Designing a Measurement Network in a Meso-scale Catchment to Provide Data for Modelling

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Abstract: In many cases, water-quality models have a poor basis of calibration and validation due to inadequate or sparse input data. Water-quality monitoring is often limited to a few sites within the stream network where samples are collected and analyzed at some intermittent frequency (e. g. monthly). In particular, this limited temporal sample coverage causes problems in modelling water-quality variables such as phosphorous that are mainly transported during short-term events.

In order to address this problem, a meso-scale catchment was equipped with a measurement network for obtaining spatially and temporally higher-resolution data of water quality, meteorological data, and soil moisture data. The selected test site is the upper catchment of the Gera River (approx. 850 km²). This catchment features different landscape forms that are typical of regions in the lower mountain range in Central Europe. Measurements started in summer 2008.

The goal of the data collection is to establish a database for the improvement and development of eco-hydrological models like the JAMS/J2000-S.

Keywords: Water Quality, Online Measurement, Measurement Network, Modelling.

1   INTRODUCTION

Water-quality models for meso-scale catchments are often limited by a poor database for calibration and validation purposes. In practice, these water-quality models are frequently used to aid in the decision-making process in water management. These models are affected by this limitation of available physical data. The decisions based on these models are of course affected as well. Water-quality monitoring is normally limited to a few points within the stream network at which samples are collected and analyzed at some intermittent frequency (e. g. monthly) (Hooper et al., 2001, Drolc et al., 2002, Donohue et al., 2005). Regardless of the sampling strategy used, the calculated loads are often subject to large errors due to the often sparse temporal and spatial resolution of the available measurement data. This is especially the case for erosion and sediment-linked contaminants such as phosphorous loads generated from diffuse sources (Schleppi et al., 2006, Quilbe et al., 2005, Roberson and Roerish, 1999, Dijkhuis, et al. 1992).

In order to obtain data with higher spatial and temporal resolution for model development, calibration, and validation, a meso-scale test site in Germany was equipped within the scope of the Friedrich-Schiller-University-Jena's ILMS-Project (Integrated Land Management System). The design of this measurement network especially focuses on the diffuse nutrient loads and nutrient transport in the stream, caused by surface runoff and erosion processes occurring on agricultural lands.

Hence, beside the climatic driver variables and soil moisture as control variable of runoff generation, the key parameters are Nitrate, Ammonium, Total Phosphorus, Turbidity, and suspended solids in the river water. Therefore, the measurement network includes online water-quality stations, meteorological stations, and soil-moisture stations for continuous monitoring. The modelling system that will be improved or developed is JAMS/J2000-S (Fink et al., 2007).

2 UPPER GERA TEST SITE

As a test site for a so-called field laboratory, we chose the upper catchment of the Gera River (approx. 850 km²). It is a typical meso-scale catchment located on the northern bound of the middle mountain range of the Thuringian forest and south to the city of Erfurt (Figure 2). The main streams in the catchment are the main stem Gera River draining the central part from south to north, the Apfelstädt River draining the western part, and the Wipfra River draining the eastern part of the catchment. The upper Gera River catchment was selected for this study, due to its heterogeneity of natural conditions and the land use. These conditions can be considered as representative of the State of Thuringia in Germany as well as large regions of Central Europe. The catchment itself features the following four specific landscape forms:

1.   The "Thüringer Wald" (Thuringian Forest) (400 to 980 m a.s.l.) is underlain by rhyolite, conglomerate, and sandstones. Most of the bedrock is covered with periglacial slope deposits which are important pathways for subsurface runoff. The soils developed from these deposits and the underlying bedrock range from leptosols on the steep slopes to dystric cambisols and podzols to fluvisols in the valleys. The Thuringian Forest area has distinct borders to the other landscape forms in the catchment (Seidel, 2003). The land cover consists of coniferous forest with small areas of deciduous forest, pasture, and meadows in the valleys. The average temperature in January is about -3 °C; during July, the value increases to 14 °C. The precipitation ranges up to 1200 mm a-1 (Hiekel et al., 2004).

2.   The "Ilm-Saale-Ohrdrufer-Muschelkalkplatte" (Ilm-Saale-Ohrdrufer-Limestone-Plate) (300–600 m a.s.l.) primarily consists of underlying limestone, dolomite, and marlstones, which locally exhibit karst features. The rendzic leptosols and mostly shallow phaeozem soils have been developed from limestone weathering and aeolic sediments. Most of the soils are shallow and exhibit limited field capacity. Due to this situation, there is little resistance to nutrient leaching. The texture of the soils is clayey to loamy. The land use is a mixture of forest, pasture, meadows, and crops. The average temperature is higher than in the "Thüringer Wald". In January, it reaches an average of about -1.5 °C and during July around 17°C. The precipitation is between 550 mm a-1 in the northern part and 750 mm a-1 at the southern border with the "Thüringer Wald" in the southeast (Hiekel et al., 2004).

3.   The "Innerthüringer Ackerhügelland" (Central Thuringian Hilly Field Country) (200–400 m a.s.l.): The geology exhibits an alternating stratification of marlstones, limestones, claystones, and sandstones. It is overlain by partly deep loess and fluvial deposits. The loess deposits are the dominating source for soil development. The typical soil types are pheozems, luvisols cambisols, and rendzic leptosols. In the floodplain, gleyic pheozems, mollic gleysols, and fluvisols are formed. Most of the soils are characterized by high field capacity and base saturation, resulting in relatively high soil fertility. Due to this high soil fertility, most of the land use consists of crops and only small areas of forests and pasture. The texture of the soils is silty to clayey where the loess deposits are dominating and sandier where the fluvial deposits have a higher influence on the soil formation. The average temperature in January is approximately -0.5 °C and in July around 17 °C. The mean annual precipitation is relatively low for Central European conditions and ranges between 500 mm a-1 and 600 mm a-1 (Hiekel et al., 2004).

4.   The "Paulinzellaer Buntsandstein Waldland" (Paulinzellaer Sandstone Woodland) (400–600 m a.s.l.): The geology is dominated by sandstones with minor

inclusions of marlstones, claystones, and glacial and fluvial deposits. Due to the type of bedrock, the soil texture is dominated by the sand fraction. The main soil types are cambisols, podsols, and small areas of luvisols. In the valleys, sandy fluvisols and gleysols are formed. Due to the sandy soil texture, the soils have a limited field capacity and a low to medium soil fertility. The land use is a mixture of coniferous forests, crops, pasture, and meadows. The average temperature for January is approximately -2 °C and for July approximately 15 °C. The mean annual precipitation ranges from 550 mm a-1 to 800 mm a-1 at the border to the "Thüringer Wald" (Hiekel et al., 2004).

3   MEASUREMENT NETWORK

The different physical-geographic characteristics inside the catchment should be captured by the setup of the monitoring network (Leeks et al., 1997). Therefore, the configuration of the observation network, established in this field-laboratory case study, was designed to delineate the characteristics of each of the landscape forms. In addition, a nested catchment approach was implemented (Figure 2).

3.1   Water-quality stations

A key component of the field-laboratory design consists of six online water-quality stations distributed in the river network of the test site. The measurement devices were manufactured by WTW (Wissenschaftlich Technische Werkstätten GmbH). All of the water-quality stations measure the following parameters: streamflow, water temperature, pH, electrical conductivity, turbidity, suspended solids, dissolved oxygen, nitrate, ammonium, total phosphorous, redox-potential, and spectral absorption coefficient (SAC) (to correlate with carbon parameters such as total organic carbon and chemical oxygen demand). The pH, electrical conductivity, and redox-potential are measured with electro-chemical sensors. Ammonium is measured with an ion-selective sensor, compensated against potassium. Within the same device also a nitrate sensor is integrated without a specific compensation. Turbidity and suspended solids are measured with infrared optical sensors. The spectral absorption coefficient is measured with an ultraviolet optical sensor. This sensor also measures nitrate. For this optical sensor a filter system was installed to provide a solid-free and bacteria-free sample. The dissolved oxygen is measured with an optical sensor on the basis of the photoluminescence method. Total phosphorous is measured with a photometric sensor using the molybdenum blue method. In advance of the photometric analysis, a digestion that converts phosphorous compounds to orthophosphate takes place. A scheme of the layout of the online station is given in Figure 1.
The temporal resolution was set at one recorded value per hour in the case of the phosphorous analyzer, whereas the other variables are recorded every 15 minutes. The data and error messages could be transferred via GSM modem to the office. The start of the data recording was in June 2008.
Within the designated subcatchments (black solid lines), the locations of the water-quality stations are indicated in Figure 2. The locations of the water-quality stations were selected to monitor the influences of the different landscape units on the water-quality parameters. The upper northern station ("Möbisburg") monitors conditions at the outlet for the entire Gera catchment. Located nearby, to the west of "Möbisburg", the station "Ingersleben" collects the values of the largest tributary of the catchment, the Apfelstädt River, comprising the three landscape forms 1, 2 and 3. West of the station "Ingersleben", the station "Wandersleben" was installed. This station monitors the values of the Rot Creek which has in its source area only the landscape form 3. For the main stem Gera River, the station "Arnstadt" has been equipped (Figure 2). This station provides data from landscape forms 1 and 2. Southeast of the station "Möbisburg" the station "Eischleben" is located, measuring the values from the second largest tributary, the Wipfra River. This river catchment comprises landscape forms 4, 2, and a minor part of 3. The station

"Niederwillingen" at the Wipfra River was installed, because it only comprises landscape form 4. Using the combined data for stations "Niederwillingen" and "Eischleben" the characteristics for landscape form 2 can be delineated. The spatial distribution of the water-quality stations in general strives to obtain distinctive characteristics for the four different landscape forms. However, the values of the landscape form 1 are not measured separately, because agricultural land use is very limited in landscape form 1. Therefore, only low concentrations of nutrients are found in the sampled water.

The stations "Möbisburg", "Ingersleben", "Eischleben", and "Arnstadt" were installed at already existing gauging stations operated by the Thuringian environmental agency. The stations "Wandersleben" and "Niederwillingen" were installed in field containers.
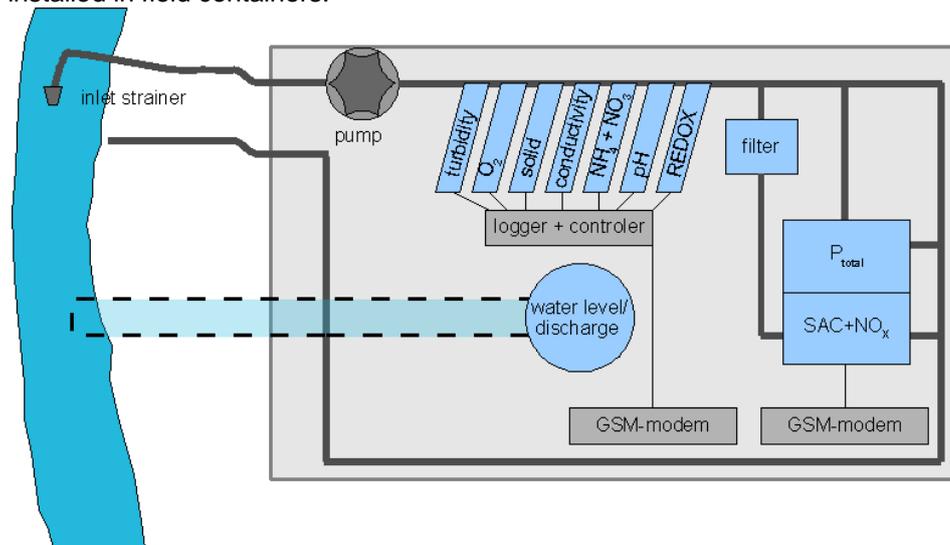

Figure 1. Scheme of the online water-quality stations

3.2   Water-quality sampling sites

Additional to the water-quality stations, 23 sample points throughout the catchment's stream network are selected. These points are sampled monthly to increase the spatial resolution of the water-quality measurements. The locations of these sample points are chosen, so that the influence of single branches within the river network as well as the influence of landscape unit 1 can be estimated. This provides a total of 29 in-situ sampling locations, including the six water-quality locations where water samples were also taken. This program has been conducted to achieve a better linkage between the data of the sample points and the data of the water-quality stations and to test or confirm the online measurements independently. The subcatchment of the water-quality station "Wandersleben" (Rot Creek) in the northern part of the test site has a higher measurement-point density due to its high percentage of arable land. The goal is to investigate this part of the catchment more intensively.

At these sample points, similar parameters are measured compared to those at the water-quality stations. Water temperature, pH, electrical conductivity, dissolved oxygen (HQ40d), and turbidity (Model 2100) are measured with handheld instruments directly at the sample points. Chemical oxygen demand, nitrate, nitrite, ammonium, total phosphorous, organic carbon, potassium, magnesium, and calcium concentrations are measured photometrically (DR2800) with cell tests in the laboratory. The samples are taken on one day and are stored in the refrigerator; on the next day, the laboratory analysis is conducted. The sensors and cell tests are manufactured by Hach-Lange GmbH.

3.3   Meteorological stations

A primary focus of this study is on processes associated with storm event-based characteristics. Therefore, climate data with a high temporal resolution are necessary and nine meteorological stations have been installed for this study. The locations of those stations were selected to obtain data for the various landscape forms. We chose locations that were observed by local people due to safety reasons. In this way, the locations were a compromise between the scientific and the practical requirements. The landscape form 1 ("Thüringer Wald") is only equipped with one station because of the relatively great focus on processes in agricultural land in this study. For this type of station, locations were sought to the extent possible in enclosures to protect the stations from vandalism. The station towards the northeast just outside of the catchment area is also used for another part of the ILMS project which is not described in this article, but it gives additional information about the test-site area. The measured parameters are air temperature, wind speed, wind direction, air pressure, humidity, precipitation, and radiation balance. These data were recorded every 5 minutes. A GSM modem is integrated to provide remote access to these data.
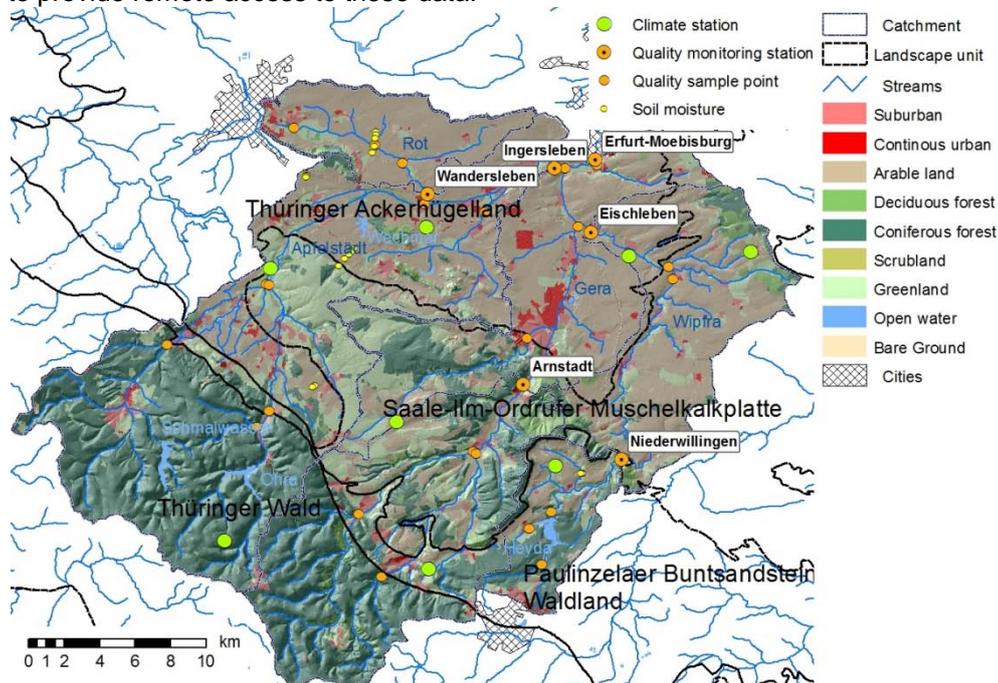

Figure 2. Landscape forms and land-use types in the upper Gera catchment and measurement network of the upper Gera catchment.

3.4   Soil-moisture stations

For the description of the hydrological balance, soil-water storage is an important parameter. It is of vital importance for estimating evapotranspiration. The condition of this storage term has also a significant influence on the distribution of water in the different runoff components – surface runoff, interflow, and percolation.
We measure soil moisture with frequency-domain probes at five different depths at a total of 24 locations on farmlands distributed throughout the different landscape forms. The locations aim to represent the different soil properties in the different landscape units in different soil catenae. The goal of those measurements is to measure water infiltration into the soil and to derive information about surface-runoff events. The values are stored every 5 minutes. The data will be transferred via a remote-telemetry network to a central station which then can be transferred through modem connection to the central database.

4   EXAMPLE OF MEASUREMENT RESULTS

An example of the continuous measurements of the online monitoring station "Möbisburg" (cf. figure 2) at the catchment outlet is shown in Figure 3. The dissolved oxygen (blue line, lower diagram) and the pH (red line, lower diagram) value exhibits the typical diurnal variation caused by photosynthetic activity during the day and respiration during the night.
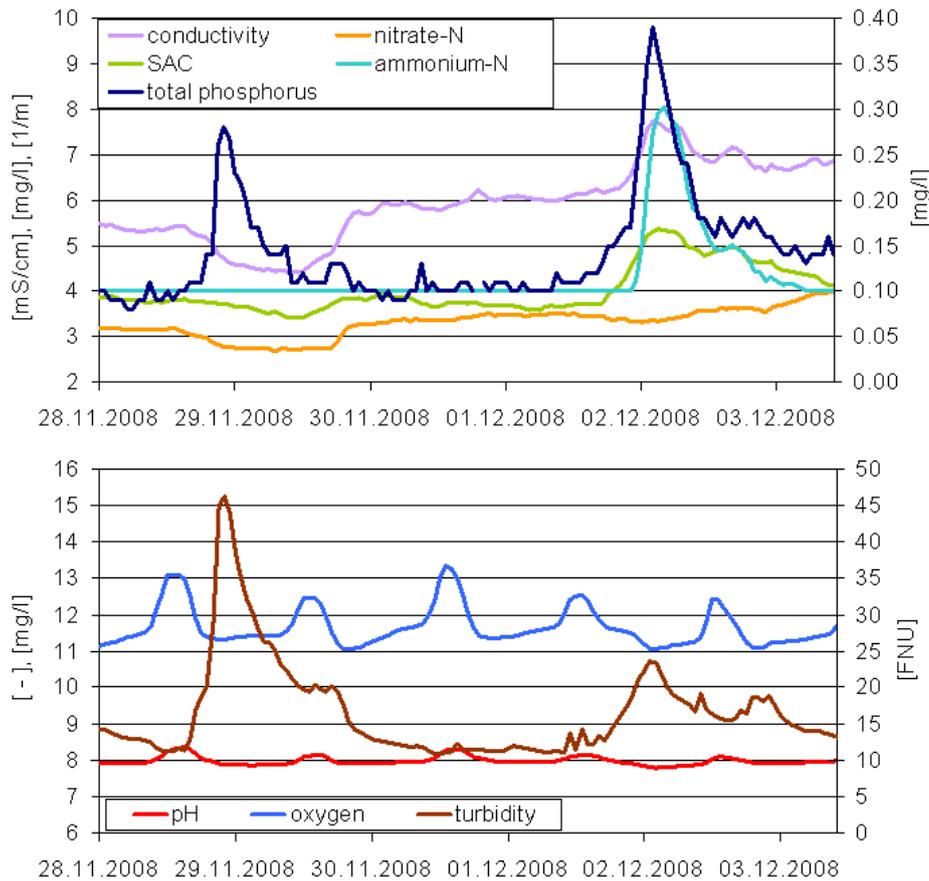

Figure 3. Conductivity, spectral absorption coefficient (SAC), total phosphorous, nitrate, ammonium (right Y-axis), pH, dissolved oxygen, and turbidity (right Y-axis) of the online station Möbisburg from 28th November to 3rd December 2008.

The total phosphorous concentration (dark blue line, upper diagram) shows two events which could also be identified in the turbidity (brown line, lower diagram). Many of the other measured parameters react differently during the two events. In the first event (29th November), the conductivity (violet line, upper diagram), SAC (green line, upper diagram), and nitrate (orange line, upper diagram) show a slight descent of the signal which is caused by dilution processes. The ammonium signal (cyan line, upper diagram) shows no variation at all during the first event. This is due to the fact that the values are below the measuring range and the dilution could not be detected. However, the second event (2nd December) exhibits a different behavior, as the signals of SAC, ammonium, and conductivity rise together with the phosphorous which can be caused by waste water or results from diffuse sources from agricultural land. To explain the difference between the two events, other sensors of the monitoring network could be utilized. In Figure 4, the average rainfall (blue bars) of the meteorological stations is presented. It is apparent that during the first event no rainfall was detected whereas at the second event a significant amount of rain was recorded. Comparing the turbidity of all online stations reveals that only the station "Ingersleben" (orange line) follows the

already shown event in "Möbisburg" (dark red line), the outlet of the largest tributary Apfelstädt (cf. Figure 2). The other stations show no systematic signal at this event, also the station "Wandersleben" (olive line), which is part of the tributary Apfelstädt, shows no reaction. At the second event, all sensors show more or less similar signals. Hence, the most likely cause for the first event is a flush coming from one of the reservoirs Ohra, Schmalwasser, or Wechmar (cf. Figure 2), that causes riverbank erosion. Furthermore, the chemistry of the water supports this assumption (cf. Figure 4), as the high amount of phosphorous could have its origin in the river bed sediments. While ammonium is not very likely in the river bed because the Apfelstädt is a fast river with high oxygen saturation so that ammonium could easily be decomposed.

This example shows an impression of the potential of the measurement network to identify processes which are important for the development of nutrient simulation models. Examples of the results of the water-quality sampling sites are given in Fink et al. 2008.
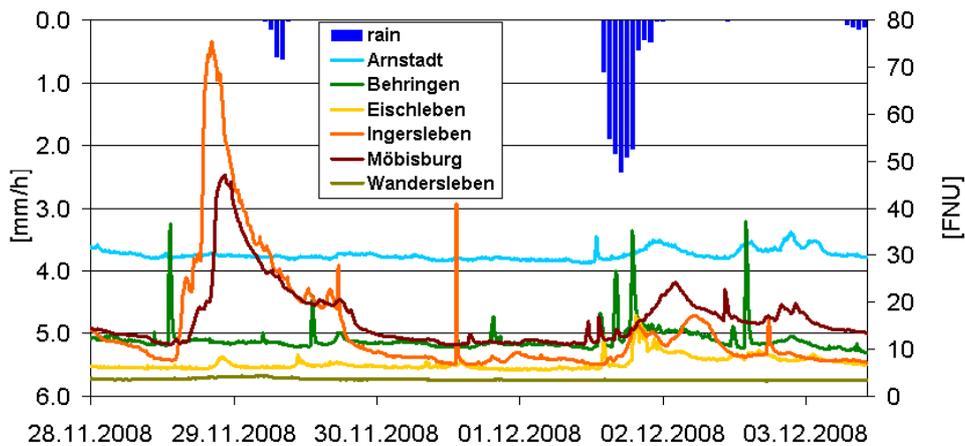

Figure 4. Turbidity of all online stations and average rain (right Y-axis) from 28th November to 3rd December 2008.

5   CONCLUSIONS AND OUTLOOK

A monitoring network installed in the catchment of the upper Gera River was introduced. The components of the network measure meteorological parameters, soil moisture, water quality and quantity. The presented results of the monitoring network show that important influences of landscape on the water quality can be identified. The results of the dynamics show that important phenomena can be captured that have a strong influence on the water quality. They also indicate that discrete observations usually conducted by environmental agencies all over the world are not sufficient to describe all relevant processes for water quality assessment.

The data gathered from this catchment's measurement network will be used for further development and validation of hydrological and nutrient transport simulation models. These data will be used in particular for the J2000-S nutrient transport model (Fink et al., 2007), an extension of the J2000 hydrological model (Krause, 2002). In addition to the hydrological part of J2000, methods for the description of land-use management, plant growth, and nitrogen balance were implemented. Within the ILMS project, we improved the existing components of the J2000-S using the gathered data. Additionally, these data will help to implement an erosion-phosphorus component which will be in the first draft based on the MUSLE (Williams 1975) approach. Stream water quality components for hydrodynamics, transport and conversion processes based on equations of the River Water Quality Model No.1 (IWA Taskgroup of River Water Quality Modelling 2001) will also be implemented. From the use of the measured data we expect a substantial

improvement of the quality and reliability for our process-based modelling system and associated applications. Since our test site comprises different landscape units which are typical of Central Europe the resulting modelling system will be transferable to other catchments.

ACKNOWLEDGEMENTS

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