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Some hydrological challenges in understanding discharge generation processes in the Rhine and Meuse basins

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Abstract

Although societal hazard related to hydrological events has increased dramatically over time, our understanding of the discharge generating processes is still deficient. The main challenges appear to be related to the scale of the processes. Hydrological processes are highly heterogeneous, non-linear and interconnected. Upscaling from micro- to catchment scale and subsequent parametrisation appears undoable because of data requirements, model complexity, computational time requirements, and equifinality (implying that different combinations of parameters generate equally good results). A new generation of hydrologists is looking for answers to match the observed complexity at the plot-scale, with the apparent simplicity that arises at the catchment scale. One of the key processes in the watersheds of the Meuse and Rhine is the rapid sub-surface flow, a process which is still poorly understood.

1. Introduction

Society is facing more and more socio-economic problems as a result of flood occurrences. Although an analysis of worldwide loss events (1987–1998) shows that there are distinct increases in economic losses, in term of the number of events, this represents no or only a moderate trend (Loster, 1999).

One of the world's largest re-insurance companies, Munich Re, describes in its Annual Review of Natural Catastrophe 2002 that floods account for 30% of all loss events and 42% of all fatalities due to natural catastrophes in 2002 (Munich Re, 2003). The total economic loss by floods was estimated at US$ 27 billion in that year (Fig. 1). Furthermore, Munich Re (2003) ranked the Rotterdam–Amsterdam (Randstad) metropole in the hazard index at position 18 of 50 mega cities worldwide. Although this is a first attempt to index hazard risks of metropoles, and in case of the Randstad the hazard is based on floods and storms, it shows that there is a major economic and societal risk, partly induced by floods.

It is generally accepted that continuation of the typical structural and engineering approach of controlling the natural river system is not sustainable. More and more it is discussed that river systems should get more room to allow for their natural behaviour and dynamics. Sustainable flood defence practices would benefit from a combination of structural and non-structural approaches (Petry, 2003).

The reasoning is that a river stream can (temporarily) store more water and hence diminish flood related problems along a river. Besides storage of discharge in the river system itself, the discussion also focuses on retardation of rainfall in the upstream area of the river catchments. Land use has changed enormously during the last century, especially with urbanisation and an intensification of agriculture and forestry. The question is whether

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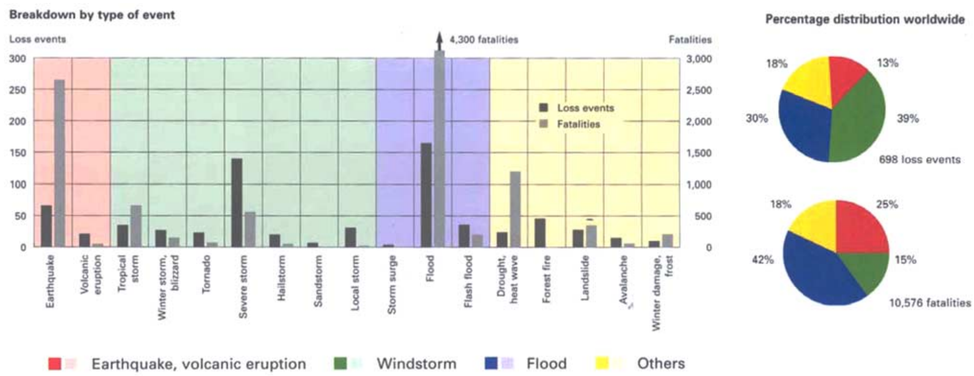

Fig. 1. Statistics of natural hazards in 2002, according to the Munich Re (2003).

and to which extent these activities have resulted in enhanced and accelerated drainage of the upstream areas (Savenije, 1996).

The Worldwide Fund for Nature (WWF) has initiated a discussion on combining nature restoration and water storage with their report 'Mountains of Water' (WWF, 2000). This 'enhancing the natural sponginess of river basins' could provide an attractive network of rivers, water and nature, diminish floods and droughts and stimulate business in tourism and recreation. As the public was told that deforestation, soil drainage, and sealing of surfaces was the cause for the increased flood frequency and magnitude, why should doing the reversed not have the opposite effect?

However, the Munich Re (2003) report is very clear about the effects of river restoration: "River restoration measures make sense and are very welcome; but their effectiveness in extreme cases is often overestimated or misrepresented. As a rule, they are incapable of preventing really catastrophic floods and in many cases will not even bring about any significant reduction. The volumes of water that amass in extreme events are simply too huge".

The IRMA SPONGE research project (Hooier et al., 2002), in which thirteen research groups collaborated, concluded that for the Rhine and Meuse river systems, climate change would imply an increasing change of peak flows with increased potential flood damage. IRMA SPONGE also states that upstream land use changes have only marginal effect on the river flows in downstream areas. Effects only exist at a local scale upstream. de Wit et al. (2003) focused in an integrated assessment on the upper part of the Meuse catchment and discussed the limited effects of reforestation, remeandering, increased inundation of floodplains, nature recovery and uncontrolled retention on the peak discharge of the Meuse at Borgharen. But these conclusions are based on extreme rain events, where all storage (be it large or modest) is used. Furthermore, questions are raised on these conclusions (e.g. WWF, 2000) as it is shown that the hydrological community does not fully understand the hydrological processes in catchments and has several problems with the modelling of discharge generation processes.

2. Problem reconnaissance for discharge generation

In 2003 two reconnaissance studies of hydrological research were made and published: the Dutch 'Foresight Committee on Hydrology' (KNAW, 2003) and 'Geosciences, the future' (IUGG, 2003). Both reports were written after several discussions and meetings. Although different from set-up both reports describe similar scientific bottlenecks and challenges for hydrology: (1) incomplete understanding of the hydrological processes; (2) incomplete theory and data sets for modelling; (3) data integration and model calibration; (4) scale issues. For flood and drought studies a fifth can be added: (5) the uncertainty on climate change and variability, which is an important scientific and management bottleneck. To quantify the effects of climate change on the hydrological cycle is very hard (Allen and Ingram, 2002).

A statement often heard is that the hydrology community stopped measuring surface water hydrological processes in the 80s of the last century. The hydrological processes on the hill slopes and in the catchments were considered sufficiently understood. McDonnell (2003) asks himself by quoting Hewlett "Where does water go when it rains, what flow path does it take to the stream and how long does it resides in the catchment?" He recognizes progress has been made in rainfall-runoff modelling, especially in parameter estimation and uncertainty analysis. However, he also states "I wonder if we have somewhat neglected updating our understanding of the rainfall-runoff process and how this informs our needed model structures and response to these three basic questions central to our conceptualisation of how catchments work?"

One of the most striking field evidence obtained with isotopic tracers in studying runoff events is the recognition that pre-event water largely dominates storm runoff. But our rainfall-runoff models are based on the assumption that storm response relates either to Hortonian overland flow or saturated overland flow, both of which are clearly conceptualised as water fluxes stemming immediately from the rainfall event! Kirchner (2003) asks why catchments store water for considerable time and then release it in a few minutes or hours? Secondly Kirchner notes that also the chemistry of 'old' water can vary with the flow regime, but that no satisfactory explanation has been found for this paradox yet. He hypothesises that the subsurface water storage must be seen as several water stores (stocks) each with their own chemical signature that release water differently under varying flow conditions. McDonnell suggests that watersheds display considerable threshold behaviour, storage effects, competitive feedbacks and hysteresis, in ways very much described by non-linearity theory. Bishop et al. (2004) reply to Kirchner's question by explaining the double paradox for the Nyänget catchment with a combination of the transmissivity feedback mechanism (progressive increase in lateral saturated conductivity towards the soil surface) and vertical distribution of hydrochemical components. Bishop et al. (2004) state that hydrochemical information should be combined with hydrometric information to solve questions about water flowpaths and travel times. Also in the forest hydrology field, questions about the state of process knowledge are being critically reviewed (DeWalle, 2003). The unsaturated zone and groundwater recharge aspects have not been taken into account in so much detail in catchment and forest hydrology research but currently attract much more attention.

As a key member of physical deterministic modelling scientists in the last two decades of the 20th century, Beven (1989, 2001) critically analysed the constraints of distributed modelling. The general idea of distributed modelling is that it represents reality better than lumped model approaches as it takes into account spatial information and—more important—it uses physical law (mass balance and energy equations) to describe the hydrological processes. But on distributed scales (if not all field scales?) we are forced to work with 'effective' parameters. In heterogeneous sub-grids the outcome of non-linear processes cannot be modelled using averaged 'effective' parameters.

The scale issues are closely related to the parameterisation of our physical models and to the measurement constraints that we have. We are simply not capable to measure all parameters at sub-grid scale. An example is the use of Richards' equation for pixels of e.g. more than 10 m scale. But what 'physically-based' theory should we put in place of the Richards' equation? Alternative formulations are criticised as being too conceptual (Beven, 2001).

Sivapalan (2003) asks himself how we can make a useful connection between the field complexity at hillslope scale and apparent simplicity inferred at the watershed scale? The field evidence and hillslope models are generally made in an upward (bottom–up) approach based on small-scale field measurements—as Beven discussed—, whereas Sivapalan states that the watershed scale normally asks for a downward (top–down) approach starting with analyses of rainfall and discharge records. Sivapalan suggests that we should progress by upscaling hillslope hydrological response using travel time distributions, which matches with the travel time distribution of the e.g. unit hydrograph approach. Savenije (2001) sees opportunities for this downward approach in the fact that relatively simple catchment response functions appear to be able to describe complex hydrological processes at scales with sufficient level of aggregation.

3. Some developments in research on discharge generation and its modelling

A lot of effort is nowadays paid to obtain a balance between practical simplifications and justifiable model complexity. But how do these model efforts relate to the field evidence process underpinning?

In the field of process knowledge understanding, the objective is to identify different runoff response mechanisms and to characterise the key state variables (Uhlenbrook et al., 2003). This should be done by extensive and long duration field observations. Field observations will obviously differ from 30 to 50 years ago as a result of increased (process) knowledge and technical improvements of field measuring equipment and laboratory analysis.

Also more attention is nowadays given to feedback mechanisms in hydrology, as the large scale interrelationship of climate and soil moisture state of an area. Also the feedback mechanisms between soil moisture and vegetation development and (local) climate receive lots of research attention, especially in long term effects of climate change.

A rapidly developing research field is that of the data assimilation for catchment hydrological modelling (Troch et al., 2003a). Basically this research aims to include all possible data sources into catchment modelling, independent of the observation scale of the data. More controversial is whether we can and should upscale process knowledge or that we should focus more on uncertainty analysis of model performances. Beven (2001) proposes to continue with the current distributed model approaches according to his Generalised Likelihood Uncertainty Estimation (GLUE) method. He agrees that this does not involve new (better) sets of equations, but he sees no alternative for the energy equations that are currently being used.

Other research groups see alternative possibilities and undertake interesting and promising methodological research to tackle the problems associated with scale and process knowledge. Several attempts are undertaken to start with new basic equations for hillslope and catchment scale hydrological behaviour, respectively the Hillslope Boussinesque Equation of Troch et al. (2003b) and Paniconi et al. (2003), and the Representative Elementary Watershed (REW) concept of Reggiani et al. (1998, 1999, 2000). These studies are now in the spotlights of the hydrological world and will be looked at especially on their capability to solve some of the mentioned problems of scale and process representation in hydrological modelling.

4. NCR initiatives: 'Discharge Generation' theme

For water management, knowledge of the hydrological processes in upstream watersheds is essential; for the Netherlands this mainly concerns the Rhine and Meuse basins. The Netherlands Centre for River studies (NCR), which is a collaboration of the major developers and users of expertise in the Netherlands in the area of rivers, has stimulated initiatives in the field of catchment hydrology. In 2001 the NCR Programme Committee has defined three research themes: (i) Discharge Generation, (ii) River and Floodplain Management and (iii) Living with the River (van Os, 2001).

The research theme on Discharge Generation was defined aiming at studying the genesis of floods and droughts, or more broadly, discharge generation in upstream areas. It stimulates and tunes the hydrological research in the Rhine and Meuse basins within the Netherlands. A number of Dutch universities, technical institutes, and governmental institutes participate in a working group to unite skills, knowledge and manpower, to stimulate data-sharing and collaboration and to define research questions that are both relevant for water management and challenging for scientists. The overall scientific objective of the research theme is to improve our understanding of the spatial and temporal controls of discharge generation under changing hydro-meteorological behaviour and land use management. The research questions have been grouped into: (i) discharge forecasting, (ii) determination of design discharge, (iii) influence of climate change, and (iv) influence of land use change.

One of the opportunities to present the ongoing work within the NCR research themes is an annual symposium, entitled 'NCR-days'. The three different themes of the NCR-days 2003, (i) Flood Management and Defence, (ii) Spatial Development and Land-use, and (iii) Regional Floodplain Management, covered to a large extend the research performed in the Netherlands nowadays, regarding river and catchment hydrology and safety against flooding. Hydrological, morphological and ecological (riverine planning) problems were clarified with modelling analysis and field survey studies. The progress of strategic policy studies and the development of instruments to enhance perceptions in decision-making processes were elaborated. Moreover innovative methods for mapping techniques and flood forecasting, as well as environmental impacts of floods and economical risk analysis were also presented.

5. Concluding remarks

It may be clear that hydrology still has many fundamental challenges. A new generation of hydrologists is active in redefining the basics of runoff generation, both by developing new ways to observe rainfall-runoff processes and measure key state variables at catchment scale, and by developing new modelling instruments and approaches. The research in the upper watersheds of the Rhine and the Meuse is highly relevant in this context, both to increase our knowledge of fundamental rainfall-runoff processes and to make a contribution to a better understanding of two of our most important river basins.

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