Fundamental hydrological research results drawn from studies in small catchments

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Abstract The history of research in small experimental and representative catchments in the 20th century is briefly displayed, in particular with regard to water quantity experiments. The early studies up to about the 1960s dealt with impacts of forest cover on runoff volumes and peak flow rates, but did not explain why catchments responded as they did. Stimulated by the IHD of UNESCO, as from the 1960s numerous small research catchments have been set up for process studies to enhance the understanding of the hydrological behaviour of catchments. Although initially only precipitation and runoff could be measured, the technological developments in the 1970s opened the road for collecting time series of actual evaporation and soil moisture estimates. Many catchments studies have been conducted on runoff generation using e.g. isotope information of the various flow components contributing to flood events. These and many other studies in small experimental and representative catchments have much contributed to a better understanding of the hydrological processes and to improved hydrological modelling.

Key words experimental and representative catchment; forest; runoff generation; evaporation; hydrological research

INTRODUCTION

The human influence on the hydrological cycle became a topic of great interest in the late 19th century. At that time several countries suffered from problems with extreme floods after cutting down forested land for agriculture. As a consequence, the role of forest in flood protection was extensively discussed in Europe and elsewhere. To provide an answer to this urgent question, small-catchment studies were initiated to identify the influence of forest coverage on flood runoff. Small, uniformly covered catchments rather than large catchments having several types of land use, were seen as an appropriate research unit to demonstrate the effect of drastic changes of land use.

From a viewpoint of specific hydrological research, two types of catchments are discriminated: experimental and representative ones (Toebes & Ouryvaev, 1970). Experimental catchments are usually defined as catchments with a relatively homogeneous soil and vegetation and with uniform physical characteristics. Representative catchments are supposed to be representative of a larger region in such a way that hydrological similarity can be presumed and monitored to investigate hydrological processes under unchanged and natural conditions.

Experimental and representative catchments have now been used for about a century, initially for studying the impact of deforestation and afforestation on runoff.

In the 1960s, the International Hydrological Decade (IHD) of UNESCO stimulated the establishment of networks of well-instrumented small catchments for hydrological process studies and modeling. The IHD was followed by the International Hydrological Program (IHP). The well-known Euromediterranean Network of Experimental and Representative Basins (ERB) was established in 1986 to facilitate scientific meetings focused on research in small catchments. From 1986 ERB has convened 12 international conferences.

THE FIRST HALF OF THE 20TH CENTURY

The first known catchment study was carried out from 1903 to 1918 in Switzerland and compared flows from two catchments, the fully forested Sperbelgraben and the scarcely forested Rappengraben (Robinson & Whitehead, 1993). The Sperbelgraben catchment area produced lower flood runoff rates as compared to the Rappengraben area, while low flows in summer appeared to be slightly higher (Engler, 1919). This well documented correlation study between two catchments demonstrated the important role of forest vegetation for flood protection. Many such investigations in small catchments followed in other countries. Well known are the Wagon Wheel Gap, Coweeta and Hubbard Brook catchment studies in the USA, which were set up in 1911, 1933 and in 1955, respectively (Ice & Stednick, 2004).

In the Wagon Wheel Gap catchments in Colorado flows were observed from two, as similar as possible, paired forest catchments during a period of eight years. Then the forest cover was felled in one catchment and the differences between the observed and the expected runoff – if the forest had not been cleared – were compared for the next period of seven years. The treated catchment's average increase in annual runoff by 30 mm was attributed to the impact of deforestation (Bates & Henry, 1928).

In 1933, small catchments in Coweeta, North Carolina, were selected for studies on deforestation and replanting of various types of forest (Douglass & Neary, 1980). These long-term experiments in Coweeta provided information on the impact of different forest types on interception losses and runoff. Large reductions in annual runoff of up to 250 mm were observed when hardwood trees were replaced by pine forest (Swank & Crossley, 1988), highlighting the importance of interception.

From the 1955s ongoing research in the Hubbard Brook catchments has confirmed that forest type conversions modify runoff hydrographs through changes in interception and transpiration (Federer, 1973; Bormann & Likens, 1979). Although most studies dealt with runoff comparison through deforestation or land use conversions, few studies on afforestation were carried out (Bosch & Hewlett, 1982; Robinson, 1998). However, extensive studies on the hydrological impact of converting grassland into forest have been carried out in New Zealand since the 1950s. These studies, performed in several small basins, have confirmed the results of changes found elsewhere. The impact on low flows, however, appears to vary from catchment to catchment (Davie & Fahey, 2005). The effect of afforestation on peak flows appeared to be considerable, in particular in terms of small and moderate flood events, although flow rates with long return periods can also be substantially reduced (Duncan, 1995). However, there is still discussion whether these effects can be seen at a large catchment scale.

In the mid 1950s, great concern rose in the UK when it was recognized that afforestation of uplands of reservoirs would reduce the supply capacity of drinking water (Marc & Robinson, 2007). This fact finally resulted in the establishment of the well-known Plynlimon experimental catchments in the late 1960s.

In 1941 a comparable study had already been undertaken in the Netherlands using huge (625 m^2) lysimeters in the dunes to explore the influence of forest vegetation on the recharge of groundwater in the coastal dunes for drink water supply (Hoeven van der *et al*., 2005a).

Overlooking the first 50 years of representative and experimental catchment studies in different geographical and climatic conditions, it clearly revealed that: (a) forest, more than other vegetation, reduces annual runoff volumes and peak flows; (b) the impact of forest on base flow appeared variable owing to differences in root development, drainage and management practices; (c) a lack of process studies did not permit an extrapolation of the results to larger catchments; and (d) although experimental catchment research suffered from several drawbacks, the idea was definitely settled that catchment studies are the only vehicles to demonstrate the hydrological effect of land use change at the catchment scale. Therefore, the historic forest catchment studies were invaluable and have largely contributed to understand the significance of land use, in particular with respect to forested areas, and the management practices involved on the catchment behavior.

Continued research was clearly necessary to improve the physical understanding of hydrological processes within catchments, besides additional statistical analyses of precipitation and runoff records. In the years since then, hydrological process studies concentrating on the factors controlling the transformation of precipitation into runoff were initiated, while the first catchment models to simulate runoff were developed, tested and applied simultaneously.

THE SECOND HALF OF THE 20TH CENTURY

IHD, IHP, FRIEND and ERB

Until the 1960s, limited hydrological instrumentation had placed strong constraints on the measurement of processes other than precipitation and runoff. Data collection was mainly based on manually read instrumentation while data processing and analysis was paper-based. Due to the fast technological developments in sensor techniques, electronic data collection and storage, highly frequent observation of all the separate components of the catchment's water balance became close at hand as well new algorithms for data analysis and of complex catchment models.

Thus in 1965 a new era in hydrology began when UNESCO launched the International

Hydrological Decade (IHD) with a special program on experimental and representative catchments to generate more fundamental studies on the hydrological processes at different spatial and temporal scales. In the following years numerous small research basins were selected and instrumented.

In cooperation with IAHS, UNESCO further stressed the great value of small catchment research for scientific hydrology through the Budapest conference on representative and experimental catchments in 1965. At this conference, results were presented of many comparative forest studies in experimental catchments and of early studies on water balances and its hydrological components (IAHS, 1965). UNESCO also formulated guidelines to promote more detailed research in physical processes in natural basins and to attack elements of uncertainty in hydrology (Toebes & Ouryvaev, 1970). In 1974, the IHD was followed by the International Hydrological Programme (IHP). The use of small catchments for research has remained on the agenda. In 1980 results were presented at a conference in Helsinki (IAHS, 1980) and in 1982 at a conference in Bern (Landeshydrologie, 1982).

Although several of the small research catchments were closed down during the 1970s, two new initiatives on catchment research were launched in the 1980s: the FRIEND project (Flow Regimes of International Experimental Network Data) as UNESCO-IHP component in 1985, and the ERB in 1986. FRIEND was a result of intensive and fundamental discussions on the possible ways of extrapolation of research results from experimental and representative catchments to other catchments. Its main approach was applying statistical analysis using a database composed of data from a large number of catchments rather than extrapolation of results from individual catchments.

The ERB is a coordination network of experimental and representative basins in Europe with twenty member countries. The aim is to exchange scientific results and experiences of catchment research and to promote research collaboration. Next to experimental catchments with an incidental monitoring program, the ERB network includes a large number of research catchments with a permanent network operating under different topographic and climate conditions. Several catchments have already been operational in the IHD period and have built up a wealth of data, model applications and research results. The research programs of these catchments cover a wide range of hydrological subjects, including water quality, sediment transport and climate variability. In the following sections, some topics will be briefly explored.

Forest hydrological research

In continued forest hydrological research many process studies in small catchments have been undertaken since the IHD period and presented at several ERB conferences.

These studies reveal that peak flow generation greatly depends on rainfall amounts, local geology and soil water storage properties. It is pointed out that local, rapid saturation of upper soil stores may contribute to flood flows (Viville *et al*., 2003). Crossing such saturation thresholds appears to govern the rapid flood formation process even in forest catchments, whereas significant impacts have also been observed of geology, soil, litter, slopes and vitality of the forest on peak flow generation (Mathys *et al*., 1997). It is observed that in wet periods differences in field characteristics are becoming less important than rainfall intensities and volumes (Etzenberg *et al*., 1997).

The effect of forest on low flows is similar to earlier findings. Recent studies in the Sperbelgraben forest catchment indicate an interdependency of flood generation and soil characteristics while the effect of the forest coverage itself on floods seems to be limited (Hegg *et al.*, 2005). However, the measured changes between the presence or absence of forest cover may not only be attributed to vegetation effects, but also to changes and compaction of the soil during logging (Marc & Robinson, 2007).

In New Zealand, studies of young growing forest reveal that the changes in peak flow are dependent on the timing of canopy closure (Davie, 1996). The effect of an increase of the canopy cover on the behavior of evaporation has been reported from catchment studies in the UK (Blackie & Robinson, 2007; Marc & Robinson, 2007) and from lysimeter studies in the Netherlands (Hoeven van der & Warmerdam, 2005b).

Runoff generation

The analysis of runoff components into surface – and one or more subsurface sources – is one of the key themes in the evaluation of the hydrological behavior of catchments, as is the adequate modeling of the processes. Instead of the traditional, rather arbitrary, methods of hydrograph separation, more advanced separation methods are being used such as geochemical tracers, environmental isotopes or simple discharge groundwater table relations to acquire information on the spatial and temporal variation of runoff producing processes. The identification and quantification of runoff components using chemical tracers (Christophersen *et al*., 1990) and environmental isotopes (Kendall & McDonnell, 1998) have been applied in many small catchments. Results have been presented at several ERB conferences (http://www.ih.savba.sk/ihp/friend5/erb7.htm).

The steep sloping Strengbach catchment in the Vosges, France, shows a rapid response from saturated areas in the valley, but also delayed flow from upstream saturated sources. This contribution to flood runoff from upstream sources is being observed only when a threshold of water storage is exceeded (Viville *et al*., 2003). Chemical analysis and environmental isotopes confirm that the majority of water in the flood hydrograph comes from saturated areas, while pre-event or "old water" water is dominating. In the Mediterranean Can Vila catchment in the Pyrenees, three separation approaches were applied: geochemical tracers, a relation between discharge and water table and hydrograph simulation using the Topmodel (Latron *et al*., 2005). All methods show that base flow rates demonstrate a rather dynamic behavior. Similar findings of large variations of runoff sources during storm periods were observed in the Hueweler bach catchment in Luxembourg (Pfister *et al*., 2005).

Although significant differences were found between these methods in individual catchments, as well as between different catchments, there is uniformity in the relative large contribution of pre-event groundwater to peak runoff. Similar results were obtained during snowmelt periods in the forested Lange Bramke catchment (Holko *et al*., 2003; Herrmann *et al*., 2007), in the steep sloping Jalovecki Creek in Slovakia (Kostka *et al*., 2003) and the Uhlriska catchment in the Jizera mountains, Czech Republic, and were confirmed by model simulations. In the latter catchment rainfall transformation at the hill slope was studied using a dual domain model, representing soil matrix respectively preferential flow computation. It was shown that preferential flow contributes significantly to the runoff response. It was also demonstrated that the soil water regime at the hill slope is an essential characteristic in governing runoff generation (Sanda *et al*., 2005). Further applications are available in the various proceedings of ERB published as UNESCO technical documents in hydrology.

Although the isotope and chemical composition of water discharged at the outlet may largely characterize the various sources of runoff, the interpretation of these components is still a matter of definition.

From several hill slope studies in mountainous catchments it is evident that knowledge of soil moisture in relation to saturation thresholds is essential to understand the various sources of water in the hydrograph.

Evaporation studies in small basins

Evaporation is a key process in catchments that greatly governs the magnitude of runoff. Clearly, a lack of reliable estimates of actual evapotranspiration does often hamper progress in hydrological modeling, catchment water balance studies and process studies for land use change and impact assessment. However, until the 1960s, a technology for direct or indirect evapotranspiration measurement was lacking.

As said before, fast technological developments took place in the 1960s, allowing substantial scientific progress towards refinement and operation of micrometeorological approaches for estimating actual surface fluxes like profile-, Bowen ratio-, eddy covariance methods (Brutsaert, 1982). These developments mainly took place inside the turbulence and boundary layer research groups.

Around the mid-1970s, the hydrological community started to apply these operational micrometeorological methods for long-term observations of surface fluxes. The aim was: (1) to collect time series of actual evapotranspiration for well-defined surfaces, mostly grassland and forest, and (2) by using these series to develop and test robust parameterizations for estimating actual evapotranspiration based on routinely estimated potential evapotranspiration (Bouchet, 1963; Gash & Morton, 1978; Brutsaert & Stricker, 1979).

These extensive studies of the microclimate and fluxes were carried out in small research catchments like the Rietholzbach in Switzerland (Schaedler, 1982), the Hupselse Beek in The Netherlands (Warmerdam *et al.*, 1982), the Lockersleigh catchment in Australia (Kalma *et al*., 1995; Boulet *et al*., 1999). These catchments functioned as anchor-areas in the WMO inter-comparison study of evapotranspiration methods (WMO, 1997). The Orgeval catchment in France (Benalleque *et al*., 1995) can be specifically mentioned for its strong interest in testing remote sensing techniques (Quesney *et al*., 1999) along with an intensive programme of hydrological and meteorological observations. The Velen catchment in Sweden (Lindroth & Norén, 1978), together with the Thetford research in UK (Stewart & Thom, 1973), and the Valday Research Laboratory in the Soviet Union (Marunich, 1975), concentrated their efforts on evapotranspiration above extended forested surfaces.

These measurement programmes were often accompanied by an observation network of soil moisture using the neutron probe technique.

The Thetford forest research offered excellent datasets for testing and validating the well-known Rutter model (Gash & Morton, 1978). Furthermore, experiments in Thetford, the Velen catchment, and the Valday Research Laboratory showed special problems with flux observations above very tall vegetation (Marunich, 1975).

CONCLUSIONS

Investigations in experimental and representative catchments have been undertaken for a century. In the first half of this period the impacts of forest on flood generation and extreme flow rates were studied by comparison of runoff from forested and non-forested catchments. In the second half of the 20 th century, advances in hydrological knowledge could also be made from physical studies in small catchments. The results of this small catchment research are invaluable and have largely contributed to the understanding of various hydrological processes and to improved and refined catchment modeling. The advent of newly developed instrumentation in the 1960s has enabled large advances in process studies, particularly in soil moisture and evaporation.

Although forests reduce flow volumes and peak flows, the majority of forest studies recognize less significant effects of forest vegetation on extreme peak flows than generally assumed.

The change in soil water storage due to an additional amount of rain appears an important parameter in understanding the flow response of catchments. A thorough understanding of soil characteristics is indispensable in attacking uncertainties in hydrological research and results.

Long-term investigations of catchments provide an extensive knowledge of processes, including their uncertainties. New concepts in hydrological research will benefit from the available field knowledge and the wealth of long-time series. Therefore, experimental and representative catchments still have to be considered a critical resource for progress in hydrological process studies.

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