantify the impact of environmental change, either due to natural climate variability or various anthropogenic influences, on long-term continental mass variations and changes in the hydrological cycle.

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