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APPLICATION OF AUTOMATED MEASUREMENT STATIONS FOR CONTINUOUS WATER QUALITY MONITORING OF THE DENDER RIVER IN FLANDERS, BELGIUM

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Abstract. During the summer of 1999, two automated water quality measurement stations were installed along the Dender river in Belgium. The variables dissolved oxygen, temperature, conductivity, pH, rain-intensity, flow and solar radiation were measured continuously. In this paper these on-line measurement series are presented and interpreted using also additional measurements and ecological expert-knowledge. The purpose was to demonstrate the variability in time and space of the aquatic processes and the consequences of conducting and interpreting discrete measurements for river quality assessment and management. The large fluctuations of the data illustrated the importance of continuous measurements for the complete description and modelling of the biological processes in the river.

Keywords: automated measurement stations, monitoring instruments, real time, river water quality, sensor

1. Introduction

Today river quality assessment is mainly based on discrete monitoring campaigns, with time intervals of several hours, weeks, months or even years. In Flanders, Belgium, the Flemish Environment Agency (VMM) measures the physical–chemical variables of the surface water quality at about 3000 locations on a monthly basis. On all sites, a basic set of variables is monitored: water temperature, pH, conductivity, dissolved oxygen, chemical oxygen demand (COD), ammonium, nitrite, nitrate, ortho-phosphate, total phosphorus and chlorides. On a selected set of sites, biochemical oxygen demand (BOD), Kjeldahl nitrogen, sulphates, total hardness, suspended solids and heavy metals (As, Cd, Cu, Hg, Pb, Ni, Zn) are also determined (Goethals and De Pauw, 2001).

For the study of highly dynamical processes such sampling schemes are often insufficient to make a reliable assessment of the river status. Examples of problematic processes are the diurnal oxygen fluctuations induced by algal photosynthesis and respiration or the short peak emissions of BOD, COD, . . . by combined sewer overflows during intensive rainfall events. Such critical situations are often not monitored by the traditional sampling schemes, while they may be detrimental to the ecosystem.

Recently the European Union has approved the Water Framework Directive 2000/60/EC (WFD). This directive states that a good ecological status of all water bodies should be achieved in all member states by the end of 2015. To that end, the WFD provides several guidelines for monitoring water bodies, leaving the practical implementation to the local governments. Each member state has to develop a consistent monitoring strategy and assessment methodology. To make sure that the new water policy will succeed, a profound analysis of the actual and future state of the water is necessary. In this context, the research presented here, the collection and interpretation of continuous measurements could be very useful to gain the necessary insight for setting up a sound monitoring network.

In this paper, results of a water quality measurement campaign on the river Dender are presented. Measurement series of pH, electrical conductivity and dissolved oxygen illustrate the variability of the measurements in time and space in a typical river in Flanders, intensively disturbed by physical–chemical and structural–morphological impacts.

2. Materials and Methods

2.1. Site description

The catchment of the river Dender has a total area of 1384 $km^2$and has an average discharge of 10 m^3/s at its mouth. As about 90% of the flow results from storm runoff and the sources make very little contribution, the flow of the river is very irregular with high peak discharges during intensive rain events and very low flows during dry periods. To allow for navigation and to temper the high flows, the Dender is canalized and regulated by 14 sluices between. Due to this, during dry periods, the Dender acts as a series of reservoirs with a typical depth of 3–5 m, a width of 12–50 m and a length of 2–8 km. During periods of high flows, all locks are opened and the river regains a more natural stream profile.

The measurement stations used for this study were located on the main river, just upstream the sluices at Geraardsbergen and Denderleeuw (Figure 1). Additional biological measurements were made during the period of the on-line monitoring (D'heygere *et al.*, 2002).

2.2. Automated measurement stations

A pump placed in the river continuously supplies water to the station. The pump was situated about 0.8 m below water level. At the entrance of the pipe system

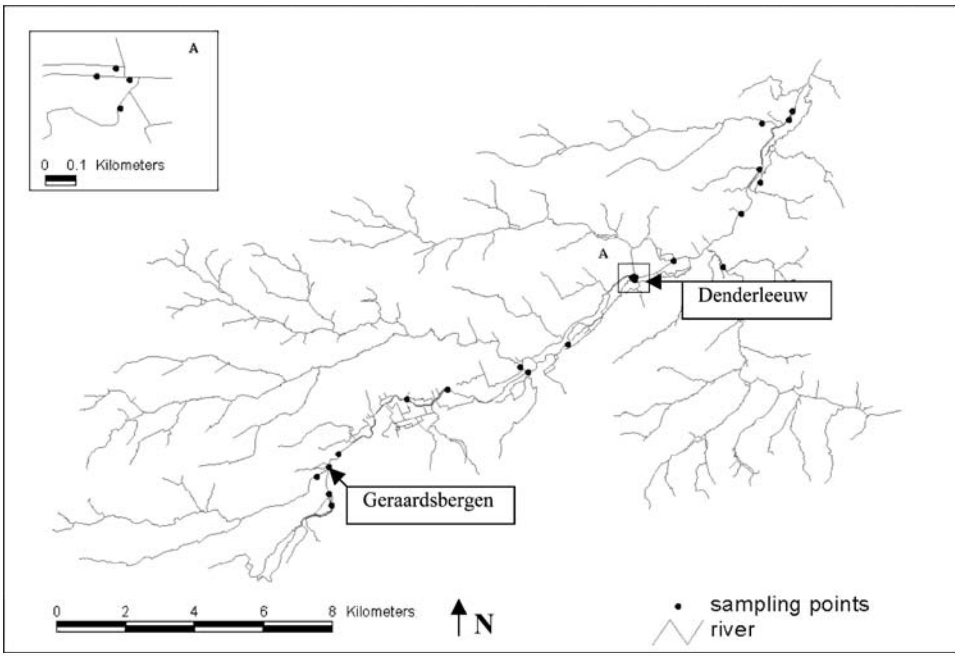


Figure 1. The Dender river basin in Flanders, and the sites where the two automated measurement stations were used to deliver on-line water quality measurements. The other dots represent the sites where additional biological measurements were conducted (D'heygere *et al*., 2002).

inside the cabin, the turbidity is measured. After filtration the water flows along sensors that measure pH, dissolved oxygen, redox potential, temperature and conductivity (van Griensven *et al*., 2000). Water level, short wave radiation and rainfall are also measured. All measurements are collected in a central data logger with a storage capacity of several days or sent directly to a central computer via wireless telephone using SMS-messages (Short Messages Service). Besides on-line measurements river water can also be taken by means of a refrigerated sampler with 24 bottles to allow for additional laboratory analyses. The sampling frequency during this campaign was set to 6 measurements per hour. In Figure 2 a schematic representation of the station is given.

The data acquisition was validated and optimized by Goethals *et al*. (in preparation), making use of control charts and statistical process control techniques. In this manner, the data quality was controlled and assured.

2.3. Discrete water quality measurements

To gain additional information about the variation of the variables related to the depth or related to the place of measurement between two sluices, samples were taken or additional *in situ* measurements were conducted with portable electrodes.

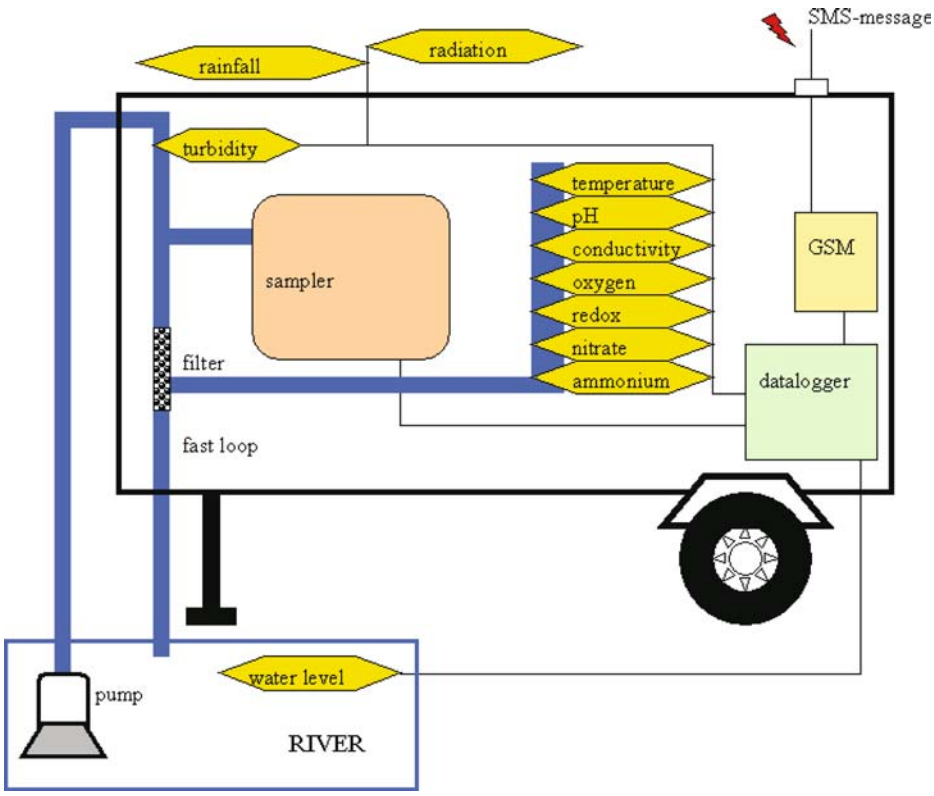


Figure 2. Scheme of the automated measurement station applied for this study.

These additional *in situ* measurements were dissolved oxygen (WTW Oxi 330), electrical conductivity (WTW LF90) and pH (Consort P114). Nitrate, ammonium and COD were measured with a spectrophotometer (Merck SQ 118).

The biological assessment of the water quality was based on the Belgian Biotic Index (BBI) (De Pauw and Vanhooren, 1983). These biological data and their interpretation are presented in D'heygere *et al*. (2002).

3. Results

Several physical, chemical and biological processes can interfere in a river system and result in a dynamical spatial–temporal gradient of oxygen and pH. Oxygen can be produced by photosynthesis of algae and higher plants when enough radiation penetrates through the water column. It can as well be consumed by respiration of animals and bacteria and also by plants and algae under dark conditions. The microbial degradation of organic components in the water column and in the sediments on the river bottom consumes oxygen and may result in anaerobic conditions. The aeration near waterfalls at weirs and sluices can be an important source of oxygen. Additional pollution sources often increase the dynamics and complexity of these processes. This is illustrated with on-line measurement series of dissolved oxygen, pH and conductivity on the river Dender.

3.1. Dissolved oxygen

In the presence of algae and higher plants, the dissolved oxygen concentration of the water develops a diurnal profile, especially during sunny periods in summer. A typical diurnal profile can be seen on the Dender on August 7 and 8 (Figure 3). During daytime, the oxygen concentration increases due to photosynthesis of the very abundant algae. In the evening, the process of photosynthesis stops and the respiration of algae starts. The dissolved oxygen concentration diminishes, depending on the abundance and activity of the algae. During the period August 7–8, the average daily air temperature was between 24 and 26 °C and the water temperature remained fairly constant: the differences between day and night were only 1° Celsius. Increased cloudiness and some rainfall explain the evolution during the following days (August 9–10). The amplitude of the fluctuations decreased, due to the combined impact of decreased photosynthesis during daytime (clouds) and an inhibited respiration activity at night as well as an increased dilution as a result from the increased flow due to rainfall.

During the measurement campaign, differences between measurements done at the water surface and measurements near the river sediment were noticed. By means of off-line measurements done upstream of the lock of Geraardsbergen, severe gradients in the oxygen profile could be registered experimentally making use of field electrodes. In Figures 4a, b and c, the results are given for measurements of dissolved oxygen, temperature and pH conducted on the 2nd of September. It could be observed that, at the bottom, the water layer was quasi without oxygen while high oxygen concentrations were found in the upper 0.5 to 1 m. The latter

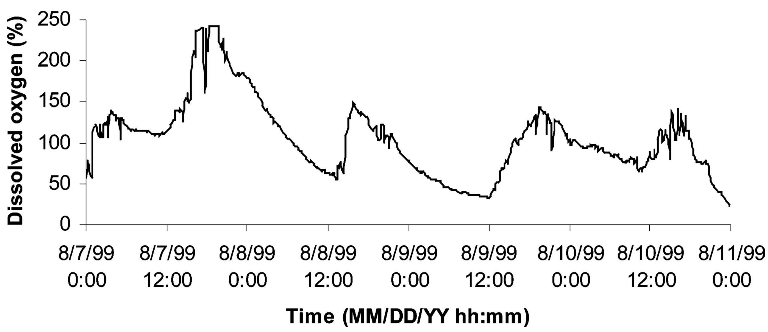
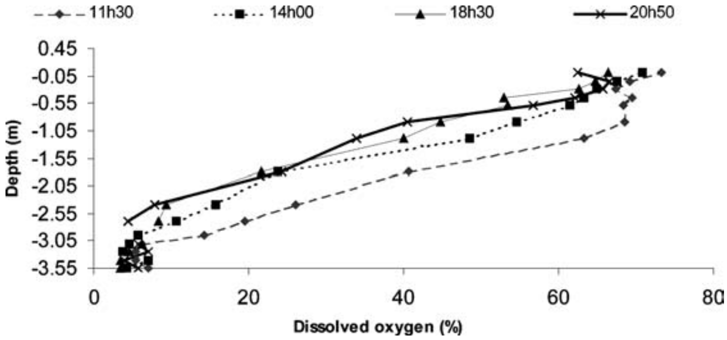
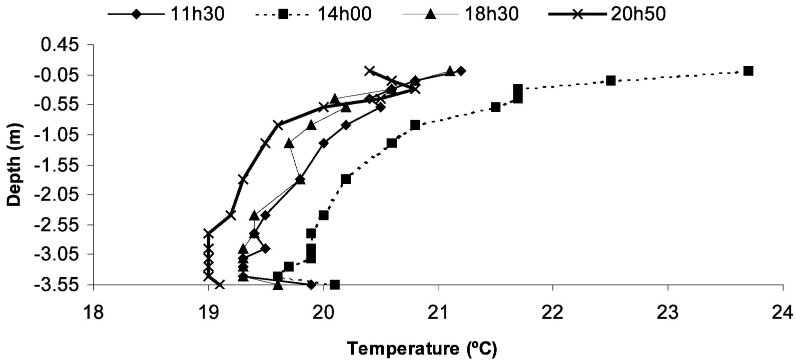


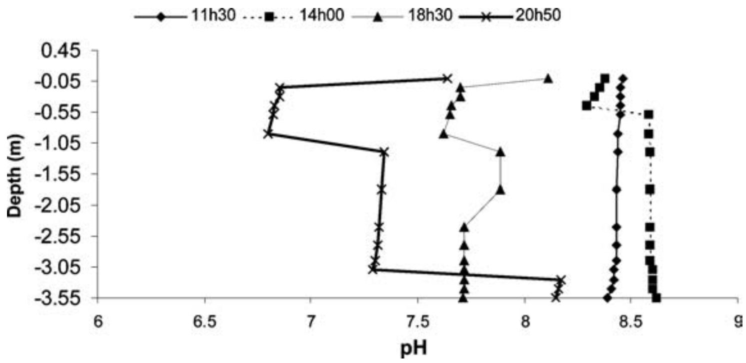
Figure 3. Diurnal variation of the dissolved oxygen in the Dender river at Geraardsbergen during the period 07/08/99–10/08/99 (DD = day, MM = month, YY = year, hh = hour, mm = minute).



(a)



(b)



(c)

Figure 4. (a) Depth profile for dissolved oxygen in the Dender river at Geraardsbergen on 02/09/99. (b) Depth profile for temperature in the Dender river at Geraardsbergen on 02/09/99. (c) Depth profile for pH in the Dender river at Geraardsbergen on 02/09/99.

layer corresponds to the layer in which light intrusion and thus photosynthesis could take place.

The gradients in the dissolved oxygen can therefore be explained by oxygen consumption during breakdown of organic material over the entire water column,

TABLE I
Ammonia and nitrate profiles in the river Dender on the 2nd September

	NH_4^+-N (mg/l)				NO_3^--N (mg/l)			
Depth (m)	11h30	14h00	18h30	20h50	11h30	14h00	18h30	20h50
−60	0.942	0.981	0.979	0.971	1.78	1.76	1.77	1.78
−135	0.951	1.06	1.24	1.17	1.72	1.81	1.65	1.64
−370	1.82	2.13	2.22	1.93	1.23	0.889	0.949	0.878

diffusion of oxygen from the upper layers to the lower layers and by oxygen consumption by processes that take place on the bottom of the river. Figure 4b makes clear that the upper layer of the water is cooling down in the evening. From Figure 4c, a clear downwards shift in the pH can be observed during daytime, starting from the top-layer around noon and resulting in a near complete shift over the whole water column near the evening. From this, one can derive that the algae activity can affect the pH significantly, probably by the consumption of carbonates during photosynthetic activity.

Measurements of the vertical gradients of ammonia and nitrate (Table I) are in line with the oxygen concentrations. Due to the poor oxygen conditions and the hampered nitrification (and possibly denitrification) near the bottom, higher ammonia and lower nitrate concentrations were determined in the vicinity of the river sediments.

During the period of 17 till 20 September (Figure 5), diurnal cycles of dissolved oxygen could be observed as a result of algae blooms. At the downstream measuring point – Denderleeuw – the oxygen concentrations were higher despite the higher ammonium concentration and chemical oxygen demand (COD) in the water and

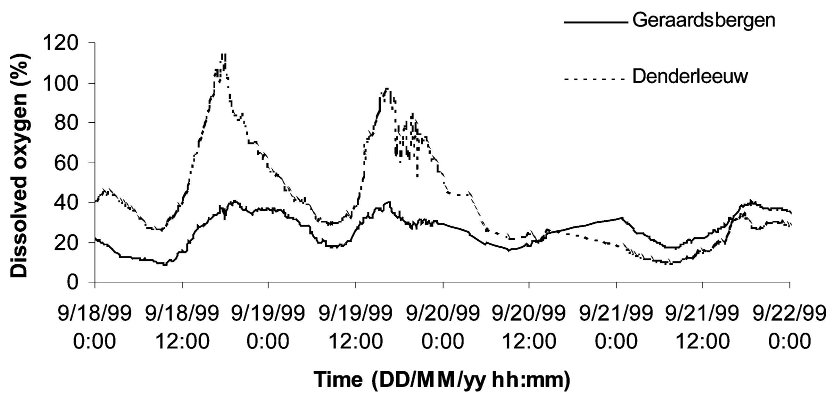


Figure 5. Diurnal variation of the dissolved oxygen in the Dender river at Geraardsbergen and Denderleeuw during the period 17/09/99-22/09/99 (DD = day, MM = month, YY = year, hh = hour, mm = minute).

TABLE II
Concentrations of ammonia, nitrate, total nitrogen and COD (in mg/l) in samples taken in the river Dender at Geraardsbergen and Denderleeuw on the 17th September

	NH_4^+-N	NO_3^--N	Total-N	COD_{fil}	COD_{tot}
Geraardsbergen	1.93	2.1	6.43	24.4	23.1
Denderleeuw	3.07	1.23	8.06	27.7	28.4

a lower nitrate concentration (Table II). Because of the more reducing conditions at Denderleeuw, a lower dissolved oxygen concentration was expected. The algae blooms probably caused the greater fluctuations in the oxygen content in the Dender river at Denderleeuw. However, more algae at Denderleeuw than at Geraardsbergen cannot be the reason for the higher dissolved oxygen concentration at Denderleeuw. In that case the dissolved oxygen concentration would be less during the night. Therefore, additional research will be necessary to find the reason for the lower oxygen concentration at Geraardsbergen.

From 20th September (after a dry period of 3 days) on it started raining until 30th September. This led to a profound change in the system (Figure 6). In contrast with the previous period, there was less dissolved oxygen in Denderleeuw than at Geraardsbergen and the difference between the two stations became larger. The global level of the dissolved oxygen concentration was clearly lower. Sewer overflows with delayed oxygen consumption, less photosynthesis due to flushing of algae and less sunlight are the most plausible explanations for these observations.

The problem of the spatial variability is also illustrated (Figure 7) with the aid of measurements between the lock of Geraardsbergen and the one in Idegem that is situated 4500-m downstream. Just upstream the locks the dissolved oxygen amount

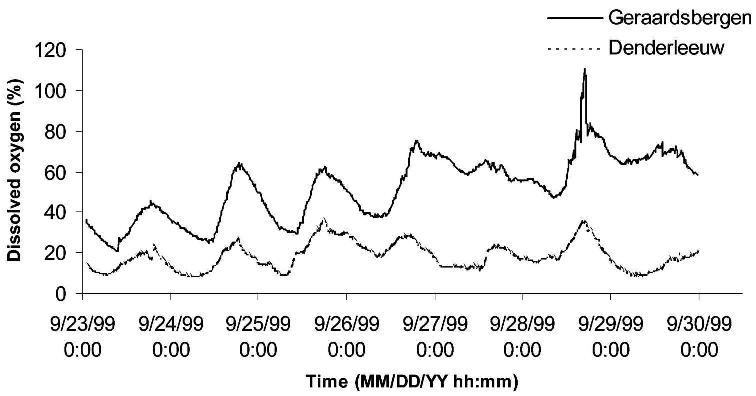


Figure 6. Diurnal variation of the dissolved oxygen in the Dender river at Geraardsbergen and Denderleeuw during the period 23/09/99–30/09/99 (DD = day, MM = month, YY = year, hh = hour, mm = minute).

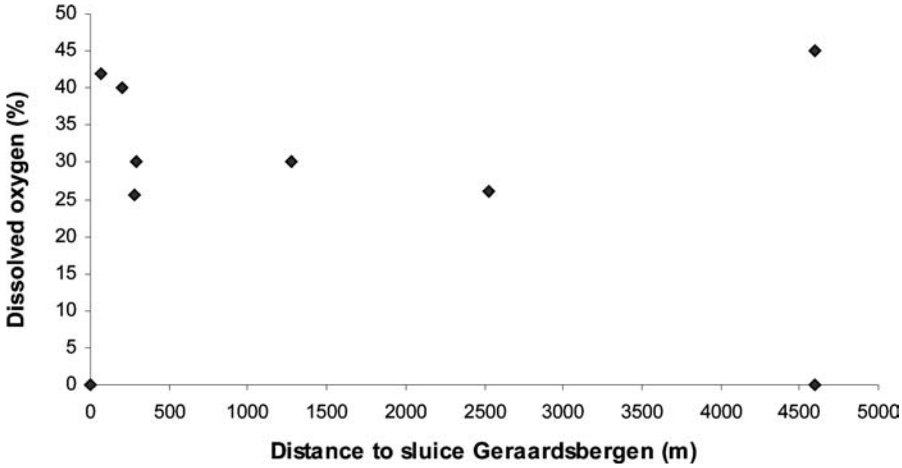


Figure 7. Dissolved oxygen concentration between the sluice of Geraardsbergen and Idegem on 17/09/99.

is zero (just under the water surface). The re-aeration at the weir increases the dissolved oxygen amount to 40–50% saturation. The amount then decreased relatively quickly to 30% and stabilises at that level over a long distance. Just upstream the weir at Idegem, the saturation degree is again zero. The latter sudden drop of the dissolved oxygen concentration is probably the result of the sedimentation of oxygen-demanding substances to the river bottom, upstream of the weir.

3.2. Conductivity

The conductivity of the water of the Dender is rather high with values of 950 up to 1400 μS/cm (Figure 8) (the water quality standard for conductivity of surface waters in Flanders is 1000 μS/cm). The decrease in the conductivity on August 6 is due to the dilution of the amount of degradable organic substances after a rain event.

3.3. pH

When the amount of dissolved oxygen in the water increases due to photosynthesis, CO_2 is taken up and the pH increases. As a consequence, large fluctuations in dissolved CO_2 usually occur during algae blooms.

Although algae blooms take place during almost the entire observation period, the pH on the river Dender varied only between 6.5 and 8.5. Consequently the water in the Dender must have a high buffer capacity. This was indeed confirmed by samples indicating a buffer capacity of 2.8 meq/l.pH for a pH of 6.5 and 0.5 meq/l.pH for a pH of 8. The buffer capacity is only 0.2 meq/l.pH for pure water in which

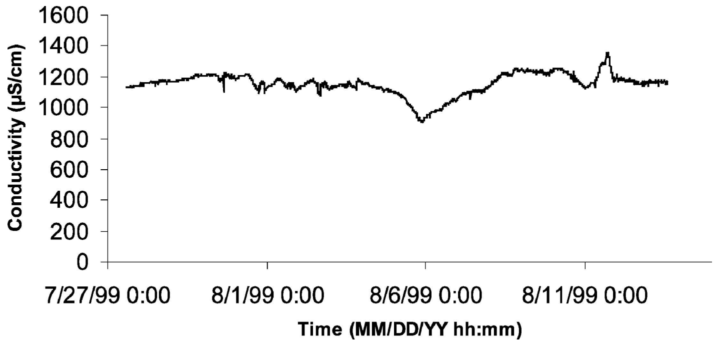


Figure 8. The conductivity of the river Dender in Geraardsbergen during the period 27/07/99–13/08/99 (DD = day, MM = month, YY = year, hh = hour, mm = minute).

the amount of CO_2 in the water is in equilibrium with the amount of CO_2 in the air (Stumm and Morgan, 1996).

The high buffer capacity of the Dender water has two important consequences. Firstly, the fauna and flora will not suffer of an additional stress by high pH fluctuations or extreme pH values. Second, the pH cannot be used as an indicator for the water quality because relatively large amounts of acids or alkaline substances can be discharged without alteration of the pH. While the latter substances will therefore not cause damage due to the pH changes in the water, the toxicity of the products might however damage the aquatic ecosystem.

4. Discussion

The use of on-line measurement instrumentation is becoming more and more popular. In most cases however, the use of on-line instrumentation for water quality monitoring is applied in the field of wastewater treatment (e.g. Vanrolleghem and Lee, 2003). Only a limited set of studies describe the experiences of this type of systems for analysing water quality variables in rivers and lakes. According to these published experiences on on-line analysers in surface waters, it seems that the applications, the type of sensors as well as the concepts to combine several measurements are rather diverse. Several studies describe rather specialised measurements, e.g. TNT (2,4,6-trinitrotoluene) in Wang and Thongngamdee (2003), while in others the combination of different variables is of major importance to gain new insights in aquatic processes, e.g. Beck *et al.* (1998). In some studies the use of a minimal set-up with low maintenance is promoted, e.g. Edwards (1998) and Johnson (1998), while in others rather complex and automated systems seem to give good results (Beck *et al.*, 1998; Du Preez *et al.*, 1998). Also the data-handling process can differ a lot and is still in full development. In particular the use of Internet for this purpose seems to be a very promising solution, as described by

Toran *et al.* (2001). The reliability of the measurements needs in particular further research, because most on-line sensors are less precise and accurate in comparison with laboratory instruments (Goethals *et al.*, in preparation). Therefore it is necessary to first investigate the required reliability of the field measurements before selecting the type of instrumentation (Mohapl, 2000; Leeks *et al.*, 1997; Schlegel and Baumann, 1996) and decide whether continuous measurements can have an added value for the purpose of the user.

The results of this research illustrated that automated measurement stations can reveal the limitations of contemporary water quality assessment networks and monitoring strategies. For the assessment of the river water quality in Flanders, the Belgian Biotic index (BBI; De Pauw and Vanhooren, 1983) and the Prati Index (Prati *et al.*, 1971) for dissolved oxygen (PIO) are being mainly used (Goethals and De Pauw, 2001). The BBI is based on the macroinvertebrates as indicators for the level of pollution. Prati *et al.* (1971) developed a transformation formula for different water quality variables to convert measured values into conveniently comparable quality indices. The PIO therefore focuses on DO as the single quality parameter and is calculated as (with PIO = 0–1: excellent; >1–2: acceptable; >2–4: slightly polluted; >4–8: polluted; >8 heavily polluted and m = number of samples):

$$DO(\%) < 50 \Rightarrow X = 4.2 - 0.437 * \frac{(100 - DO)}{5} + 0.042 * \left(\frac{(100 - DO)}{5}\right)^2$$

$$50 < DO(\%) < 100 \Rightarrow X = 0.08 * (100 - DO)$$

$$PIO = \frac{1}{m} \sum_{i=1}^{m} X_i$$

In Flanders, the Flemish Environment Agency (VMM) uses the PIO on the basis of the monthly or bi-monthly physical and chemical sampling results for its water quality evaluation. In view of the variability of the observations of the physical and chemical variables in time and space, as shown in this paper, it is clear that classical sampling with a monthly periodicity on a restricted amount of locations should be questioned for the determination of a physical–chemical quality index such as the PIO. Clearly, a lot of attention should be paid to the sampling location(s) and the timing of the sampling (day vs. night; flow regime; hydro-meteorological conditions, etc.). Even the use of a sample as an instantaneous observation for a given location has to be questioned, considering the observed depth profiles, which are also described in similar studies, such as Lee and Lee (1995). While the depth-averaged oxygen concentration in Geraardsbergen on the 2nd September is 35%, for example, a sample taken at a depth of 0.2 m under the water surface gives 65%. Using the PIO for the assessment, one would conclude from the averaged concentration that the water is heavily polluted, while the point measurement results in a slightly polluted river.

Sampling of river water is also necessary in view of the calibration of water quality models, needed to evaluate the impact of planned pollution abatement scenarios. Thomann (1982) discusses issues of model calibration and verification and stresses the importance of using data sets that reflect different field conditions. This places a burden upon the model user to conduct multiple field measurements over a variety of stream flow and meteorological conditions. In a study about the Dender by Vandenberghe *et al.* (2001) the usefulness of continuous measurements to reduce the model parameter uncertainty and thus to increase the reliability of the model predictions was demonstrated. The latter authors extended the research to the optimal design of measurement campaigns, in view of maximising the model reliability (Vanrolleghem *et al.*, 1999), given the logistic and financial constraints. D'heygere *et al.* (2002) optimised the monitoring strategy for macroinvertebrates, making use of the insights in the seasonality of the biological as well as chemical processes. In this manner, these type of monitoring can help to define which variables are useful and necessary to predict biological communities, because this is still one of the major difficulties in the development of ecological models for decision support in water management (Adriaenssens *et al.*, 2004; D'heygere *et al.*, 2003).

5. Conclusions

Reliable and representative continuous measurement series of water quality variables in rivers are not easy to achieve. Also further optimisation of the acquisition of reliable continuous measurement series and reduction of the maintenance costs of the on-line instrumentation will be necessary (Goethals *et al.*, in preparation). Nevertheless, continuous measurements can be valuable for river assessment and complementary to the routine discrete observations conducted by most environment agencies all over the world. These continuous series result in a more representative image of the water quality. In the second place, they can mean a solid basis to develop a more scientific approach on the sampling strategy and the needed amount of additional samples and the required chemical analyses (Beck *et al.*, 1998; D'heygere *et al.*, in preparation; Evans *et al.*, 1997). Continuous measurements can also allow for detecting sudden changes in rivers, for example due to accidental discharges. Therefore, in the future they will become more and more necessary as tools for water quality control and for the building and the calibration of detailed and complex models useful for decision making in water protection and restoration management (Du Preez *et al.*, 1998; Summers and Tonnessen, 1998).

With the continuous measurement campaigns done on the Dender river some conclusions could also be made concerning the water quality. The effect of the algae bloom during the summer of 1999 had some impact but did not cause a critical decrease of the oxygen concentration. On the other hand, the first important rainfall event caused an obvious decrease in the oxygen concentration (after a dry summer) as a result of the high organic loads that entered the system through sewer overflows and because algae were flushed out of the system. Another important aspect is the observed stratification in the Dender River for the variables pH, temperature and dissolved oxygen. Some periods (e.g. 17–20 September) still need further research to get the necessary insights for a complete understanding of the river ecosystem and the impact by the numerous human activities. That prooves that additional research is needed and continuous measurements will be an essential tool for it.

This study also showed that in certain cases discrete measurements to calculate PIO indices are often insufficient to draw conclusions from. Short periods of bad water quality can already harm the fauna and flora in the river. When those periods are not taken into account it can be difficult to explain why biological life in the river is not as expected and cause–effect relationships cannot be defined. It would be even more interesting to link the results from continuous measurements with the biological observations in the river and directly relate the impacts of the different target groups with the biological communities. In this manner the relations between the water quality, physical habitat, and the biological communities could be better understood in this river and from which the water management could benefit.

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