Hydrol. Earth Syst. Sci., 13, 813–817, 2009
www.hydrol-earth-syst-sci.net/13/813/2009/

Hydrology and Earth System Sciences

Editorial

Remote sensing in hydrological sciences

W. Wagner[1]**, N. E. C. Verhoest**[2]**, R. Ludwig**[3]**, and M. Tedesco**[4]

[1]Christian Doppler Laboratory at the Institute of Photogrammetry and Remote Sensing,
Vienna University of Technology, Vienna, Austria
[2]Laboratory of Hydrology and Water Management, Ghent University, Ghent, Belgium
[3]Department of Geography, Ludwig-Maximilians-Universität München, Munich, Germany
[4]City University of New York, USA

1 Introduction

Space age, and with it the era of earth observation, is generally considered to have begun more than 50 years ago with the launch of Sputnik-1 on 4 October 1957 (Kramer, 2002). Sputnik's beeping radio signals did not only serve to demonstrate the technological capabilities of the Soviet Union, they were also used to gather information about the electron density of the ionosphere. In legacy of Sputnik, most of the Earth observation satellite missions that were to follow served multiple purposes. Unfortunately, up to this day, political and technological motives may be more important drivers for the design of remote sensing missions than the requirements and needs of the geoscientific community. It is probably for this reason that remote sensing continues to be underutilized in many Earth science applications. Hydrology is not an exception.

This mismatch of technological capabilities and use of remotely sensed data has increasingly been recognised in the 1990s. Consequently, an increasing number of space-related programmes with the goal to bridge the gap between remote sensing data providers and users have been initiated. One example is GMES[1] (Global Monitoring for Environment and Security), a joint programme of the European Commission and the European Space Agency (ESA) designed to establish a European capacity for the provision and use of operational information for monitoring and management of the environment and for civil security. Another example is GEOSS[2] – the Global Earth Observation System of Systems – aiming at creating a comprehensive, coordinated and sustained observation system, in order to improve monitoring of the state of the Earth, increase understanding of its processes, and enhance prediction of the behaviour of the Earth system.

It is within this international context that significant advances have been made in remote sensing in recent years. The range of geophysical products retrieved from spaceborne and airborne remote sensing data has now much expanded beyond the traditional land cover maps and digital elevation models. Of relevance to the hydrologist are, for example, highly dynamic land surface parameters such as soil moisture, evaporation, or snow cover, and seasonally varying land surface features such as vegetation structure or hydrodynamic roughness. Yet, the accuracy of remote sensing products, which is in general variable in space and time, is often not well known. Also, it is often not well understood if and how remote sensing data can be used for solving hydrologic problems, such as e.g. formulated by the PUB (Prediction in Ungauged Basins) initiative (Sivapalan et al., 2003). With this in mind, we organised this special issue to discuss how novel or improved remote sensing techniques may contribute to foster hydrologic sciences and applications. The research papers deal with geophysical parameter retrieval, uncertainty assessment, scaling, model calibration and data assimilation.

2 Common challenges in remote sensing and hydrological sciences

Remote sensing and hydrology are two disciplines with vastly different interests and traditions. While remote sensing has a strong technological foundation, aiming at developing non-contact sensor and processing systems to gather reliable information about the Earth and other physical objects[3], hydrology is more strongly science oriented aiming at

Correspondence to: W. Wagner
(ww@ipf.tuwien.ac.at)

---

[1] http://www.gmes.info/

[2] http://www.earthobservations.org/

[3] See, for example, the definition of the International Society for Photogrammetry and Remote Sensing at http://www.isprs.org/.

Published by Copernicus Publications on behalf of the European Geosciences Union.

describing the occurrence and behaviour of water above, over and through the Earth (Savenije, 2009). Yet, they have many fundamental science questions in common and are complimentary with respect to their principle goals.

One of the scientific issues that is often hotly disputed in both disciplines is model complexity. Complex models that try to solve the problem (e.g. runoff forecasting in hydrology or geophysical parameter retrieval in remote sensing) by considering sub-processes in as much physical detail as possible are often regarded to be superior to more simple, phenological approaches. Yet, both in remote sensing and in hydrology one can make use of only a limited number of measurements for validating and driving the models. Therefore it is often not possible to falsify complex models, simply because different model structures and parameter sets may explain the observations equally well. This equifinality problem is well known in hydrology (Beven, 2001) but probably not yet sufficiently recognised in the field of remote sensing.

Besides the concern that complex hydrological- and remote sensing models may not be falsifiable by observations as called for by the Austrian philosopher Karl Popper (Popper, 1989), the human perception of what processes are most important for the problem at hand may be deeply flawed. This problem was well described by Savenije (2009) for the hydrologic case. He argued that the human being is blinded by the scale at which he/she observes hydrologic processes, while at catchments scales ranging from a few to hundreds of kilometres the dominating processes may be completely different ones. The same is presumably true for remote sensing scientists who, intrigued by the complexity of the land surface, might miss to recognise those features which are most important for the interpretation of the remotely sensed data. This problem is aggravated when working with sensors operating outside the visible part of the electromagnetic spectrum. These wavelength regions (e.g. thermal- and microwave domain) are inaccessible for the human visual perception and are hence less accessible for human cognition.

Considering these challenges, is the often expressed hope that remote sensing can provide reliable data for validating and driving hydrological models justified? Can we make better predictions by using more but nonetheless uncertain data? While it is natural for remote sensing scientists to take on a positivistic view, hydrologists have to be more cautious with their answer to this question (Beven, 2001). Nevertheless, as the following discussion of the special issue papers demonstrates, the integration of remote sensing in hydrological sciences has recently made important progress.

3 Remote sensing of soil moisture, snow and evaporation

The retrieval of soil moisture from active and passive microwave remote sensing data has recently attracted special attention. This is due to the launch preparations for the first two satellites dedicated to the task of soil moisture retrieval, namely the Soil Moisture and Ocean Salinity (SMOS) satellite and the Soil Moisture Active Passive (SMAP) mission, and the increasing availability of global soil moisture products from existing satellite missions (Wagner et al., 2007). The first satellite-based near-real-time soil moisture service was declared operational by EUMETSAT in December 2008. The service is based upon active microwave data acquired by the Advanced Scatterometer (ASCAT) on-board of the Meteorological Operational (METOP) satellite and delivers global 25 km soil moisture data to users within 135 min after sensing (Bartalis et al., 2007). Albergel et al. (2009) present the first validation of the ASCAT soil moisture data using 13 in-situ soil moisture monitoring sites in southwestern France. They found that the ASCAT data compare favourably to measurements at 5 cm depth, and if filtered with an exponential function to produce the so-called Soil Water Index (SWI) also to measurements collected at 30 cm depth. The usefulness of the exponential filtering technique to estimate profile soil moisture from surface soil moisture time series was further investigated by Albergel et al. (2008) using in-situ observations and modelled soil moisture data. The authors introduced a recursive formulation of the exponential filter which eliminated the need to store and reprocess long data records. Generally the method was found to work satisfactory, after the characteristic time length of the filter was optimized. Similar results for both the surface and profile soil moisture content were also obtained by Paris Anguela et al. (2008) in the Grand Morin watershed located 35 km east of Paris, France. They used soil moisture data derived from the ERS (European Remote Sensing satellite) scatterometer, which is the predecessor instrument of METOP ASCAT. These three studies showed that the error of the profile soil moisture content may be less than $0.04\,\mathrm{m}^3\,\mathrm{m}^{-3}$ even though the estimated error of the remotely sensed surface soil moisture data may be higher.

At much finer spatial scales (<100 m) soil moisture may be retrieved from Synthetic Aperture Radar (SAR) data. Given the high sensitivity of SAR measurements to local variations in surface roughness, the retrieval of soil moisture is more challenging than in the case of coarse resolution microwave radiometers and scatterometers. To better constrain the retrieval Mattia et al. (2009) proposed merging SAR retrieval and hydrological modelling. The rational of the approach was to use modelled soil moisture fields as a priori information for the SAR retrieval algorithm to improve the spatial detail and accuracy of the soil moisture maps. Even though the improvements turned out to be modest for their study area in northern Germany, this is considered to be a very promising approach making best use of the information provided by hydrologic models and remote sensing data.

Compared to the retrieval of soil moisture, mapping of snow cover in the visible and near-infrared part of the electromagnetic spectrum might appear a relatively straight forward task given the strong contrast between the reflectance of snow and the reflectances of vegetation and soil. However, the discrimination between clouds and snow is still a source of uncertainty, especially over very bright surfaces. Probably the most widely used snow products are the daily snow cover map from NASA's Moderate-resolution Imaging Spectroradiometer (MODIS) and the Interactive Multisensor Snow and Ice Mapping System (IMS) distributed by NOAA. Regarding the MODIS product, various validation studies have found it to be of good quality (Parajka and Blöschl, 2006), yet cloud cover limits its usefulness in hydrologic applications (Dozier et al., 2008). Gafurov and Bárdossy (2009) therefore investigated different techniques for eliminating cloud covered pixels over the Kokcha catchment located in north-eastern part of Afghanistan. They could remove, on average, 30% of the cloudy pixels.

Evaporation cannot be observed directly by Earth observation satellites. Therefore it can only be estimated from remote sensing data if combined with models that describe the land-atmosphere exchanges of water and energy. Ma et al. (2009) proposed a new parameterisation scheme for deriving land surface variables and heat fluxes from ASTER (Advanced Space-borne Thermal Emission and Reflection radiometer) images and tested it over an experimental study site located on the Tibetan Plateau. The comparison with in-situ measurements showed that the relative error of the three ASTER derived evaporation estimates was less than 10%. This compares favourably with relative errors reported in the literature which are generally in the range 15–30% (Kalma et al., 2008). Yet, as noted by Ma et al. (2009), the method is still in the development stage.

4 Soil moisture and hydrologic models

Remotely sensed soil moisture data may be used in multiple ways in hydrologic modelling, e.g. for evaluation (Liu et al., 2008; Laguardia and Niemeyer, 2008), calibration (Parajka et al., 2009), and data assimilation (Crow and Ryu, 2009). The main rationale behind using the satellite derived soil moisture data is probably not that one expects them to be more accurate than modeled soil moisture data, but that the error structures of the two data sources are different. Thus, a combination of them may be less biased and exhibit less random errors than any of them individually (Parajka et al., 2009).

Liu et al. (2008) used ERS scatterometer derived surface soil moisture data along with in-situ measurements to assess an eco-hydrological model over the Wuding River Basin in China. Although they observed differences between the simulated soil moisture data and the other two data sets, the temporal trends matched quite well. This encouraged them to use the hydrologic model to study the trend in soil moisture from 1956 to 2004. Their results confirmed that soil moisture has been decreasing in this area, a phenomenon referred to in China as the "Northern Drying". Laguardia and Niemeyer (2008) compared the ERS scatterometer derived Soil Water Index (SWI) to the outputs of the LISFLOOD hydrologic model over entire Europe. The two datasets showed good agreement over the major part of the European land area. Inconsistencies were found over mountainous areas such as the Alps, tundra regions in Scandinavia and along the eastern coast of Spain. While without additional datasets it was not possible to draw robust conclusions of where the inconsistencies stem from, the study results nevertheless gave a good impression about problem areas in Europe where both remote sensing data and regional-scale hydrological models should be used with care.

Parajka et al. (2009) used ERS scatterometer derived surface soil moisture data and runoff data for calibrating a conceptual dual layer hydrologic model over 148 catchments in Austria. They found that when only runoff was used in the calibration, runoff was simulated well while the agreement between the topsoil observations and simulations was poor. However, when both runoff and soil moisture were considered in the calibration, soil moisture was realistically simulated while not degrading the runoff model performance. They concluded that the added value of scatterometer data in such a calibration scheme lies especially in a more robust estimation of model parameters. Beyond this it would of course also be desirable that satellite-based soil moisture retrievals contribute to improving runoff forecasts. As shown by Brocca et al. (2009) over three catchments in central Italy, it is for example possible to estimate antecedent wetness conditions from ERS scatterometer data, allowing to predict runoff using an event-based rainfall-runoff model. But, as Crow and Ryu (2009) pointed out, there are a number of important situations where antecedent soil moisture conditions are of relatively minor importance for determining the basin response to rainfall. They suggested that remotely sensed soil moisture data should additionally be used to filter errors present in rainfall accumulation products. Crow and Ryu (2009) therefore reframed the hydrologic forecasting problem in such a way that potential benefits of remotely sensed soil moisture on state (i.e. antecedent soil moisture) and flux (i.e. rainfall) estimation are captured simultaneously. In a synthetic twin experiment, they demonstrated that the assimilation system can be designed in such a way as to avoid the potentially deleterious effects of correlated errors. While the performance of this assimilation approach still needs to be tested in real world situations, it can be expected that these fundamental ideas will trigger significant research and development particularly in data-poor areas.

5 Terrain characterisation and hydraulic models

Airborne laser scanning, also referred to as airborne lidar (Light Detection and Ranging), is a remote sensing technology which was introduced in the mid 1990s as a tool for topographic mapping (Flood, 2001). Just within a few years it became the standard technique for acquiring precise digital terrain models (DTMs) required for flood modelling. Yet, the use of lidar data in hydraulic models is not without scientific challenges. One is that hydraulic models require a particular representation of the terrain model that allows a stable numerical solution of the water flow equations. Another problem is that for pure computational reasons hydraulic models cannot cope with densely sampled DTMs. These two problems were addressed by Mandlburger et al. (2008) who presented new methods for data reduction and conditioning the terrain model by imposing conditions on the orientation and shape of the hydraulic mesh. They showed that these DTM post-processing steps are essential for achieving a realistic simulation of the inundation area and flow velocity of the extreme flood of the river Kamp in Lower Austria in 2002.

A new generation of airborne lidar sensors, referred to as full-waveform sensors, captures the complete return signal of the laser pulses scattered backwards by the terrain. These sensors provide, in addition to the geometric information, a number of physical observables such as the backscatter cross section or the width of each registered echo. This makes them very attractive for mapping of near-surface vegetation and other objects that may influence the flow of water over land (Wagner et al., 2008). Bretar et al. (2009) presented methods for processing of full-waveform lidar data, applying them over an experimental area in the south of the French Alps used for studying erosion and hydrological processes. The results showed that full-waveform data are useful for identifying small gullies and crests, and for the classification of land, road, rock and vegetation.

A further important means for improving hydraulic simulations is to calibrate the models with water stage maps derived from remote sensing images taken during flooding events. This calibration usually involves modifying the effective roughness coefficients. While cloud cover often impedes the acquisition of optical images, SAR images can be acquired under any weather conditions. Nevertheless, the quality of SAR derived flood extent maps is limited by the spatial and radiometric resolution (speckle) of the sensors which is why new high-resolution spaceborne SAR sensors such as TerraSAR-X are expected to significantly improve the usability of such data. Zwenzner and Voigt (2009) showed that when TerraSAR-X data were merged with lidar derived terrain models then it was even possible to generate flood extent maps of comparable quality as those from airborne imagery. Montanari et al. (2009) put forward the idea to use SAR derived water stages for updating a coupled hydrologic-hydraulic model. Their hypothesis was that such maps implicitly represent basin saturation, thus providing a means for monitoring the time variation of runoff coefficients. With data collected during a storm event over the Alzette River in Luxembourg they showed that, although it was not possible to identify "best" values for the coefficients, the range of meaningful values could be narrowed.

Finally, Mahrzahn and Ludwig (2009) presented a method for extracting fine-scale surface roughness parameters from polarimetric SAR data which may be useful for improving the parameterisation of local-scale water flow over bare soil surfaces. Within this method, it appears feasible to indirectly assess spatial patterns of soil bulk density parameters, such as soil porosity and void ratio.

6 Conclusions

Earth observation has become a much more user oriented discipline than it was in the past. One important paradigm shift was that remote sensing missions should be designed starting from user requirements. Another important recognition was that users cannot be expected to process raw or low-level remote sensing data products. Therefore, more and more satellite missions have a ground segment which delivers geophysical data products such as soil moisture or snow cover in an operational manner. But even the integration of such higher-level remote sensing products in hydrological models still represents a significant challenge as the direct ingestion of remote sensing products into hydrological models is in general not possible. Rather, it is often necessary to adapt the models and to develop suitable data assimilation techniques. As the papers of this special issue demonstrate these challenges have spurred many new scientific ideas, some of which should eventually lead to improved hydrologic predictions in gauged and, probably even more so, ungauged basins.

References

Albergel, C., Rüdiger, C., Pellarin, T., Calvet, J.-C., Fritz, N., Froissard, F., Suquia, D., Petitpa, A., Piguet, B., and Martin, E.: From near-surface to root-zone soil moisture using an exponential filter: an assessment of the method based on in-situ observations and model simulations, Hydrol. Earth Syst. Sci., 12, 1323–1337, 2008, http://www.hydrol-earth-syst-sci.net/12/1323/2008/.

Albergel, C., Rüdiger, C., Carrer, D., Calvet, J.-C., Fritz, N., Naeimi, V., Bartalis, Z., and Hasenauer, S.: An evaluation of ASCAT surface soil moisture products with in-situ observations in Southwestern France, Hydrol. Earth Syst. Sci., 13, 115–124, 2009, http://www.hydrol-earth-syst-sci.net/13/115/2009/.

Bartalis, Z., Wagner, W., Naeimi, V., Hasenauer, S., Scipal, K., Bonekamp, H., Figa, J., and Anderson, C.: Initial soil moisture retrievals from the METOP-A Advanced Scatterometer (ASCAT), Geophy. Res. Lett, 34, L20401, doi:10.1029/2007GL031088, 2007.

Beven, K.: How far can we go in distributed hydrological modelling?, Hydrol. Earth Syst. Sci., 5, 1–12, 2001, http://www.hydrol-earth-syst-sci.net/5/1/2001/.

Bretar, F., Chauve, A., Bailly, J.-S., Mallet, C., and Jacome, A.: Terrain surfaces and 3-D landcover classification from small footprint full-waveform lidar data: application to badlands, Hydrol.

Earth Syst. Sci. Discuss., 6, 151–205, 2009, http://www.hydrol-earth-syst-sci-discuss.net/6/151/2009/.

Brocca, L., Melone, F., Moramarco, T., and Morbidelli, R.: Antecedent wetness conditions based on ERS scatterometer data, J. Hydrol., 364, 73–87, 2009.

Crow, W. T. and Ryu, D.: A new data assimilation approach for improving runoff prediction using remotely-sensed soil moisture retrievals, Hydrol. Earth Syst. Sci., 13, 1–16, 2009, http://www.hydrol-earth-syst-sci.net/13/1/2009/.

Dozier, J., Painter, T. H., Rittger, K., and Frew, J. E.: Time-space continuity of daily maps of fractional snow cover and albedo from MODIS, Adv. Water Resour., 31, 1515–1526, 2008.

Flood, M.: Laser altimetry: from science to commercial lidar mapping, Photogramm. Eng. Rem. S., 67, 1209–1217, 2001.

Gafurov, A. and Brdossy, A.: Snow cover data derived from MODIS for water balance applications, Hydrol. Earth Syst. Sci. Discuss., 6, 791–841, 2009, http://www.hydrol-earth-syst-sci-discuss.net/6/791/2009/.

Kalma, J. D., McVicar, T. R., and McCabe, M. F.: Estimating land surface evaporation: A review of methods using remotely sensed surface temperature data, Surv. Geophys., 421–469, 2008.

Kramer, H. J.: Observation of the Earth and its Environment, Survey of Missions and Sensors, 4th Ed., Springer, Berlin, 1510 pp., 2002.

Laguardia, G. and Niemeyer, S.: On the comparison between the LISFLOOD modelled and the ERS/SCAT derived soil moisture estimates, Hydrol. Earth Syst. Sci., 12, 1339–1351, 2008, http://www.hydrol-earth-syst-sci.net/12/1339/2008/.

Liu, S., Mo, X., Zhao, W., Naeimi, V., Dai, D., Shu, C., and Mao, L.: Temporal variation of soil moisture over the Wuding River Basin assessed with an eco-hydrological model, in-situ observations and remote sensing, Hydrol. Earth Syst. Sci. Discuss., 5, 3557–3604, 2008, http://www.hydrol-earth-syst-sci-discuss.net/5/3557/2008/.

Ma, Weiqiang, Ma, Yaoming, Li, Maoshan, Hu, Zeyong, Zhong, Lei, Su, Zhongbo, Ishikawa, Hirohiko, and Wang, Jiemin: Estimating surface fluxes over the north Tibetan Plateau area with ASTER imagery, Hydrol. Earth Syst. Sci., 13, 57–67, 2009, http://www.hydrol-earth-syst-sci.net/13/57/2009/.

Marzahn, P. and Ludwig, R.: On the derivation of soil surface roughness from multi parametric PolSAR data and its potential for hydrological modeling, Hydrol. Earth Syst. Sci., 13, 381–394, 2009, http://www.hydrol-earth-syst-sci.net/13/381/2009/.

Mandlburger, G., Hauer, C., Höfle, B., Habersack, H., and Pfeifer, N.: Optimisation of LiDAR derived terrain models for river flow modelling, Hydrol. Earth Syst. Sci. Discuss., 5, 3605–3638, 2008, http://www.hydrol-earth-syst-sci-discuss.net/5/3605/2008/.

Mattia, F., Satalino, G., Pauwels, V. R. N., and Loew, A.: Soil moisture retrieval through a merging of multi-temporal L-band SAR data and hydrologic modelling, Hydrol. Earth Syst. Sci., 13, 343–356, 2009, http://www.hydrol-earth-syst-sci.net/13/343/2009/.

Montanari, M., Hostache, R., Matgen, P., Schumann, G., Pfister, L., and Hoffmann, L.: Calibration and sequential updating of a coupled hydrologic-hydraulic model using remote sensing-derived water stages, Hydrol. Earth Syst. Sci., 13, 367–380, 2009, http://www.hydrol-earth-syst-sci.net/13/367/2009/.

Parajka, J. and Blöschl, G.: Validation of MODIS snow cover images over Austria, Hydrol. Earth Syst. Sci., 10, 679–689, 2006, http://www.hydrol-earth-syst-sci.net/10/679/2006/.

Parajka, J., Naeimi, V., Blöschl, G., and Komma, J.: Matching ERS scatterometer based soil moisture patterns with simulations of a conceptual dual layer hydrologic model over Austria, Hydrol. Earth Syst. Sci., 13, 259–271, 2009, http://www.hydrol-earth-syst-sci.net/13/259/2009/.

Paris Anguela, T., Zribi, M., Hasenauer, S., Habets, F., and Loumagne, C.: Analysis of surface and root-zone soil moisture dynamics with ERS scatterometer and the hydrometeorological model SAFRAN-ISBA-MODCOU at Grand Morin watershed (France), Hydrol. Earth Syst. Sci., 12, 1415–1424, 2008, http://www.hydrol-earth-syst-sci.net/12/1415/2008/.

Popper, K.: Logik der Forschung, 9 ed., J.C.B. Mohr (Paul Siebeck), Tübingen, 477 pp., 1989.

Savenije, H. H. G.: HESS Opinions "The art of hydrology", Hydrol. Earth Syst. Sci., 13, 157–161, 2009, http://www.hydrol-earth-syst-sci.net/13/157/2009/.

Sivapalan, M., Takeuchi, K., Franks, S. W., Gupta, V. K., Karambiri, H., Lakshmi, V., Liang, X., McDonnell, J. J., Mendiondo, E. M., O'Connell, P. E., Oki, T., Pomeroy, J. W., Schertzer, D., Uhlenbrook, S., and Zehe, E.: IAHS Decade on Predictions in Ungauged Basins (PUB), 2003–2012: Shaping an exciting future for the hydrologic sciences, Hydrolog. Sci. J., 48, 857–880, 2003.

Wagner, W., Blöschl, G., Pampaloni, P., Calvet, J.-C., Bizzarri, B., Wigneron, J.-P., and Kerr, Y.: Operational readiness of microwave remote sensing of soil moisture for hydrologic applications, Nord. Hydrol., 38, 1–20, 2007.

Wagner, W., Hollaus, M., Briese, C., and Ducic, V.: 3D vegetation mapping using small-footprint full-waveform airborne laser scanners, Int. J. Remote Sens., 29, 1433–1452, 2008.

Zwenzner, H. and Voigt, S.: Improved estimation of flood parameters by combining space based SAR data with very high resolution digital elevation data, Hydrol. Earth Syst. Sci., 13, 567–576, 2009, http://www.hydrol-earth-syst-sci.net/13/567/2009/.