Use of artificial flood events to demonstrate the invalidity of simple mixing models

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Abstract The whole of a basin responds to a precipitation event. The resulting flood wave introduces a complex pattern of interrelated processes which occur in the vegetation, soil, bedrock, human facilities, channel and in the different parts of the basin. The main advantage of field experiments is that it becomes possible to exclude several governing factors or sources and to control others by the experimental design. In a small brook near Trier (Germany), artificial flood events are created. In-channel transport processes of sediment are investigated without taking into account the interference of soil erosion and runoff. It is demonstrated that kinematic waves—describing the translation of flow with limited hydraulic dispersion or diffusion—also occur in small basins. The kinematic waves—travelling only a few hundred meters—have a large impact on the relationship between the hydrograph and dissolved or particle-bound substances. Consequently, classifications and simple mixing models between those components are impeded.

Key words artificial floods; kinematic wave; suspended sediment; mixing model

Utilisation de crues artificielles pour prouver l'invalidité des modèles de mélange simple

Résumé Le bassin versant entier réagit à une précipitation. L'onde de crue, qui en est le résultat, génère un schéma complexe de processus liés qui se déroulent dans la végétation, dans le sol, dans la roche, dans les aménagements anthropiques, dans le ruisseau lui-même, ainsi que dans les différentes parties du bassin. L'avantage principal des expériences sur le terrain réside dans la possibilité de s'affranchir de certains paramètres influents et de contrôler les autres. Des expériences utilisant des crues artificielles ont été faites dans une petite rivière près de Trèves, en Allemagne. Les phénomènes de transport dans la rivière sont examinés sans interférence avec l'érosion du sol ni l'écoulement des versants. Il apparaît ainsi que les ondes cinématiques—traduisant un écoulement avec une dispersion hydraulique et une diffusion limitées—existent aussi dans de petits bassins. Ces ondes cinématiques, parcourant seulement quelques centaines de mètres, ont un impact important sur la relation entre l'hydrogramme et les matières en suspension et en solution. Par conséquent, les classifications et les modèles de mélange simple basés sur ces composantes sont réfutés.

Mots clefs crues artificielles; onde cinématique; matières en suspension; modèle de mélange

INTRODUCTION AND OBJECTIVES

In a pilot study, experiments with artificial flood events have shown that during substance transport by flowing water, even at a small distance, there is a disconnection of the dissolved phase and suspension from the flood wave. This reaction lag can amount to 10 min for 1 km (Krein & Symader, 1998) and can be explained by kinematic wave theory. Lighthill & Whitham (1955) were the first scientists to show

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that a flood wave moves like a kinematic wave. The resulting reaction lag between changes in streamflow and chemical response was highlighted in an isotopic hydrograph separation performed by Nolan & Hill (1990) for a small basin near San Francisco (11 km^2). Changes in isotopic content and conductivity lagged behind changes in streamflow. They argued that this time lag is due to the displacement of pre-event water in the stream channel network in advance of the downstream passage of event water. Another description of this effect is given by Buttle (1994). This lag between the phases is extremely significant in the interpretation of discharge connected chemographs at the water gauge. One isolated part of the hydrograph cannot necessarily be assigned to the chronologically corresponding chemographs. Therefore, the investigation for the substance sources is made more difficult because the source material arrives at the gauges after the discharge reaction. To the present it has been believed that kinematic waves dominate during flood flows in large basins, as described by Glover & Johnson (1974) or Mahmood & Yevjevich (1975).

The purpose of this experiment is to shed more light on the governing factors of the kinematic flood routing in a small mountainous drainage basin. Of greatest interest here are the shapes of the hydro- and chemographs as well as their change along the brook axis. In this context, the paper considers the significance of the kinematic wave for mixing models.

EXPERIMENTAL SITE

The experiments were conducted in the northern basin area of the Olewiger Bach (Brook) (Fig. 1). The size of the basin, located in the northern Hunsrück mountains near Trier, Germany, is about 35 km^2. Devonian shales with quartz and diabase veins dominate the geology. Pleistocene terraces of the River Mosel lie on the surface of the solid geology in the northern part of the drainage basin. They cover the bedrock with Pleistocene gravel, sand and loess. The vegetation is a type of patchwork with arable land on the plateau, forest on the north and east facing slopes of the valley, and vineyards on the south facing slopes. The valley bottom consists of pastures. The municipal water works of Trier control the discharge from their main reservoir into a canal (Irscher Bach) that was originally constructed to lead the water over a water wheel. Two hundred metres upstream Station A this mill-race debouches into the Olewiger Bach. The drinking water reservoir is located in the neighbouring basin area (Ruwer River). Artificial flood water from a pipeline is fed directly into the Olewiger Bach. It shows low conductivity values (< 100 $\mu S\ cm^{-1}$) with very low suspended sediment concentrations (< 2 $mg\ l^{-1}$). Detailed information about stream bed morphology and sediment characteristics is given by Krein & Schorer (2000) and De Sutter *et al.* (2000). The cross-sections of the Olewiger Bach and Irscher Bach are rectangular with vertical river banks in argillaceous material. Seven homogeneous sections (slope, width) from the water works inlet to Station B can be separated (Table 1).

Testing at the reservoir outlet and at two gauging stations with defined profiles which are 1064 m (Station A) and 3134 m (Station B) downstream the water works inlet makes it possible to investigate the transport behaviour of the dissolved and particle-bound substances. The sampling and analysing programme at the three measurement points covers aspects of hydrological conditions (discharge, conductivity, water temperature) and the concentration of suspended solids.

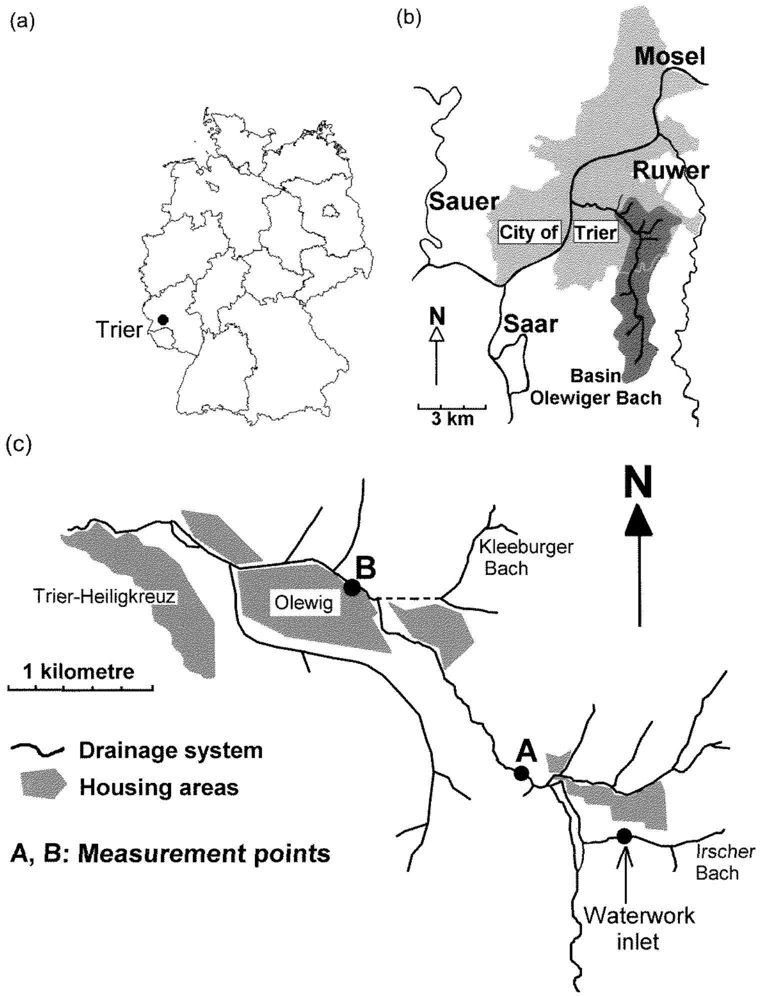

Fig. 1 Area of investigation: (a) Germany; (b) Trier region; (c) northern Olewiger Bach basin.

Table1 Channel characteristics of the Olewiger Bach between the water works and Station B.

Reach	Length (m)	Slope (%)	Width (m)
Water works inlet			
1	490	7.35	0.8
2	106	1.08	3.2
3	102	0.41	3.3
4	100	0.48	3.2
5	106	0.24	3.1
6	160	4.69	0.7
Station A			
7	2230	1.36	2.7
Station B			

METHODS

The design of the wave can be freely chosen as a function of scientific demands. A trapezoidal artificial wave design is repeated in early June, August, and the end of November 1999. A maximum discharge of 280 $l\,s^{-1}$ is reached in six equal steps (Fig. 2). The first two steps are maintained for 20 min, while the next four steps are maintained for 5 min only. The first two steps are still detectable at Station A while the other four steps form a continuous rising discharge signal. Maximum discharge is held for 20 min. The descending limb consists of six downward steps that are each maintained for 5 min giving a continuous falling signal at the stations. The trapezoidal form of the design is created to mimic the build-up of a typical natural winter flood event of the Olewiger Bach. To simulate summer events, an artificial flood with a different structure was induced in April 2000. This event was a combination of two rectangular waves with a different duration of the maximum discharge (280 $l\,s^{-1}$) period. The first wave with a duration of 20 min is divided by a break of 2 h from a second event of 30 min duration (see Fig. 4, later in the text). The baseflow is much greater at Station B with 440 $l\,s^{-1}$ than in the small Irscher Bach (30 $l\,s^{-1}$) where the water is discharged (Fig. 1). This leads to differing peak discharges at both measurement points. Altogether 870 and 831 m^3 reservoir water were discharged on 1 June 1999 and 4 April 2000, respectively. The stepped waves and the rectangular shape were chosen as it was not otherwise technically possible for the water works to discharge water by the middle of 2000.

Flood water samples of 2 l were taken midstream when changes of water level, turbidity, smell or colour were observed. The sampling frequency ranged from 2 min in the rising limbs to 10 min during the falling branches. These time sequences were chosen as the suspended sediment concentrations rapidly increase with the waves, but with receding discharge they gradually sink. Suspended sediment concentrations were determined by filtering the samples through 0.45 μm filters. Discharge was measured with ultrasonic measurement tools and datalogger (UNIDATA, Starflow). Conductivity and water temperature were measured with WTW LF 340 measurement tools. In addition, the water velocity was measured with propellers in order to calculate the Froude numbers at the stations.

KINEMATIC WAVE THEORY

The kinematic wave describes the translation of flow with limited hydraulic dispersion (lateral spreading of a hydrograph as it travels down a river reach) or diffusion (attenuation of the hydrograph crest) (Singh, 1996). The passage of a kinematic flood wave will be seen as an uniform rise and fall in the water surface elevation over the duration of the flood. If a person travels along with the wave, he will observe the wave as a steady flow movement. The equations of continuity and momentum for gradually varied unsteady flow are the St Venant equations:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0 \tag{1}$$

$$S_f - S_0 + \frac{\partial h}{\partial x} + \frac{v}{g}\frac{\partial v}{\partial x} + \frac{1}{g}\frac{\partial v}{\partial t} = 0 \tag{2}$$

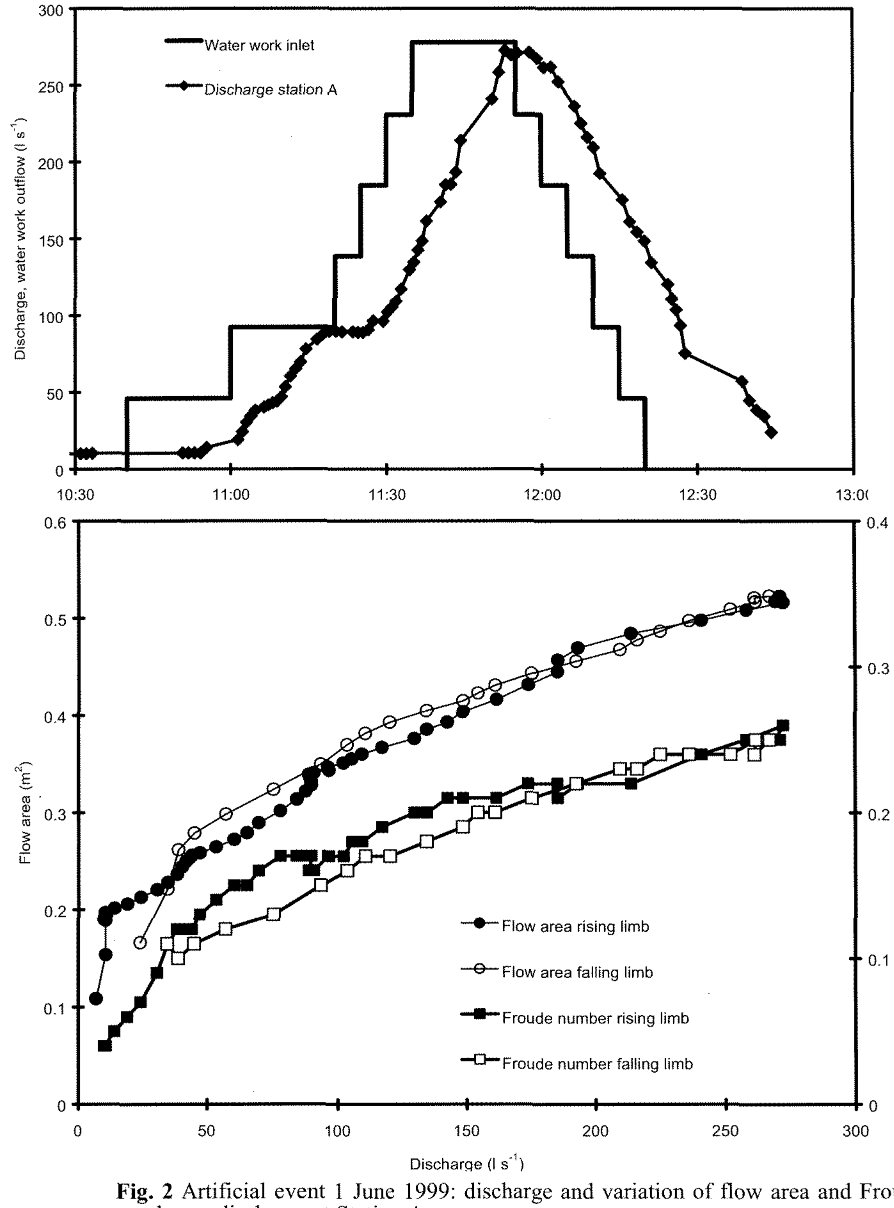

Fig. 2 Artificial event 1 June 1999: discharge and variation of flow area and Froude number *vs* discharge at Station A.

Sometimes, the momentum equation is expressed in the form:

$$A = \alpha Q^{\beta} \qquad (3)$$

where Q is the discharge (l s^{-1}); A is the flow area (m^2); x is the longitudinal coordinate (m), t is the time (s); S_f is the friction slope (dimensionless); S_0 is the bottom slope (dimensionless); h is the water level (m); v is the velocity (m s^{-1}); g is the acceleration of gravity (m s^{-2}) and α, β are dimensionless coefficients. The application of the kinematic flow principle is only valid if the bed slope S_0 is much larger than the three following terms in equation (2). The kinematic wave approximation holds in most cases for thoroughly subcritical, very shallow flows (Singh, 1996). There are three classes of flood waves:

(a) If the bed slope is large, only S_0 will be significant.
(b) Reducing S_0 brings the other three slope terms into consideration.
(c) A further reduction in S_0 means that the last two terms in equation (2) drop out.

The values of S_0 appropriate to each class depend on the flood hydrograph (Henderson, 1963). If the last three terms in equation (2) are neglected, the discharge is a function of the water level only and the corresponding wave is termed kinematic. The discharge is propagated downstream with a kinematic wave celerity, c (m s^{-1}), given by equation (4). The ratio of c/v is always greater than one, because $\mathrm{d}v/\mathrm{d}A$ is always positive.

$$c = \frac{\mathrm{d}Q}{\mathrm{d}A} = v + A \cdot \frac{\mathrm{d}v}{\mathrm{d}A} \tag{4}$$

RESULTS

Kinematic waves dominate not only during flood flows in large basins, as postulated by Glover & Johnson (1974) or Mahmood & Yevjevich (1975). The measurements on the Olewiger Bach basin prove that the influence of kinematic waves should not be neglected in smaller drainage basins either. Figure 2 shows the rating curve of an artificial flow event recorded at Station A in June 1999. The flow area shows no hysteresis *vs* discharge. There is an unique relationship between the discharge and the water level, which proves the applicability of the kinematic flow concept. Further evidence can be found in the consideration of the Froude number. Kinematic waves are of greater importance than dynamic waves if the Froude number is smaller than 1.5 (Woolhiser & Liggett, 1967). This criterion is given for overland flow. However, Singh (1996) concludes that kinematic waves on an overland plane can also occur for Froude numbers greater than 1.5. Nevertheless, the maximal value of the Froude number for the artificial flood events in the Olewiger brook is only 0.3 (Fig. 2).

The time of travel of a flood wave will usually not be equal to the ratio of channel length and velocity at crest flow. Because a flood wave travels at the wave celerity c, which is greater than the mean water velocity v, there is a lag in the arrival of the flood water behind the rise in stage. This can be understood by considering the translation of a monoclinal wave through a channel that is already subject to a certain initial discharge (Fig. 3). This wave travels down the channel at a constant celerity c. An observer running along with the same velocity c may regard the wave as stable and as taking in a steady discharge $Q = (c - v_1) \times A_1$ at the front while leaving an equally steady discharge $Q = (c - v_2) \times A_2$ behind. This also means that the variation in time of the concentration of suspended solids or the concentration of various ions will lag behind the discharge variation. Larger flood rises, which have greater wave velocities, will have shorter lag times than smaller rises. It is postulated that this lag time is short, difficult to notice and unimportant for small basins of less than 100 km^2 (Glover & Johnson, 1974).

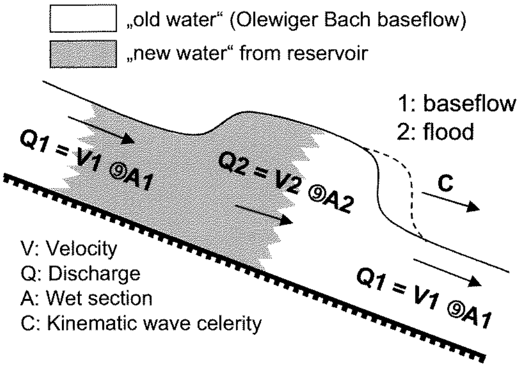

Fig. 3 Kinematic flood routing.

Kinematic waves lead to important time lags even in the Olewiger Bach. Figure 4 outlines the time variation of conductivity lagging behind the associated time evolution of the discharge as recorded in the Olewiger Bach at the water works outflow and Station B. Due to a higher baseflow in the Olewiger Bach (440 l s^{-1}) in contrast to the Irscher Bach (40 l s^{-1}), there is an increase in peak discharge from 320 l s^{-1} at the water works measurement point to 670 l s^{-1} at Station B. After travelling 3 km between the

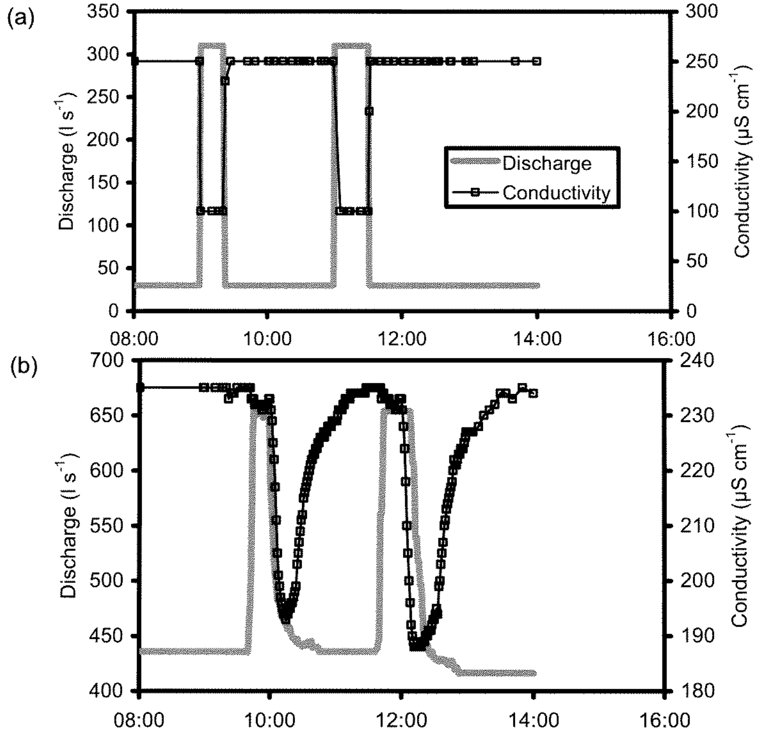

Fig. 4 Artificial event of 4 April 2000: discharge and conductivity (a) at the water works outflow and (b) at Station B.

measurement points, discharge and conductivity are clearly separate in time. New water from the reservoir, with a much lower conductivity than the dry weather flow, arrives 30 min after the discharge increased. So a large proportion of old water is pushed in front of the wave and creates the increasing water body. By that, it may be assumed that the lag time is present and applies equally to small basins.

Based on the work of Ponce *et al.* (1978), rectangular waves such as in Fig. 4 are only limitedly kinematic. According to Ponce *et al.* (1978), the steeper the slope, the shorter the period required to satisfy the kinematic flow assumption. The present experiments and the conductivity values show that the very steep waves on 4 April 2000 demonstrate a lag of 30 min for 3 km distance and are very much kinematic. The theoretical remarks by Ponce *et al.* (1978) therefore are not confirmed.

De Sutter *et al.* (2000) show that the lag time is not only significant for rectangular flood waves in the Olewiger Bach. In 55 different experiments the measured lag time is about 10 min per kilometre on average. If the length of a stretch is L, the wave travel time will be L/c and the water mass travel time will be L/v (Glover & Johnson, 1974). The increase in lag time over a stretch L will amount to:

$$\Delta t = \frac{L}{v} - \frac{L}{c} = \frac{L}{c} \times \left(\frac{c}{v} - 1 \right) \tag{5}$$

Considering that the observed wave celerity c equals about 100 m in 2 min, the ratio c/v would be 1.75, corresponding to the theoretical Manning's c/v ratio for a rectangular section with width much greater than water level (Glover & Johnson, 1974).

The time lag between discharge reaction and the beginning of decreasing conductivity at Station B is illustrated in Fig. 5. Twenty-seven events with similar amounts of discharged flood water (about 280 l s^{-1} maximum) were chosen. Generally, with an increasing baseflow there is a decrease in the time lag at the Olewiger Bach. The semilog relationship gives the best fit. In order to obtain a valid explanation for this, further experiments will have to be conducted using a lower baseflow.

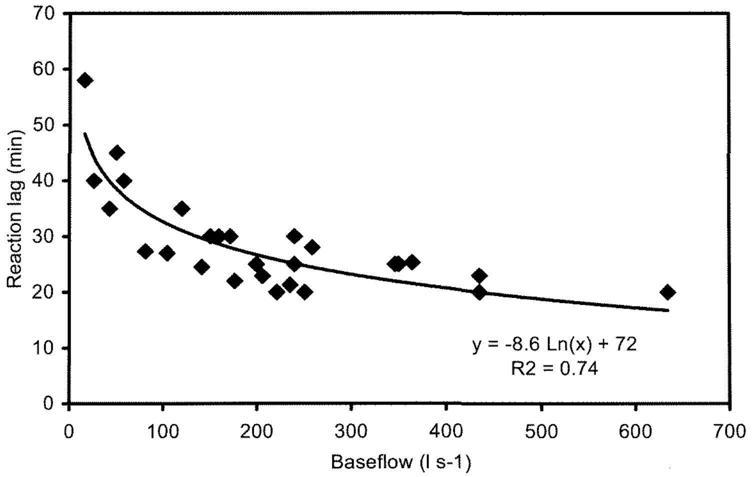

Fig. 5 Time lag between discharge reaction and the beginning of decreasing conductivity during all artificial flood events with a similar amount of flood water—Station B.

The relationship between the suspended solids concentration and the river discharge during storm events has been studied intensively in hydrology. Most studies on hysteresis effects describe clockwise or positive hysteresis loops (Asselman, 1999). This may be caused by sediment depletion or early sediment supply from a tributary in a downstream point. Anti- or counterclockwise hysteresis occurs less frequently, but is often prominent when sediment originates from a distant source or when the valley slopes form the most important source (Heidel, 1956). It is obvious that transport is higher in the rising limb of a hydrograph than in the falling limb for the same flow rate. Figure 6 illustrates that the frequently mentioned rating curves between suspended sediment concentration and discharge are influenced by kinematic flood routing. The baseflow increase between the stations from 40 $l\ s^{-1}$ at Station A to 120 $l\ s^{-1}$ at Station B is caused by a larger baseflow influx from the Kleeburger Bach (Fig. 1). It is shown that discharge and suspension have become disconnected. The wave exhibits a faster speed than the suspended cloud. The main erosion happens in the mill race above Station A. In the natural channel of the Olewiger Bach there is mainly transport and sedimentation. There appears to be no renewed remobilization occurring between Stations A and B. Accounting for this is the decrease of the concentration of suspended particles between the stations. The reaction lags brought about by the kinematic wave result in loops changing from clockwise to counterclockwise movement between Stations A and B.

DISCUSSION

The time lag indicates that changes in water chemistry during a wave passage are more complex than suggested by solute balance equations. Particularly in headwater basins, mixing models are used in the investigation of the runoff generation process. However, the results of the present experiments show that there is no simple dilution occurring simultaneously with the rising stage. Such observations are confirmed by the work of Jordan-Meille *et al.* (1998), who were working in a headwater basin on Lake Geneva. An artificial event with 5 $l\ s^{-1}$ baseflow and 20 $l\ s^{-1}$ peak flow shows—at a distance of only 460 m—a lag of 60 minutes. Jordan-Meille *et al.* (1998) explain this with kinematic wave movement induced by the increase of discharge. With this, their investigation confirms that, even in headwater basins of few hectares in size, an important time lag takes place. Therefore, approaches where the separation of streamflow components is based on the simple mixing equation $\text{Conc}_{tot} \times Q_{tot} = \text{Conc}_1 \times Q_1 + \text{Conc}_2 \times Q_2$ (Caissie *et al.*, 1996) cannot describe the natural runoff process. The study by Caissie *et al.* (1996) was conducted in a small basin (52 km^2) in the Miramichi River system of New Brunswick, Canada. However, the kinematic wave is not considered. In many small basins there is no total mixing between the baseflow component Q_1 and the new water Q_2 under kinematic conditions. This paper shows that, even over short distances, a large part of the baseflow is mobilized along with the discharge wave. The proportion increases with growing distances. Mixing models must take into account these influencing parameters. In addition, it should be taken into consideration that there is a connection between reaction lag and baseflow, as well as with the flood water amounts. This influence is not constant and must be considered individually in every mixing calculation.

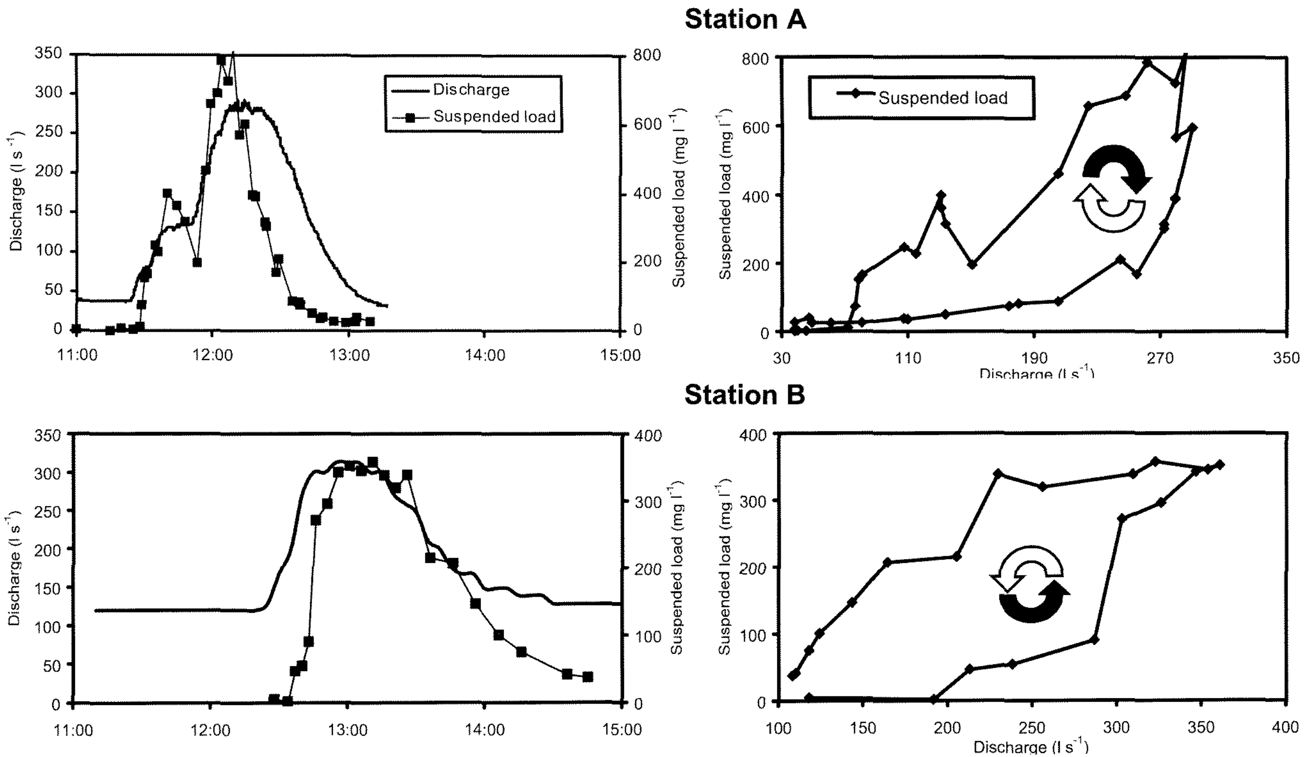

Fig. 6 Artificial event 30 November 1999: discharge, suspended sediment concentrations and corresponding rating curves at Stations A and B (arrows indicate loop direction of rating curve).

Investigations in which the first wave part shows baseflow characteristics often consider piston flow, in which pressure from precipitation works its way through the surface soil into the channel, as an explanation (Uhlenbrook & Leibundgut, 1997). However, a fact which is often ignored is that the postulated groundwater or soil water component, which it is claimed is being pushed into the channel by rain events, is often merely an incorporated baseflow in front of a kinematic wave. The kinematic effect is not solely limited to the sluice bed. It can also be registered by flowing water outside the channel (Singh, 1996).

Simple rating curves between discharge and suspended loads intended to calculate the total load by hydrographs are overly simple. The different velocities of the particle cloud under variable hydrological conditions show that there is no relationship between those parameters. At the particular brook that was investigated, even the position of the gauging station is important, because the time lag between sediment cloud and discharge increases over distance.

CONCLUSION

The existence of kinematic waves in small basins is demonstrated and proven. Important consequences are described. The variation of the characteristics of both the suspended and the dissolved load can be used to broaden one's knowledge of transport mechanisms. It becomes clear that the existing procedures describing water chemistry changes and suspended load behaviour during floods should be reconsidered, as their behaviour is more complex than was originally assumed. The measurements prove that the influence of kinematic effects on the relationship between hydrograph and suspended sediment should not be neglected in smaller basins. The time lag shows that it is not always possible to connect particle-bound substances of defined samples to the corresponding section of the hydrograph. The different velocities show that, after the particles have been transported over several hundred metres, there is no relationship between those parameters. Consequently, classification between discharge component and suspended sediment at the sampling points is impeded.

REFERENCES

Asselman, N. E. (1999) Suspended sediment dynamics in a large drainage basin: the River Rhine. *Hydrol. Processes* **13**, 1437–1450.

Buttle, J. M. (1994) Isotope hydrograph separations and rapid delivery of pre-event water from drainage basins. *Progr. Phys. Geogr.* **18**(1), 16–41.

Caissie, D., Pollock, T. L. & Cunjak, R. A. (1996) Variations in stream water chemistry and hydrograph separation in a small drainage basin. *J. Hydrol.* **178**, 137–157.

De Sutter, R., Krein, A. & Van Poucke, L. (2000) Simulation of sediment transport in a small basin with artificial flood events. In: *Advances in Fluid Mechanics* (ed. by M. Rahman & C. A. Brebbia) (Proc. Montreal Symp., 2000), 549–558. WIT Press, Southampton, UK.

Glover, B. J. & Johnson, P. (1974) Variations in the natural chemical concentration of river water during flood flows, and the lag effect. *J. Hydrol.* **22**, 303–316.

Heidel, S. G. (1956) The progressive lag of sediment concentration with flood waves. *Trans. Am. Geophys. Union* **37**, 56–66.

Henderson, F. M. (1963) Flood waves in prismatic channels. *J. Hydraul. Div. ASCE* **89**(4), 38–67.

Jordan-Meille, L., Dorioz, J.-M. & Mathieu, N. (1998) An artificial flood to determine the hydrological network's contribution to phosphorus exports in a small rural watershed. *Wat. Res.* **32**(6), 1801–1810.

Krein, A. & Schorer, M. (2000) Road runoff pollution and its contribution to river sediments. *Wat. Res.* **34**(16), 4110–4115.

Krein, A. & Symader, W. (1998) Artificial flood release, a tool for studying river channel behaviour. In: *Environmental Hydraulics* (ed. by J. H. W. Lee, A. W. Jayawardena & Z. Y. Wang) (Proc. Hong Kong Symp., 1998), 739–745. Balkema, Rotterdam, The Netherlands.

Lighthill, M. J. & Whitham, G. B. (1955) On kinematic waves: flood movement in long rivers. *Proc. Roy. Soc. (London),* Series A **229**, 281–316.

Mahmood, K. & Yevjevich, V. (1975) *Unsteady Flow in Open Channels.* Water Resources Publications, Fort Collins, Colorado, USA.

Nolan, K. M. & Hill, B. R. (1990) Storm-runoff generation in the Permanente Creek drainage basin, West Central California—an example of flood-wave effects on runoff composition. *J. Hydrol.* **113**, 343–367.

Ponce, V. P., Li, R. M. & Simons, D. B. (1978) Applicability of kinematic and diffusion models. *J. Hydraul. Div. ASCE* **104**(3), 353–360.

Singh, V. P. (1996) *Kinematic Wave Modelling in Water Resources: Surface Water Hydrology.* John Wiley & Sons, New York, USA.

Uhlenbrook, S. & Leibundgut, C. (1997) Abflußbildung bei Hochwasser in verschiedenen Raumskalen (The runoff generation process at different scales, in German). *Wasser und Boden* **49**(9), 13–22.

Woolhiser, D. & Liggett, J. (1967) Unsteady, one-dimensional flow over a plane. *Wat. Resour. Res.* **3**(3), 753–771.

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