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Study of a Section of a Self-Purifying Stream in Specific Relation to its Water Flow Behaviour

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Abstract. The Mettma, a mountain stream in the Black Forest in Germany, had been polluted at a point source by effluent discharge from a brewery, and showed a section of self-purification along 8 km, without further interferences, following the effluent outfall. This section of stream had served as an excellent study model of the self-purification phenomenon, as much in the physico-chemistry and biology as in the hydrodynamic attributes of the water. The biological evolution along the stretch of self-purifying stream showed a succession of species typical of the food chain. To document the hydrodynamics of the stream water the Drop Picture Method, a standardized testing method developed by Theodor Schwenk, was used, based on optically revealing internal flow structures. The watersamples upstream of the pollution source showed diverse and well shaped flow structures, whereas the samples at the effluent outfall appeared with a drastic reduction and inhibition of flow shape diversity and differentiation. After that point the internal flow structures became increasingly intense and diverse the further downstream. This evolution in movement diversity proceeded in parallel to the development of the biotic community, which showed a similar increase in diversity, differentiated morphology and functional differentiation away from the pollution point to the extent that at a distance of 8 km of the point source downstream a state similar to upstream of the effluent outfall was re-established.

Keywords. Self-purification, water quality, flow structure, hydrodynamics, drop picture method.

INTRODUCTION

The evaluation of water quality in lotic systems relies in principle on the analysis of physical, chemical and biological characteristics. Our proposition here is to study a new descriptor of water quality, not just based on its constituent elements but taking into account the general and most outstanding characteristics of water as a liquid: its ability to move and flow, an essential function in its role as a life mediator. The hydrodynamics of water can be shown by using the Drop Picture Method, developed by Theodor Schwenk and published in 1967.[1] We looked at this new criterion of hydrodynamic behaviour and applied this methodology along a length of stream polluted at point source by biodegradable organic effluent, and compared the results with customary testing parameters.

I. STUDY FRAMEWORK AND SAMPLING

This study included ten measurement campaigns from 1972 to 1977 carried out on the Mettma,[2] a mountain stream in the Black Forest, in collaboration with the Institute of Limnology, University of Freiburg (Germany).[3,4,5] The Mettma is a trout-inhabited stream, oligotrophic and with a low flow rate (150 to 1500 L/s) depending on the season. The ten surveys were done in different situations, including all seasons of the year. In this article however, we used the results collected in a testing survey carried out during a period of low water (192 L/s), the 26th of July 1974. At a certain point a brewery discharged organic pollutant into the stream, in a row effluent quantity of 6000 inhabitants equivalent. Subsequently, the stream crossed a wooded mountainous zone and had no other interference apart from a dilution factor of 3 due to small tributaries. The study was terminated by the installation of a treatment plant at the brewery in 1977, and was spatially limited by the construction of a weir 9 km downstream of the effluent injection. The study included 11 sampling stations, one upstream and further stations 50, 300, 700, 1450, 1800, 3000, 3900, 5100, 7150 and 8000 m downstream of the effluent injection. Different parameters were measured: temperature, pH, surface tension, dissolved oxygen, ammonium, phosphate and nitrate concentration. In addition, the biological situation of the ecosystem at the stations and the hydrodynamical quality of the water were analysed.

II. ANALYSIS AND SEQUENCE OF PHYSICAL-CHEMICAL PARAMETERS

II.1 Temperature

The introduction of effluent increased the stream temperature from 10 to 13°C. The temperature was only slightly reduced over the total study section of 8000 m (Fig. 1)

II.2 pH

The Mettma is naturally slightly acidic, with pH values of typically between 6.1 and 7.0. Immediately downstream of the effluent injection, pH values oscillated between 6.1 and 10.4 because of the neutralization of the effluent. The pH levels stabilized after 3000 m.

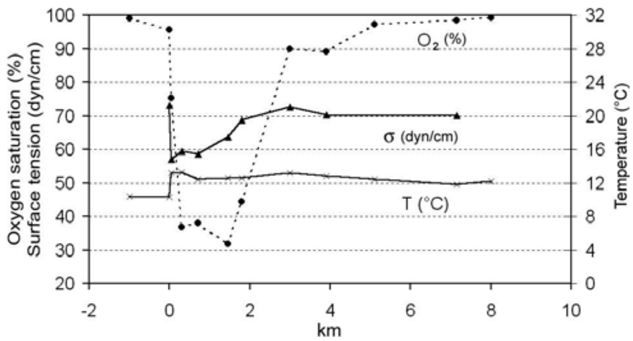

Figure 1. Evolution of temperature, dissolved oxygen and surface tension along the length of study section of the self-purifying stream (Peter 1994).

II.3 Surface Tension

The initial surface tension values corresponded to water free of surface-active substances, but decreased drastically at the effluent injection from 73 to 57 dyne/cm. The brewery effluent was chiefly composed of organic matter. 3000 m downstream, surface tension values stabilized at levels somewhat lower than the initial values (Fig. 1).

II.4 Dissolved Oxygen

Close to total saturation upstream of the outfall, the dissolved oxygen values dropped dramatically to 35% at the injection due to the high oxygen demand of bacterial activity and oxidation of organic matter. Oxygen levels progressively returned to their initial values 7150 m downstream (Fig. 1).

II.5 Ammonium and Phosphates

Organic nitrogen and phosphorus were introduced by the effluent and microbially mineralised to ammonium and phosphates. Phosphates reached maximum concentrations 50 m and ammonium 300 m downstream as products of the breakdown of the introduced organic matter. These pollutants were totally metabolised at the downstream checkpoint of 7150 m (Fig. 2).

II.6 Nitrate

A product of the oxidation of ammonium, nitrate was initially only present at low levels. Its concentration increased progressively along the length of the study section, levels did not totally stabilize at 8000 m downstream of the effluent injection (Fig. 2).

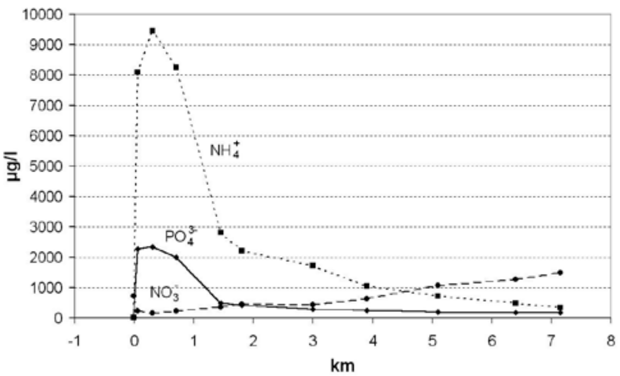

Figure 2. Ammonium (NH_4^+), nitrate (NO_3^-) and phosphate (PO_4^{3-}) concentration in µg/l, as well as the oxygen saturation in % (Peter 1994).

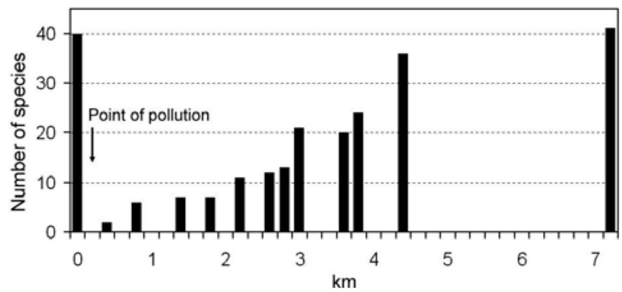

Figure 3. Number of species (taxa) of animals on the stone substrate during the course of the self-purifying section (after Schreiber 1975[6]).

III. BIOLOGICAL ANALYSIS

III.1 Evolution of the Biotic Community

Initially, the Mettma was an oligosaprobic balanced stream ecosystem typical to the trout zone. It was inhabited by a wide variety of animal and plant species which constituted its biotic community. 40 different species of benthic fauna were indicative of this diversity (Fig. 3).

The brewery effluent added an organic load equivalent to the raw effluents of 6000 inhabitants. This profoundly modified the ecological equilibrium of the ecosystem (Fig. 4). The system became polysaprobic. Life conditions favoured the development of filamentous bacteria (*Sphaerotilus natans*) and ciliates and excluded other species. In this first polysaprobic zone which stretched for approximately 300 m, the number of benthic species plummeted to 2. The filamentous bacteria eventually detached themselves and were transported several hundred meters further, where they were deposited and became important nutrients for colonies of sludge-worms (*Tubifex tubifex*) and chironomid larvae (*Prodiamesa olivacea*). This degradation zone where the breakdown of organic matter dominated, ended with the appearance of blackfly larvae (*Odagmia ornata*) and monocellular algae 2000 m downstream of the injection point. This marked the beginning of the primary production zone, with a succession of plant species from algae and mosses to higher vegetation. Species of herbivores, such as freshwater limpets (*Ancylus fluviatilis*) and mayfly larvae (*Baethis rhodani*) as well as carnivores, such as stream amphipods (*Gammarus fossarum*) and

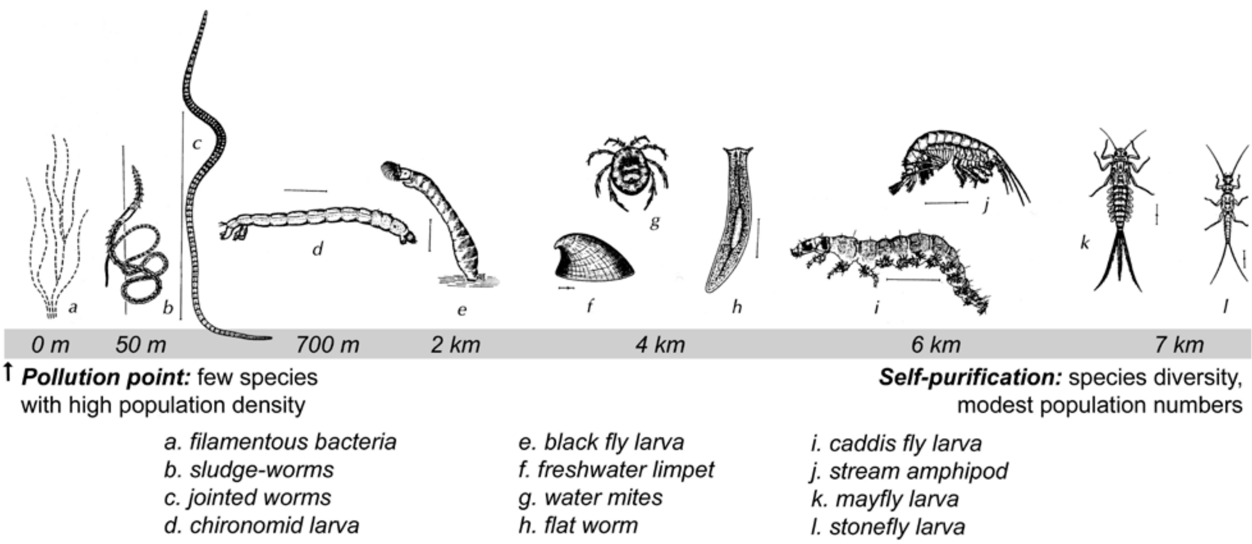

Figure 4. Typical representatives of the benthic fauna the length of the self-purifying stream section (according to Peter 1994).

predatory larvae of various insect species, reinhabited the biotope. The trout-zone had fully regenerated after 7000 to 8000 m, the number of fauna species in the benthic zone reattaining its initial value.

III.2 Polarities

If we take into consideration the evolution, distribution, variety, morphology, mode of nutrition and locomotion of the benthic fauna, the following can be observed:

- At the beginning of the self-purifying study section, species diversity was very reduced while population density was high. The organisms generally had a homogenously segmented morphology with radial symmetry. Sensorial organs were very primitive. Most organisms were sedentary and saprophage. Their rhythm of activity depended only on the supply of nutrients, their life activity being orientated towards metabolism.
- At the end of the self-purifying study section - as before the effluent outfall - there was a greater species diversity while the population numbers remained modest. The morphology of the organisms was more complex with heterogeneous segmentation, axial symmetry and a greater body surface area. Sensorial organs were located at the head, organisms were more mobile and were herbivores or carnivores. They followed day-and-night and seasonal rhythms. Their activities were orientated towards sensorial functions and locomotion.

IV. HYDRODYNAMIC ANALYSIS

IV.1 The Drop Picture Method

The Drop Picture Method, developed by Theodor Schwenk, allows the study of water's aptitude for movement, its hydrodynamics. The method is carried out by the systematic and controlled agitation of a water sample through the impact of drops of distilled water released at 5 second intervals. Each impact on the very shallow water sample creates internal movement and flow forms. The addition of a tiny amount of glycerine to the water samples facilitates the photographic optical visualization of the flow movements via a Schlieren optic system. Successive drops renew the created flow movements, so that a whole series of 30 drop-generated images was documented for each sample (Fig. 5).

The Drop Picture Method was examined in the 2000s to optimise and standardize the testing methodology.[7,8] The results are usually interpreted qualitatively, but may additionally be analysed based on quantitative analysis of for example the degree of development of vortex forms. The Drop Picture Method indicates the given movement capacity of a water sample based on the level of complexity and differentiation of its internal flow forms. It is a morphological method, complementary to physical-chemical analysis, revealing more information about the hydrodynamic qualities of a water sample than its chemical composition. It is a system to evaluate water quality based on positive, life-giving criteria, rather than on exclusion of negative criteria.

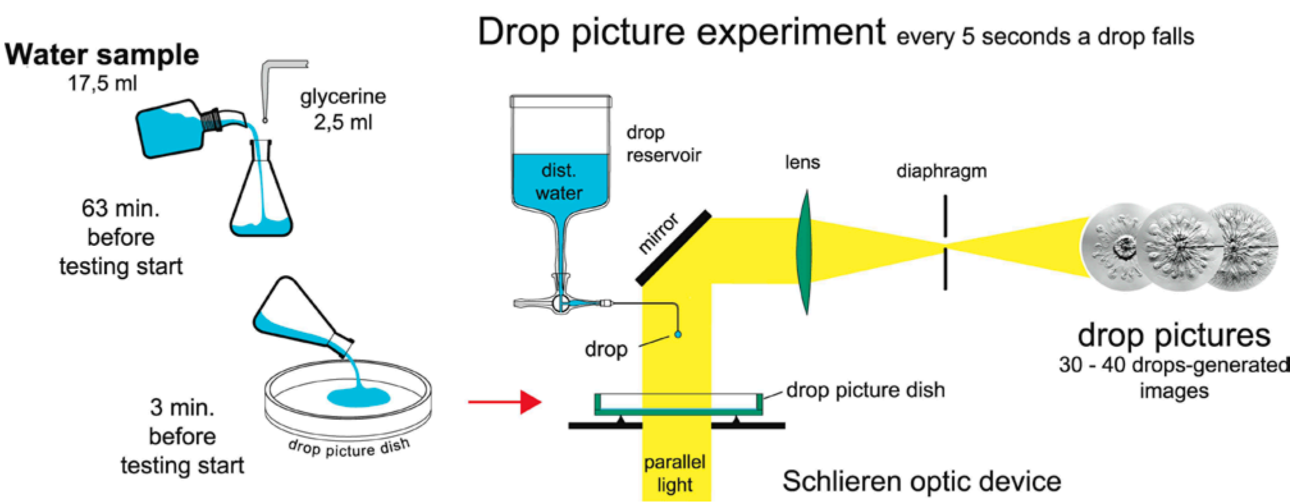

Figure 5. Drop Picture Method procedure and chlieren optic device.

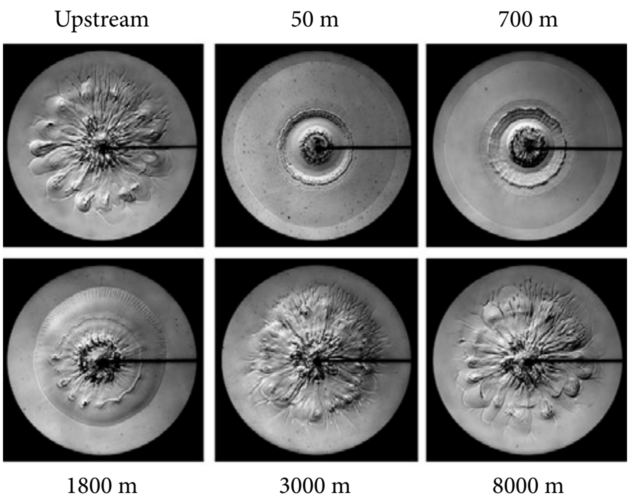

Figure 6. Drop-generated images after the 20th drop the length of self-purification.

IV.2 Application to the Section of Self-Purifying Stream

The testing points were identical to those of the previous studies. The water samples were analysed on the same day as they were collected. 30 images were produced for each water sample. Here the 20th is selected to facilitate comparison between samples (Fig. 6). We will now discuss the most distinctive phases along the stream self-purifying section.Upstream of the effluent outfall, drop-generated image revealed a garlanded composition of vortices where more extended vortices alternate with more stocky ones. Leafy vortices could be observed, as well as radial dendritic structures. The successive 30 images during the analyse were relatively balanced, showing differentiated and varied structures, which were regenerated with each successive drop.

Downstream of the effluent injection the drop-generated images were significantly different. They were simply and solely composed of a disc-shape structure centred on the central point of impact. The forms were rudimentary, undifferentiated and monotonous.

- 1800 m downstream, the disc-shape structure shrunk while in the centre the beginnings of differentiation - the buds of heads of vortices - could be identified.
- About 3000 m downstream, the beginnings of leafy vortices and dendritic structures could be observed again. The closed disc-shape form had disappeared.

By the end of the studied stretch of stream, the internal flows of the drop-generated image had returned to be the varied, complex and differentiated and polymorphic as in the sample upstream of the effluent injection.

V. COMPARISON OF THE DIFFERENT DESCRIPTORS

V.1 Physical-Chemical Parameters and Hydrodynamic Evaluation

V.1.1 Point of Inflexion

The evaluation of the hydrodynamics of a given water sample is not based on any one drop-generated image but rather on the evolution of the ensemble of images. At some point each of the samples reaches a state where after a certain number of drops the garlanded structure shrinks, disappears and is replaced by a more rigid disc-shaped structure. This is what we call the "point of inflexion", which occurs sooner or later in the tests, depending on the hydrodynamic qualities of the sample in question. This is a useful parameter. The drop number at which it occurs can be used to compare water samples taken along the length of study stream in question. When a disc-shaped structure appears in the first drop-generated image, the point of inflexion has already taken place before the start of the testing.

V.1.2 Comparison of Results

The graphical comparison of the levels of oxygen saturation, the point of inflexion and surface tension demonstrated a relationship between levels of oxygen and the point of inflexion. This relationship was however not causal but demonstrated that there is a correlation between these two factors and water quality. In most of the measurement surveys, the evolution of physical and chemical parameters stabilised well upstream compared to where the point of inflexion had stabilised (Fig. 7). This in contrast only returned to its pre-effluent levels at the very end of the length of studied stream, parallel to the reestablishment of the biotic community to its initial

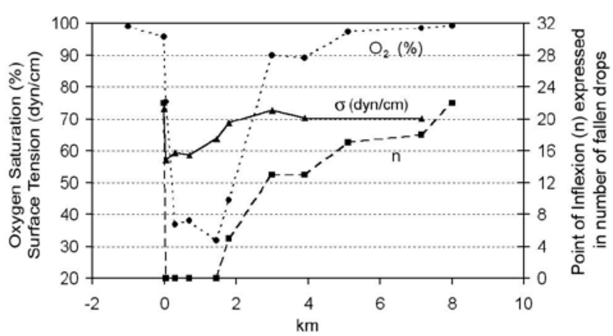

Figure 7. Evolution of oxygen saturation, surface tension and point of inflexion (Peter 1994).

levels. This point of inflexion thus appeared to be a more sensitive descriptor, indicative of the overall state of the stream ecosystem.

V.2 The Biotic Gradient and Stream Hydrodynamics

It appeared that along the stream in question:

- Where the drop-generated image, in reference to previous images, had a closed, disc- and monotonous shape
- Where the drop-generated image showed a lack of mobility and a predetermined evolution,
- There was the least species diversity, with the presence of sedentary, simple-structured organisms, whose activities were confined to their metabolic activity, that is to say after the effluent outfall.

In addition:

- Where the drop-generated images revealed a maximum of polymorphic, diverse flow shapes, with the greatest complexity of movement in the water, where the images had a differentiated structure without being predetermined in their evolution
- This is where biotic populations were varied and balanced, individual organisms having a more differentiated anatomy, complex nutrition and locomotion as well as being more sensitive to their environment due to more advanced sensorial organs, that is to say upstream of the effluent outfall and at the end of the stretch of self-purification.

CONCLUSIONS

This comparative study of the physical-chemical, biological, and hydrodynamic characteristics of a self-purifying section of the Mettma proved that there are parallels between the degree of diversity in the biotic community and the degree of movement diversity in water samples from the same testing stations. In the degradation zone, where metabolism processes determined the physiology and activity of the animal population, water samples showed monotonous and weakly defined flow shapes. In contrast, in the primary production zone where, thanks to primary production by vegetation, anabolic processes dominated, the water samples showed diverse and differentiated water flow shapes. Thus, very different phenomena could carry the same signature of a shared intrinsic quality. Physical-chemical parameters are descriptors of a specific moment of the stream. The biological indicators reveal a more integrated long-term picture of the water, whereas the hydrodynamic analysis revealed the momentary but holistic state of the water.

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