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Ecological impact of urban stormwater runoff studied in experimental flumes: population loss by drift and availability of refugial space

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ABSTRACT

Urban stormwater runoff discharged through sewer systems into streams causes flush spills of water and pollutants in the receiving water. To make the right decisions in future plannings of the very costly rehabilitation of sewer systems, a solid ecological data base on the critical parameters of sewer overflows is badly needed. Therefore, we designed a laboratory flume which was operated in circular flow mode (to ensure adaptation of the test organisms) and in flow-through mode during the simulation of sewer overflows (to allow a proper evaluation of population loss by drift). Examples on the behaviour during the adaptation phase and the population loss during the exposure to flush spills of water and/or a mixture of sewage and clean water of a benthic invertebrate (*Gammarus pulex*) demonstrate the potential of the flume to identify critical parameters of sewer overflows at "quasi-real-world-conditions". We found clear evidence for synergetic effects since the exposure to high flow and sewage caused higher population loss of *Gammarus* than the sum of population loss at exposure to only high flow or only sewage. Population loss considerably depended on the availability of refugial space: if the interstices of the gravel in the flume were silted, this loss was higher than at open interstices. Only ten minutes of movement of the material forming the flume bottom reduced the population of *Gammarus* to about 60 or 50% of its initial size. Hence, our data strongly suggest that the characteristics of the receiving stream (refugial space, bed stability) play an important role for the potential ecological impact of a sewer overflow. Changes of stream morphology and/or creation of refugial space plus an appropriate technical solution for overflow treatment may be less costly and more effective than a large-scale technical project. Thus, the stream itself should be a major element in future management decisions.

1. Introduction

Technical progress has increased the efficiency of sewage treatment plants in many parts of the world. Therefore, engineers and ecologists focus their interest on other sources of water pollution in order to decrease man-made impacts on water quality and aquatic communities. Since the beginning of this century a main subject of civil engineering has been the construction of pipe systems to collect the sewage from urban areas and the building of sewage treatment plants. The main task of the treatment plants was the reduction of the continuous organic carbon load in order to improve the oxygen conditions in the receiving waters. Consequently, engineers and ecologists working in this field orientated their work towards the relations between heterotrophic activity and the composition of aquatic communities, focussing, e.g., on the saprobic system (Metcalfe, 1989). In recent years, it had to be learned that despite big efforts in the reduction of continuous emissions from sewage treatment plants the ecological status of receiving waters did not always improve as expected. Therefore, engineers and ecologists started to research effects of other sources of pollution with a high potential of ecological damage. For running waters the problem of urban stormwater runoff is a major issue of the current discussion (e.g. 2nd Wageningen Conference "Urban Stormwater Quality and Ecological Effects upon Receiving Waters", Sept. 1989; 1st Conference "Niederschlagsbedingte Schmutzbelastung der Gewässer", Karlsruhe, March 1990).

Stormwater from sealed surfaces can be discharged into streams in two types of systems. If the wastewater and the stormwater are transported in separate pipes, rain runoff flows directly through a storm sewer into the receiving water. If the stormwater and the wastewater produced in an urban area are transported in one pipe, this is called a combined sewer. If a storm event exceeds a particular level, surface runoff water plus wastewater plus sediments scoured from the combined sewer are discharged into the stream, either directly or after treatment in storage settling basins or other devices (Hogendoorn-Roozemond, 1985; Ten Hove et al., 1985). Though storm sewer overflows (SSOs) are to some extend polluted (Uunk, 1985), the emission of pollutants from combined sewer overflows (CSOs) is higher (Vat, 1985). Thus, ecological effects below SSOs are less distinct than below CSOs (Willemsen et al., 1989), where the benthic invertebrate community can be almost extincted (Widera et al., 1989).

The current question is, which of the parameters of urban stormwater runoff cause these negative effects in streams, and how runoff water can/must be treated in order to reduce the emission of critical parameters and thus ecological damage. Since an enormous amount of money will go into the construction of retention basins and the rehabilitation of sewer systems in the near future, ecologists are forced to pass their answers to the involved engineers soon.

A review of the relevant literature on the ecological effects of potentially critical parameters of urban stormwater runoff (flow, suspended solids, oxygen, NH_3, oil, detergents) ended with the statement that very little information is currently available (Blohm and Borchardt, 1989). For someone familiar with the philosophy of experimental designs in biology this could have been expected, since the "state of the art" usually requires adaptation of the organism to the conditions it shall be tested at in order to get replicable results. Consequently, situations similar to the sudden, short-term flush spills from SSOs and CSOs were rarely considered in past research.

Even less is known on potential synergetic effects of particular critical parameters under these conditions. Garric et al. (1990) found synergetic effects of low oxygen and increased suspended solids on the lethal time of brook trout fry. Gammeter and

Frutiger (1989) reported comparable effects at low oxygen and increased NH_3 on the drift and mortality of benthic invertebrates. Both studies did not consider potential effects of changes in water flow, which can be dramatic during an intense storm (the flush from a sewer overflow can cause a flood in the stream within a minute or so). Since flow characteristics are a very essential factor in shaping stream communities (Statzner et al., 1988), we designed a flume in which the ecological effects of both, the flushing water and the pollutants it contains can be studied.

This is demonstrated by experiments on the population loss by drift of *Gammarus pulex* (Amphipoda, Crustacea), a benthic invertebrate from a genus, which is dominant in the zoobenthos community of many European streams. Gammarus, as most benthic invertebrates in streams, uses the interstices of the stream bottom as a refugial space (Statzner and Bittner, 1983; Statzner et al., 1988). Since these interstices are often completely silted below CSOs (Widera et al., 1989, own observations), we included experimental manipulations of this refugial space.

The objectives of this paper are i) to demonstrate the potential of our experimental approach to identify ecological impact of particular critical parameters of SSOs and CSOs in the synergetic context; ii) to stimulate research in a field, where a solid data base is badly needed, in order to make the right decisions in a very costly field of future stream management. Therefore, we describe i) the design of our somewhat unusual flume; ii) examples of the population loss by drift of *Gammarus pulex* at flushing discharge and/or a mixture of sewage and clean water for open or silted interstices of the stream bottom.

2. Methods: flume design and flume options to simulate sewer overflows

2.1. *Rationale for flume design*

The two types of channels used in experimental stream ecology are either circular or flow-through (usually straight) flumes. The advantage of circular flumes is that the "stream" does neither start nor end, and populations or whole communities can be kept for long periods in these channels (Lamberti et al., 1987; Schmidt, H.H., personal communication). Their disadvantage is that ecological relevant responses like, e.g., population loss by drift can hardly be assessed, especially not during flush conditions, when it is impossible to block the whole cross section with a fine meshed net. Such an evaluation (population loss by drift) is much easier in flow-through flumes, where all outflowing water can be filtered by a net of a sufficient area. However, it is difficult to keep populations of mobile animals therein for longer periods. Depending on the flow conditions, specimens of, e.g., *Gammarus* or other invertebrates accumulate either at the inflow or the outflow (Ambühl, 1959; Meijering, 1972), and mortality can be rather high (e.g., 10% in mayfly or stonefly populations over approximately 24 h; Gammeter and Frutiger, 1989). Thus, it is unsafe to assume that mobile animals can be kept in a quasi-natural state in laboratory flow-through flumes with small risks of experimental artifacts.

As a solution to this dilemma we decided to design a channel that can be operated in both ways: as a circular flume during phases of adaptation of test organisms or between repeated stormwater runoff simulations and as a flow-through flume during phases of experimental sewer overflows.

2.2 *The flume* (Fig. 1)

The reservoir had an inlet (1) and an outlet (2) pipe, allowing a continuous renewal of flume water in phases before or between experimental sewer overflows. Water reaching the reservoir through the inlet pipe was filtered and aerated ground water. Its inflow rate was used to control water temperature. A continuously operated pump [(3) type: KSB AMA DRAINER 40–7.2 SD; pump rate: 24 m^3/h] transported water from the reservoir to a T-piece (4) of a pipe. The position of two valves controlled how much of the water flowed through a by-pass (5) back to the reservoir or through another pipe (6) into the flume. The flume and its inlet and outlet tube were made from pieces of a PVC pipe (DN 200; diameter: 20 cm), glued together with silicon. A group of tubes (length: 20 to 25 cm; diameter: 3 cm) forming a honeycomb over the cross section of the flume (not visible in Fig. 1) assured that water pumped into the inlet tube was directed towards cm 0 of the open part of the channel (where the wall of the pipes had been partly removed). The flume was not in level. Thus, water pumped into it flowed "uphill" over the first section (see also Fig. 4A).

When the flume was operated in circular flow mode the slide of the outlet tube (8) was closed, and a block of foam rubber obstructed the entrance from the main channel to the outlet tube. The second slide (7) was completely up. Excess water left the flume through a net area [(9) mesh size: 0.5 mm] and flowed back to the reservoir (10). To switch from circular flow to flow-through mode the foam rubber block was removed from the outlet tube and, at the same time, the slide at the outlet tube (8) was opened, while the second slide (7) was pushed down, so that all water was directed towards the outlet tube. To switch back to circular flow mode this procedure was run reverse.

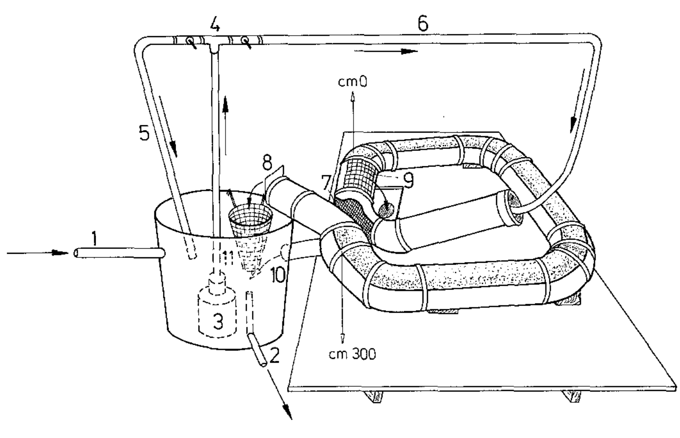

Figure 1. The experimental flume (see text in section 2.2 for detailed explanations)

Positioning of the valves at the T-piece of the pipe allowed adjustment of the flow in the flume in circular mode. In flow-through mode, flow in the flume was additionally adjusted by the position of the slide at the outlet tube (8).

This set up enabled us to switch from circular flow to flow-through mode at the start of the simulation of a sewer overflow (and, of course, to get controls). At that moment the amount of water pumped to the flume and/or the quality of the water in the reservoir (by adding chemicals, suspended solids, or sewage) were suddenly changed in order to expose the test organisms to a flush spill comparable to the situation they would experience during a sewer overflow in a stream. The number of organisms leaving the flume during these events by drift was registered by a net [(11) mesh size: 0.5 mm], which filtered the total amount of water leaving the outlet tube.

2.3 Conditions in the flume: adaptation, control and simulation of storm or combined sewer overflows at open or silted interstices of the flume bottom

The bottom of the flume was primarily covered with relatively coarse inorganic material. The lowest layer contained 20 l of 3 to 20 mm grain size. On top of this 7.5 l of 20 to 40 mm grain size were placed. All material was evenly distributed over the whole length of the circular part of the flume (except the part with the tubes forming the honeycomb). To reduce the interstitial space of this coarse bottom material to about 50%, 7 to 8 l of sand < 2 mm in grain size were added. To silt the interstitial space completely (approximately 100%), 15 to 18 l of sand < 2 mm were added to the coarse material. The sand was washed into the interstices of the coarser material before test organisms were added to the flume. Thereby different characteristics of the flume bottom could be achieved, both in the cumulative distribution of grain size

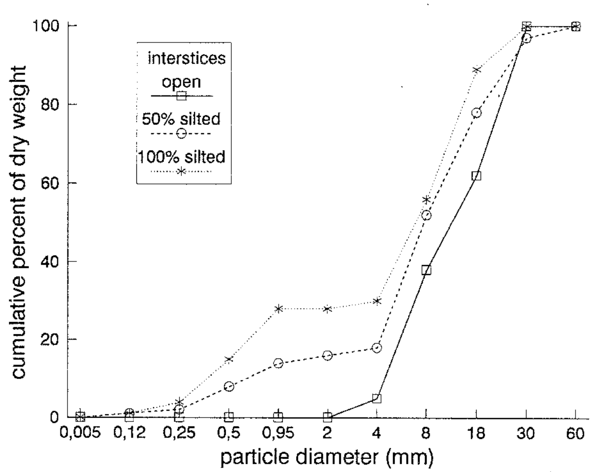

Figure 2. Potential manipulations of interstitial space: Three examples of grain size distribution of inorganic material of the flume bottom (labels are approximate percentage of siltation of the interstices)

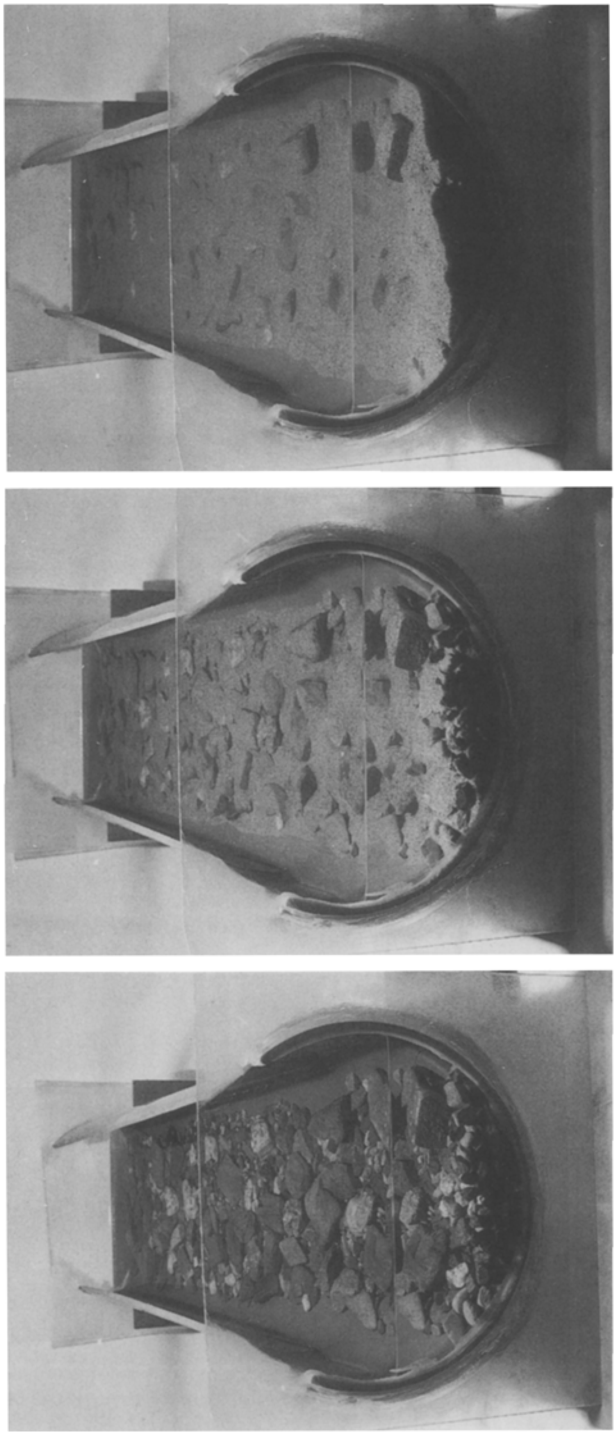

Figure 3. Potential manipulations of interstitial space: Visual appearance of the flume bottom for grain size distribution curves shown in Fig. 2 (from *left to right*: *interstices open, 50% and 100% silted*)

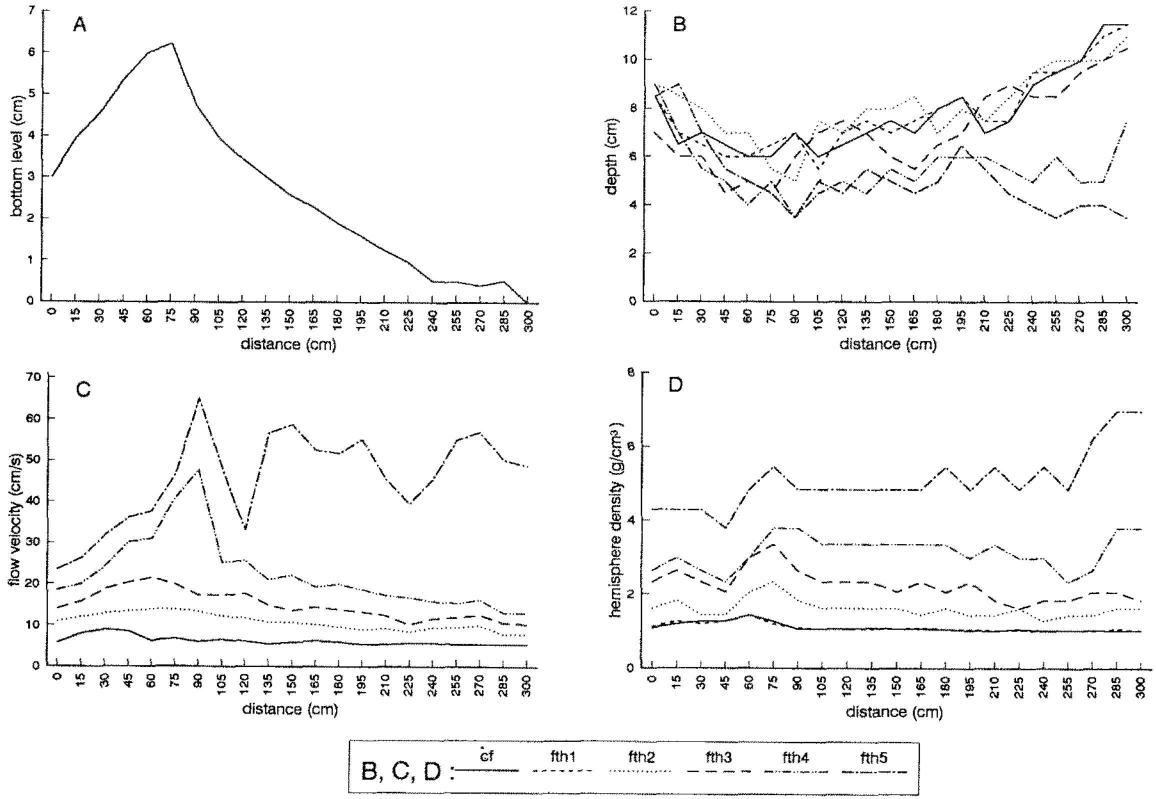

Figure 4. Physical characteristics of the flume, describing its open section from cm 0 to cm 300 (see Fig. 1). A: Bottom level, as elevation above the end of the outlet tube)see Fig. 1). B, C, D: Circular flow (cf) and five different options for flow-through (fth 1 to fth 5) showing depth (B), mean velocity (C), and the density of the heaviest FST-hemisphere just moved by the flow (D). The latter is an indicator of forces and turbulence of the flow close to the bottom and thus a relevant measure of the flow environment of benthic organisms (higher hemisphere densities indicate, for example, higher shear stress or higher boundary Reynolds Number; Statzner and Müller, 1989). We are aware that block diagrams would be the more appropriate presentation of data here and in most of the following figures. We stayed with line diagrams, because they require much less space

classes (after DIN 1983: Fig. 2) as in the visual appearance (Fig. 3). In addition to the inorganic material we distributed 1 l of coarse organic material (twigs and ash leaves collected in the same stream as the test organisms) in the flume, which served as food for *Gammarus*.

Because the flume was not in level, its bottom had a rising slope upstream of the inlet tube and a falling slope towards its outlet tube (Fig. 4 A). Figure 4 B to D show a variety of options of flow manipulations in the flume, considering i) the depth of flow (measured with a meter stick); ii) the mean velocity (measured with a Ott current meter, type C2 "10.150", wheel diameter 2.8 cm, at approximately 0.4 of total depth above the inorganic material of the flume bottom); iii) the forces or turbulence of flow close to the flume bottom (measured with FST-hemispheres, see Statzner and Müller, 1989, for calibration curves). The latter are a relevant characteristic for the flow environment of benthic organisms. It was easy to replicate these physical conditions in another flume. Figure 5 shows this for example for the flow conditions at the flume bottom as described by the hemisphere method in the open sections of both flumes.

The circular flow and flow-through 1 (fth 1) phase represented near-bottom flow conditions, at which our test organism *Gammarus pulex* was collected in the Esse stream near Kassel and kept in the laboratory prior to experiments. All flow characteristics (depth, mean velocity, and forces or turbulence close to the bottom) were the same in the adaptation phase of *Gammarus* (circular flow) as in the control phase in flow-through mode (fth 1). The maximum flow (fth 5) achieved in the experimental flumes, expressed in terms of density of FST-hemispheres moved, corresponded to the highest values reported from two mountain streams during base flow (Statzner and Müller, 1989). The flow forces at flow-through 5 were too low to cause a significant movement of the coarse inorganic bottom material in the flumes. Therefore, bedload transport was simulated by disturbing the bottom material with a rake.

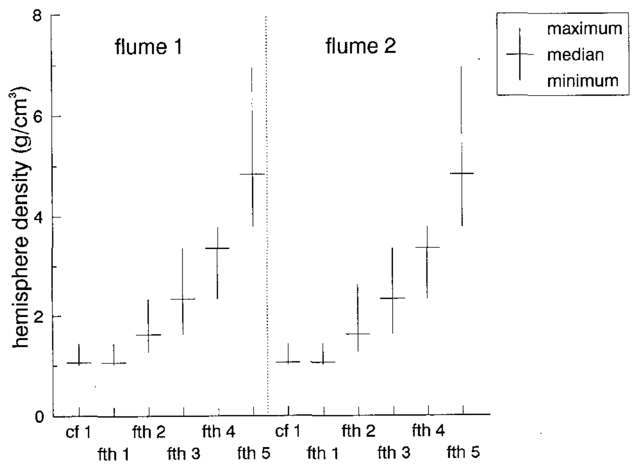

Figure 5. Replicability of physical conditions in two flumes, expressed in terms of hemisphere densities moved in the open sections of both flumes (cm 0 to cm 300, see Fig. 1). Circular flow (cf) and flow-through (fth 1 to fth 5) as in Fig. 4

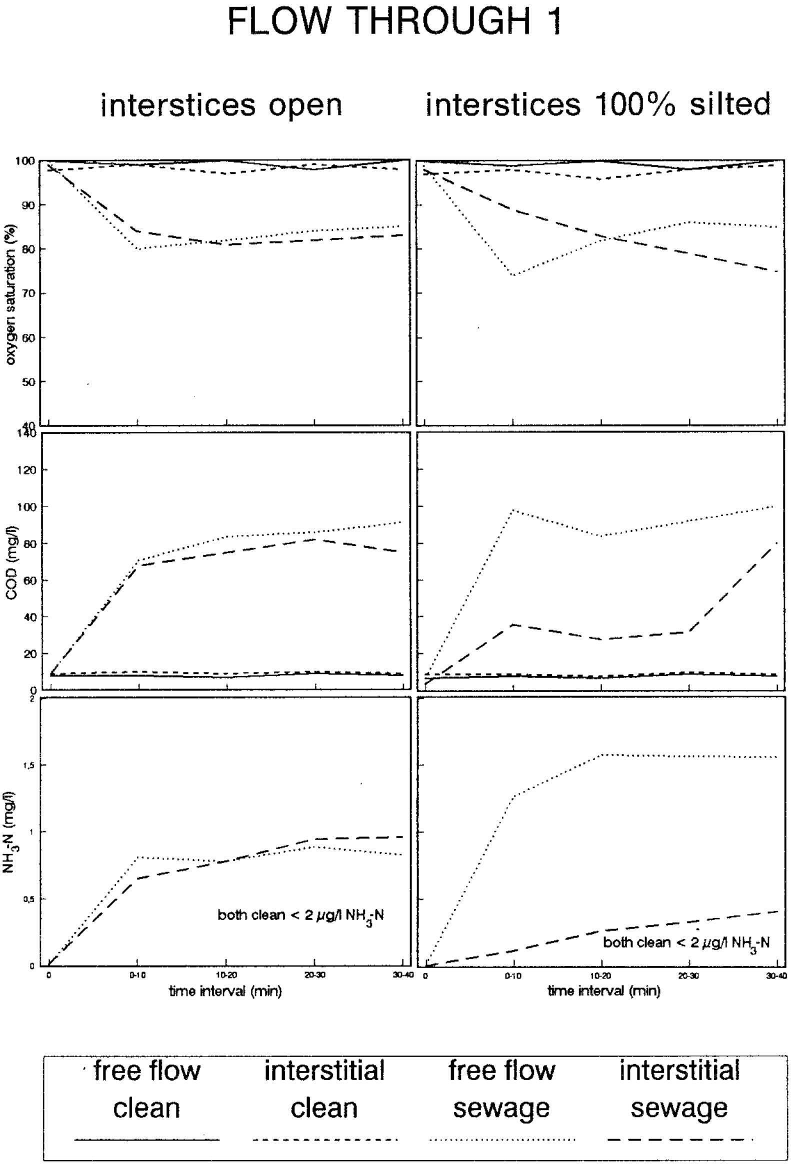

Figure 6. Oxygen saturation, COD and NH_3 in clean water and in a mixture of clean water and sewage (90%) during low flow (flow-through 1) at cm 300 (see Fig. 1). Data for continuously taken mixed water samples collected over four 10-min-periods (interstitial water was sampled at small rates (80 to 100 ml/10 min) from the lowest bottom layer)

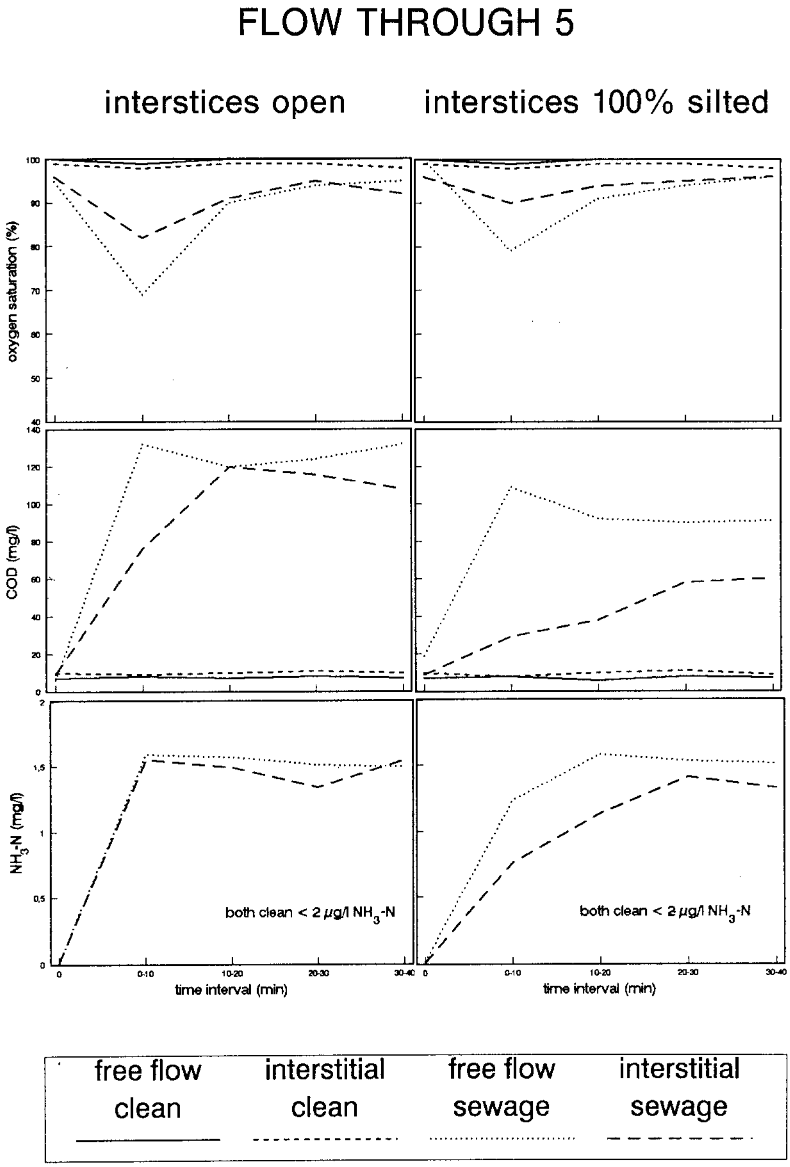

Figure 7. Oxygen saturation, COD and NH_3 in clean water and in a mixture of clean water and sewage (90%) during high flow (flow-through 5). See Fig. 6 for further details

Manipulation of water quality of the flush spill was relatively easy for NH_3 concentrations (by adding an appropriate amount of NH_4Cl) or suspended solids (by adding the appropriate amount of fine particulate matter). The reduction of oxygen concentrations to defined levels was more complicated, since the flumes had a high physical reaeration, which was mainly due to the overflow of excess water to the reservoir (see Fig. 1). By adding Na_2SO_3 catalysed by CO^{2+} (Thyssen et al., 1987) oxygen could be depleted down to zero and every level above.

A simple way to simulate CSOs was to add an appropriate volume of the effluent of the settling tank of the central sewage treatment plant in Kassel. Figure 6 and 7 give an example of how a mixture of clean water and sewage (90%) differed from clean water during the first four 10-min-periods of flush spills of 44 min duration (44 min is close to the median overflow period of a combined sewer obtained from long term observations; Krauth and Stotz, 1985). This is shown for oxygen saturation (oximeter clark type WTW EO 196–1.5), COD (photometric determination of chromium (III) concentration after 2-h-oxidation with potassium dichromate, sulphuric acid, and silver sulphate at 148 °C), and NH_3 (based on NH_4 analyses after DIN 1985; NH_3 portion as tabulated in Emerson et al., 1975, for a given temperature and pH as determined with an electrode WTW E 50). Water temperature ranged between 17 and 19 °C in these experiments.

In all cases clear differences were observed between the clean water and the simulated combined sewer overflow. If the interstices were open, we found no differences between free flowing and interstitial water, which became immediately contaminated at the beginning of the spill. If the interstices were silted, COD and NH_3 concentration of the interstitial water increased with some delay after the start of the sewage spill (compared to the free flowing water). For NH_3, this delay was less pronounced at high flow (fth 5) than at low flow (fth 1).

3. Results: Examples of ecological responses of *Gammarus pulex*

The data presented here were collected using a defined size class of *Gammarus pulex* (passing through a mesh of 2 mm, but retained through a mesh of 1 mm during 10 min of gentle wet sieving).

3.1 Adaptation phase

When adapted to the flume (circular flow mode), specimens behaved normally (ate, went into pre-copula), comparable to *Gammarus* observed in the field (Statzner and Bittner, 1983). They distributed themselves over the whole length of the flume (Fig. 8), their highest densities were observed in patches of coarse organic material (twigs and leaves).

At two occasions we tested the mortality of 500 specimens over 24 h: if the interstices were open, 0.2% of specimens were dead (June 1989, range of water temperature 14 to 17 °C); if the interstices were 100% silted, 0.4% died over this period (July 1989, range of water temperature 17 to 19 °C).

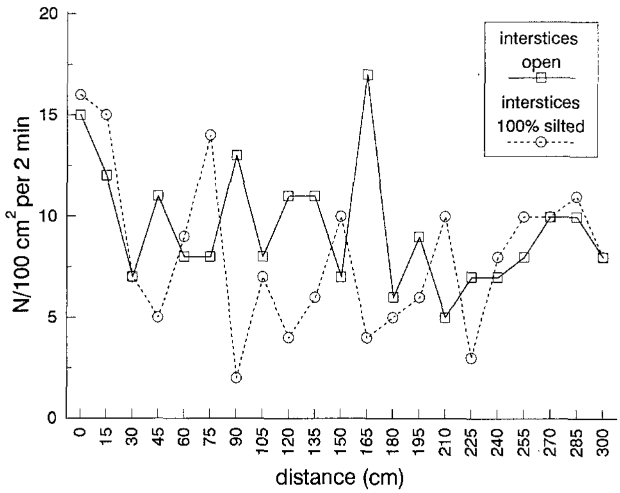

Figure 8. Density distribution of *Gammarus pulex* (counts of visible specimens) from cm 0 to cm 300 (see Fig. 1) in the flume during the adaptation phase (circular flow)

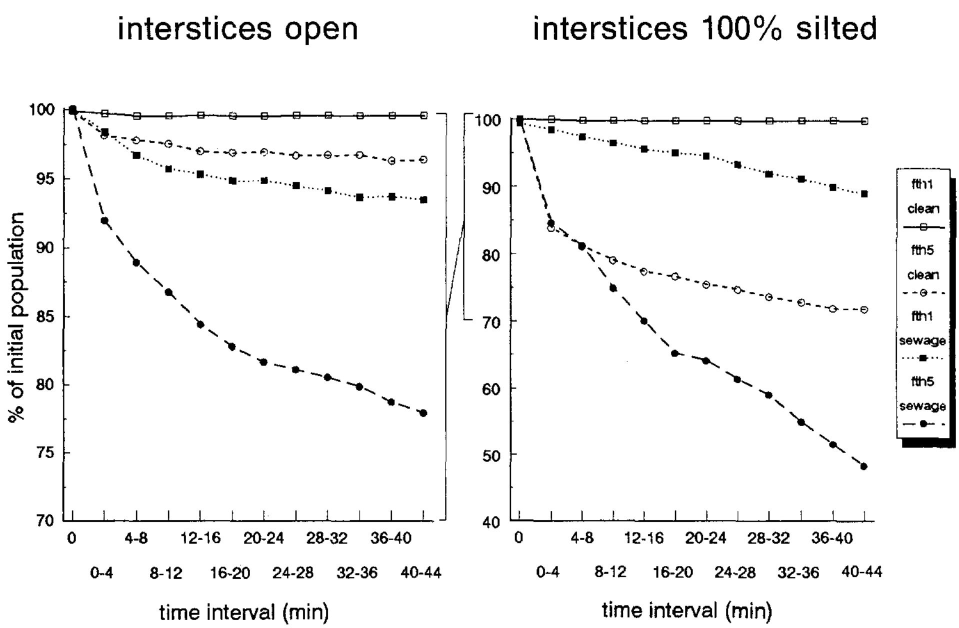

Figure 9. Population loss by drift of *Gammarus pulex* at experimental conditions as described in Figs. 6 and 7

3.2. Population loss by drift during simulated sewer overflows

In each experiment, 500 specimens were adapted to the flume for 24 h and then exposed for 44 min to conditions as described in Figs. 6 and 7.

Switching from circular flow to flow-through 1 under clean water conditions (i.e. keeping the flume environment for *Gammarus* constant) resulted in little population loss by drift (Fig. 9), which as 0.4% (interstices open) and 0.2% (interstices 100% silted).

At open interstices in the flume, population loss increased from high flow (flow-through 5) – clean water over low flow (flow-through 1) – sewage addition to high flow – sewage addition (Fig. 9). Obviously synergetic effects of high flow and sewage exposure existed since both combined led to higher population loss (22.9%) than the sum of population losses at exposure to only sewage (4.8%) or only high flow (3.6%). This was due to the behaviour of *Gammarus*. Immediately after the start of the flush of clean water specimens disappeared in the interstices of the flume bottom, using it as refugial space against exposure to high flow. Sewage exposure alone caused the animals to leave the interstices of the flume bottom, but at low flow relatively few animals were eroded and washed out from the flume. Since *Gammarus* also left the interstices, when sewage was added at high flow conditions, a large portion of the population was directly exposed to the increased current, eroded, and lost by drift.

When the interstices were 100% silted, population losses were almost higher under sewage and/or high flow exposure than at open interstices (Fig. 9). This was especially the case at clean water – high flow conditions since *Gammarus* could not escape into the interstices of the silted stream bottom (though, over the duration of the experiment, wash out of fine bottom material increased the availability of interstitial space). Consequently, the synergetic effects were less pronounced at silted interstices (population losses: only high flow: 28.2%; only sewage: 11.2%; both combined: 50%).

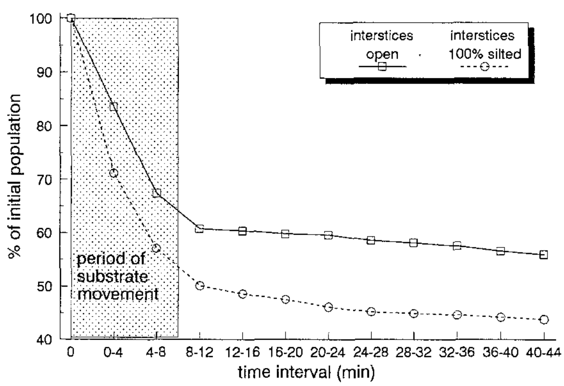

Figure 10. Population loss by drift of *Gammarus pulex* at high flow (flow-through 5), if the bottom material of the flume was moved with a rake for 10 min

If the bottom material moved for only ten minutes, high population loss was recorded under clean water – high flow conditions at both, open and silted interstices (Fig. 10).

4. Discussion

4.1 Potential of the flume design

Adjustment of the flow allowed the adaptation of the test organisms to the flume at conditions occurring in their natural habitat. Since adaptation occurred at circular flow, specimens were distributed over the whole length of the flume. The "normal" behaviour of *Gammarus* and its low mortality during the adaptation phase indicated that the test organisms were in a quasi-natural state in the flumes. This was confirmed by the low drift rates at flow conditions occurring in their natural habitat (flow-through 1, clean water), which corresponded to values known from other experiments with benthic invertebrates under almost natural conditions (Statzner et al., 1984; Statzner et al., 1987). All these facts point to low risks of artifacts, if effects of SSOs or CSOs are tested, i.e. the results should give a representative picture of the "real world". Since any critical parameter of sewer overflows can be manipulated alone or in combination with others at defined habitat conditions (e.g. with or without refugial space) the use of an equipment like ours can contribute to the solid ecological data base needed for future management decisions in this field.

4.2 Preliminary implications for future management routes

Since three independent studies demonstrated synergetic effects of potentially critical parameters of sewer overflows (Gammeter and Frutiger, 1989; Garric et al., 1990; this study), it is unwise to evaluate the impact of this kind of disturbance by "single factor approaches". Our data indicate that the factor "flow" is very essential in this context. This may explain, why we found relatively high drift responses under NH_3-N concentrations of about 1.5 mg/l at increased flow compared to other results for mayflies and stoneflies of 13 to 18.5 mg/l NH_3-N at unchanged flow (and at high oxygen saturation; Gammeter and Frutiger, 1989).

If a sewer overflow discharges relatively clean water into a stream (e.g. SSOs), availability of refugial space and bed stability potentially decide about drift responses. Hence, a possible management decision below SSOs could be to reduce flow forces per area of the stream bottom by building an appropriate channel morphology and to increase refugial space.

For CSOs a more diverse solution must be found. If their major critical parameters are identified in the synergetic context for various representative species of lotic communities, technical treatment (e.g. retention basins, filtration) should reduce the critical emission to a tolerable level. What this level is should depend again on the characteristics of the receiving stream. If the flow forces at the stream bottom distinctly increase during overflows and no refugial space is available, this level must be more restrictive than in a stream with abundant refugial space (especially if it is little affected by pollutants) and a channel morphology which keeps the flow forces per area stream bottom relatively constant during overflows.

Hence, our data strongly suggest that the characteristics of the receiving stream play an important role in the potential ecological impact of sewer overflows. Thus, the stream itself should be a major element in future management decisions. Changes of stream morphology and/or creation of refugial space plus an appropriate technical solution may be less costly and more effective than a large-scale technical project (e.g. the construction of a big retention basin, which reduces the frequency of many small sewer overflows, but hardly buffers the dozen or so large annual overflow events). To optimize costs and effects in this field an intense cooperation between both, engineers and stream ecologists is required. This is badly needed, as is indicated by the worst cases in our data set (40, 50 or 55% population loss in 44 min) and the frequency of sewer overflows (in many catchments 50 or more per year: Krauth and Stotz, 1985; Pecher, 1988). This implies that good management decisions concerning sewer system/receiving stream could considerably improve the ecological situation in running waters under the impact of urban stromwater runoff.

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REFERENCES

Ambühl, H., 1959. Die Bedeutung der Stömung als ökologischer Faktor. Schweiz. Z. Hydrol. 21:133–264.

Blohm, H.-P. and D. Borchardt, 1989. Stoßartige Belastungen in Fließgewässern – Auswirkungen auf ausgewählte Organismengruppen und deren Lebensräume. Schriftenreihe Deutsch. Verband Wasserwirtschaft Kulturbau 88:211–271.

DIN, 1983. Bestimmung der Korngrößenverteilung durch Siebung und Sedimentation (DIN 1810023). Deutsches Institut für Normung (Normenausschuß Bauwesen), Beuck Verlag, Berlin.

DIN, 1985. German standard methods of the examination of water, waste water and sludge: Determination of Ammonia-Nitrogen (DIN 38405-E5). Deutsches Institut für Normung (Gesellschaft Deutscher Chemiker und Normenausschuß Wasserwesen), VCH Verlagsgesellschaft, Weinheim.

Emerson, K., R. C. Russo, R. E. Lund and R. V. Thurston, 1975. Aqueous ammonia equilibrium calculations: effects of pH and temperature. J. Fish. Res. Board Can. 32:2379–2383.

Gammeter, S. and A. Frutiger, 1989. Wirkung kurzer Belastungsspitzen auf die Kleinlebewesen der Flußsohle. Gaz Eaux Eaux usées 69:703–713.

Garric, J., B. Migeon and E. Vindimian, 1990. Lethal effects of draining on brown trout. A predictive model based on field and laboratory studies. Water Res. 24:59–65.

Hogendoorn-Roozemond, A. S., 1985. Combined sewer overflow pollution abatement. In: J. C. Hooghart (ed.), TNO Committee Hydrol. Res. 33, TNO, The Hague: Water in urban areas, pp. 115–127.

Krauth, K. and G. Stotz, 1985. Minimierung des Schmutzstoffeintrages aus Siedlungsgebieten in Vorfluter. Deutsche Forschungsgemeinschaft, Schlußbericht Kr 624/3-2, Stuttgart.
Lamberti, G. A., L. R. Ashkenas, S. V. Gregory and A. D. Steinman, 1987. Effects of three herbivores on periphyton communities in laboratory streams. J. N. Am. Benthol. Soc. 6:92–104.
Meijering, M. P. D., 1972. Experimentelle Untersuchungen zur Drift und Aufwanderung von Gammariden in Fließgewässern. Arch. Hydrobiol. 70:133–205.
Metcalfe, J. L., 1989. Biological water quality assessment of running waters based on macroinvertebrate communities: history and present status in Europe. Environ. Pollut. 60:101–139.
Pecher, R., 1988. Sind Regenüberläufe so schlecht wie ihr Ruf? Korrespondenz Abwasser 35:660–667.
Statzner, B. and A. Bittner, 1983. Nature und causes of migrations of Gammarus fossarum Koch (Amphipoda) – a field study using a light intensifier for the detection of nocturnal activities. Crustaceana 44:271–291.
Statzner, B., C. Dejoux and J.-M. Elouard, 1984. Field experiments on the relationship between drift and benthic densities of aquatic insects in tropical streams (Ivory Coast). 1. Introduction: review of drift literature, methods, and experimental conditions. Rev. Hydrobiol. trop. 17:319–334.
Statzner, B., J.-M. Elouard and C. Dejoux, 1987. Field experiments on the relationship between drift and benthic densities of aquatic insects in tropical streams (Ivory Coast). 3. Trichoptera. Freshwater Biol. 17:391–404.
Statzner, B., J. A. Gore and V. H. Resh, 1988. Hydraulic stream ecology: observed patterns and potential applications. J. N. Am. Benthol. Soc. 7:307–360.
Statzner, B. and R. Müller, 1989. Standard hemispheres as indicators of flow characteristics in lotic benthos research. Freshwater Biol. 21:445–459.
Ten Hove, D., M. A. De Ruiter and D. Vat, 1985. The effect of storage settling tanks on pollution emission from combined sewer systems. In J. C. Hooghart (ed.), TNO Committee Hydrol. Res. 33, TNO, The Hague: Water in urban areas, pp. 129–142.
Thyssen, N., M. Erlandsen, E. Jeppesen and C. Ursin, 1987. Reaeration of oxygen in shallow, makrophyte rich streams: I. – Determination of the reaeration rate coefficient. Internat. Revue ges. Hydrobiol. 72:405–429.
Uunk, E. J. B., 1985. Urban stormwater runoff pollution. In: J. C. Hooghart (ed.), TNO Committee Hydrol. Res. 33, TNO, The Hague: Water in urban areas, pp. 77–98.
Vat, D., 1985. Pollution emission from combined sewer systems; a full scale investigation programme. In: J. C. Hooghart (ed.), TNO Committee Hydrol. Res. 33, TNO, The Hague: Water in urban areas, pp. 99–113.
Widera, J., J. Rennerich, B. Thiesmeier and S. Darschnik, 1989. Wiederbesiedlung eines rückgebauten Stadtbaches unter dem Einfluß von Regenauslässen. Verh. Ges. Ökol. Essen 1988:569–572.
Willemsen, G. D., H. F. Gast, R. O. G. Franken and J. G. M. Cuppen, 1989. Urban stormwater discharges: effects upon communities of sessile diatoms and macro-invertebrates. Proc 2nd Wageningen Conf. "Urban storm water quality and ecological effects upon receiving waters": 8 pp.

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