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Variation in turbidity with precipitation and flow in a regulated river system – River Göta Älv, SW Sweden

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Abstract

The turbidity variation in time and space is investigated in the downstream stretch of the river Göta Älv in Sweden. The river is heavily regulated and carries the discharge from the largest fresh water lake in Sweden, lake Vänern, to the outflow point in Göteborg Harbour on the Swedish west coast. The river is an important waterway and serves as fresh-water supply for 700 000 users. Turbidity is utilised as an indicator to ensure sufficient quality of the intake water to the treatment plant. The overall objective of the study was to investigate the influence of rainfall, surface runoff, and river water flow on the temporal and spatial variability of the turbidity in the regulated river system by employing statistical analysis of an extensive data set. Six-year long time series of daily mean values on precipitation, discharge, and turbidity from six stations along the river were examined primarily through linear correlation and regression analysis, combined with nonparametric tests and analysis of variance. The analyses were performed on annual, monthly, and daily basis, establishing temporal patterns and dependences, including seasonal changes, impacts from extreme events, influences from tributaries, and the spatial variation along the river. The results showed that there is no simple relationship between discharge, precipitation, and turbidity, mainly due to the complexity of the runoff process, the regulation of the river, and the effects of lake Vänern and its large catchment area. For the river Göta Älv, significant, positive correlations between turbidity, discharge, and precipitation could only be found during periods with high flow combined with heavy rainfall. Local precipitation does not seem to have any significant impact on the discharge in the main river, which is primarily governed by the precipitation at catchment scale. The discharge from the lake Vänern determines the base level for the turbidity in the river, whereas local surface runoff and tributary discharge induced by rainfall govern the temporal variability in turbidity. Autocorrelation analysis indicates a temporal persistence in turbidity of about 10 days. The results also show that erosion in the main river, from the river bed and banks, is not a dominant contributor to the suspended sediment transport in the river. Further studies on the correlation between

turbidity and suspended sediment transport and in relation to erosion processes are suggested.

1 Introduction

1.1 Background

Suspended sediment, a major contributor to turbidity, is a potential contaminant carrier (Håkanson, 2006; Lick, 2009; Schoellhamer et al., 2007; Zonta et al., 2005), as well as being connected to bacterial impact and light suppression with effects on BOD, DO, and pH (Bhutiani and Khanna, 2007; Gauthier et al., 2003; Håkanson, 2006; Lawler et al., 2006).

Several studies have demonstrated a strong relationship between discharge and suspended sediment concentration, with different time lags depending on the characteristics of the river/catchment system (Alexandrov et al., 2007; Antonelli et al., 2008; Lawler et al., 2006; Townsend-Small et al., 2008; Vericat and Batalla, 2005; Zabaleta et al., 2007; Zonta et al., 2005). Numerous regression relationships (i.e. sediment rating curves) have therefore been developed in order to predict suspended sediment concentration during flood events (Iadanza and Napolitano, 2006; Picouet et al., 2001; Schmidt and Morche, 2006; Townsend-Small et al., 2008; Vericat and Batalla, 2005; Wang et al., 2008; Yang et al., 2007). Nevertheless, the relationship between discharge and suspended sediment concentration is not straightforward (Hodgkins, 1999) since it is influenced by the sediment supply from the catchment, the intensity and spatial distribution of precipitation, human activities (i.e. deforestation, agricultural reclamation, urbanisation, reinforcement of river banks), as well as the erosive power of the river (Wang et al., 2008).

The close relationship between suspended sediment concentration and turbidity has resulted in turbidity often being used as a surrogate for the concentration of suspended sediment (Chanson et al., 2008; Hamilton et al., 1998; Kineke and Sternberg, 1992;

Ochiai and Kashiwaya, 2010; Pavanelli and Bigi, 2005a,b; Thomas and Lewis, 1995; Williamson and Crawford, 2011). Turbidity is therefore a key parameter when monitoring surface water quality because of its relation to suspended sediment concentration but also because of its effect on the eco-environment. In contrast to direct sampling for analysis of sediment concentration, a turbidity monitor employs optical techniques based on the scattering of light and provides the possibility for continuous, spatial and temporal measurements in a cost-effective manner (Gao et al., 2008; Kineke and Sternberg, 1992; Pavanelli and Bigi, 2005b; Pavanelli and Pagliarani, 2002). Measures of turbidity include suspended particles and colloids, dead and living organisms, and inorganic and organic particles (Bhutiani and Khanna, 2007; Håkanson, 2006). However, the optical technique makes the monitor sensitive not only to the sediment content in the water, but also to climatological and biological factors (Gao et al., 2008; Hawley, 2004; Håkanson, 2006; Wass et al., 1997). Recorded turbidity levels are affected by particle size, aggregation, air bubbles, runoff characteristics, waste water discharge properties, weeds and their break down products, humic acids and other organic compounds from decay of organic matters, high iron concentration. Thus, calibration is typically necessary for relating sediment concentration to turbidity (Hamilton et al., 1998; Pfannkuche and Schmidt, 2003; Wass et al., 1997; Williamson and Crawford, 2011).

Previous studies have shown correlation between turbidity and precipitation (Hamilton and Luffman, 2009; Lopez-Tarazon et al., 2009) and turbidity and discharge (Hamilton and Luffman, 2009). Periods with high turbidity are normally associated with the wet season when surface runoff transports sediments from the soil to the river and when the water flow is generally higher and more turbulent, which does not allow for the settlement of particles on the river bed (Bhutiani and Khanna, 2007; Maillard and Pinheiro Santos, 2008). Other studies have demonstrated relationships between turbidity and microorganisms, such as faecal coli forms (Hamilton et al., 1998; Huey and Meyer, 2010; Maillard and Pinheiro Santos, 2008; Åström et al., 2007) and plankton (Néstor et al., 2001), as well as between turbidity and nitrogen (Maillard and Pinheiro Santos, 2008). There are indications that turbidity is positively correlated with temperature during spring/summer (Vernile et al., 2009), because of algal growth, and negatively correlated during fall/winter due to the decay of plants, leaves etc. Negative correlation has been found between turbidity and conductivity (Winston and Criss, 2002).

1.2 Objectives and procedure

The overall objective of this study is to improve the understanding of the variability of turbidity (measured as Formazin Nephelometric Units; FNU) in a regulated river. Specifically, significant dependencies were sought between turbidity and rainfall, surface runoff, and river flow. A high-quality data set that encompasses detailed turbidity measurements in time at six stations along the river Göta Älv in Sweden was analysed.

Statistical analyses were performed based on a selected number of hypotheses regarding the main processes governing the turbidity in the river. First, the turbidity data were examined at different temporal scales, including daily, event-based, seasonal, and annual scale. Then, spatial variations in turbidity were explored together with the relationships between measurement stations along the river. Finally, analysis of variance (ANOVA) was carried out to investigate the contribution from different processes to the recorded turbidity.

2 Site description

2.1 Göta Älv study area

The focus of this study is on the lower part of the river Göta Älv and its catchment. The study area includes the river stretch from lake Vänern to the outlet at the City of Göteborg (see Fig. 1), comprising a length of 93 km with a catchment area of about 3500 km^2. The study area constitutes a small part of the entire Göta Älv river basin, which also include the lake Vänern catchment. This catchment area encompasses about 50 000 km^2, making it the largest in Sweden (Kvarnäs, 2001). Lake Vänern is also the largest lake in Sweden with a volume of about 153 km^3 and it contributes to more than 90 % of the flow in the studied river stretch, whereas the rest originates from local tributaries, direct runoff, and groundwater. At least 25 tributaries have their outflows to the river south of lake Vänern, of which Slumpån, Gårdaån and Grönån are the three largest ones (Fig. 1). South of the City of Kungälv, the river Göta Älv bifurcates around a large island; the northern branch (the river changes name to river Nordre Älv) receives approximately 2/3 of the total discharge, whereas the remaining 1/3 takes the route through the southern branch (still referred to as the river Göta Älv). The mean annual discharge into the sea (both branches) is 565 m^3 s^{-1}, whereas the maximum (regulated) discharge from Vänern is 1030 m^3 s^{-1}. The river is regulated by three hydropower stations located at Vargön (Vänersborg, near gauging station Gäddebäck), Trollhättan, and Lilla Edet (see Fig. 1). In addition, there is a flow shield in Nordre Älv to protect the river from salt-water intrusion. The water level in lake Vänern together with the energy demand govern the variation in river discharge.

The river sediments consist mainly of thick layers of cohesive material with thin layers of silt and sand. The river morphology is influenced by occasional landslides. The mean width of the river is about 100–200 m but it widens to 300 m just before the bifurcation, after which it again narrows down to about 100–200 m. The thalweg has a depth of 7–10 m with deeper local cavities. The areas surrounding the river are pasture land, forests, bed rock, and small urban areas. Almost no sedimentation occurs in the river, and the transport of inorganic suspended particles has been estimated to 180 000 t yr^{-1}, of which 70 000 t yr^{-1} are transported through the southern branch. Figure 2 illustrates a sediment budget for the studied river stretch downstream Vänern, compiled from various sources (Göransson et al., 2011; Rydell et al., 2011; Sundborg and Norrman, 1963). The river was divided into four different reaches in accordance with the general morphology and the prevailing transport processes. For the reach between Vänern and Lilla Edet municipality, bank erosion dominates, whereas the reaches south of Lilla Edet primarily exhibit bottom erosion.

2.2 River water usage

The river Göta Älv is an important waterway, the recipient of treated wastewater, as well as the source of drinking water for 700 000 users. The water quality in the river is primarily affected by direct runoff from urban, rural, and livestock areas, wastewater from urban areas, combined sewer overflow during heavy rainfall (Åström et al., 2007), leakage from contaminated sites, and accidental spills from industries and vessels (Göransson et al., 2009). In addition, the inflow from lake Vänern and the discharge from the different tributaries into the river have impact on the water quality.

Turbidity (as well as pH, redox, and conductivity) is continuously recorded at seven gauging stations along the investigated river stretch with the purpose of providing an early warning in case of deteriorating water quality. The most downstream gauging station is located at the fresh water intake (Lärjeholm; see Fig. 1). A turbidity level of 12 FNU is employed as a simple criterion to temporarily close the intake.

3 Method

3.1 Data collection

Turbidity data were obtained from the water supply plant at Lärjeholm, which belongs to the City of Göteborg. This study includes turbidity data from gauging stations Skräcklan, Gäddebäck, Garn, Södra Nol, Surte and Lärjeholm (Fig. 1). Measurements at gauging station Älvabo started recently; thus, this station only has a short data record, and it was excluded from the analysis. Turbidity values reported here were measured in FNU, which is recommended in the Swedish standard. All turbidity monitors (Hach surf scatter 6) yield stable recordings with an accuracy of about ±5 %. The turbidity is recorded as minute-averaged values at the different stations, but in this study daily averages were employed. The water intake to the optical turbidity monitors are located 1–2 m above the bottom, at 2–3 m water depth (except for Skräcklan

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that is located at 8–10 m depth in a bay of lake Vänern). Measurements have shown that the vertical variation in turbidity is low since turbulence in the river flow provides good vertical mixing for the sediment. Biofouling on the optical sensors may affect the output, depending on the level of biological activity in the river. Thus, the sensors are cleaned once a week and it is assumed that the biofouling had negligible influence on the measurements. Before the turbidity data were analysed, the data set was checked for anomalies caused by power failures and other technical problems.

Data on river flow were obtained at the hydropower stations (located at Vargön, Trollhättan, and Lilla Edet) and at one location in river Nordre Älv. The flow in the continuation of river Göta Älv downstream the bifurcation is calculated as the difference between the discharge at the hydropower station in Lilla Edet and the flow in river Nordre Älv. Water levels are recorded at the hydropower stations, where the stations in Trollhättan and Lilla Edet include locks to facilitate navigation. As an example, Fig. 3 shows the precipitation, flow, and turbidity for two different years (2002/3 and 2006/7) in the time series studied. The data are plotted with respect to the annual cycle of the hydrological processes, here chosen to be 1 August to 31 July (a hydrologic year). In 2006/7 the fall was a period with intense, long-duration rainfalls over a large part of W/SW Sweden, which is reflected in the unusually high discharge during this period. The year 2002/3 is more normal in terms of flow and turbidity variations.

Data on precipitation were obtained from the Swedish Meteorological and Hydrological Institute (SMHI), where data from Göteborg (gauging station GöteborgA) and the community of Lilla Edet (gauging station Garn) were used in the present study. GöteborgA is located about 4 km SSW of the turbidity gauging station Lärjeholm (Fig. 1). The basic precipitation data employed, as well as the other data series, encompassed daily averages between 2002 and 2007 with respect to gauging station Lärjeholm, and in general between 2004 and 2006 with respect to gauging station Garn (due to missing data). There is no information in the data if the precipitation has fallen as rain or snow. The annual mean precipitation (year 2001–2007) for Göteborg was 922 mm. A longer period with frontal rainfall normally occurs from November to January, with shorter periods of convective rainfall in July and August (see Fig. 3).

3.2 Data analysis

The strategy of the data analysis involved a stepwise statistical approach focusing on daily, monthly, and yearly data on turbidity, flow, water level, and precipitation, with the purpose to identify, describe, and explain the turbidity variations in time and space. The present analysis did not include short-term variation in turbidity on a time scale of less than a day; for example, turbidity variations induced by vessel traffic (see Althage and Larson, 2010). It is expected that such signals are negligible or make a similar contribution on a daily basis because of the short peak duration, and will not have any significant impact on the variation in the daily mean values.

Linear correlation and regression analyses were used for different data sets derived from the recorded mean daily values. Also, nonparametric tests (for the assurance of the test method) and analysis of variance (ANOVA) were performed. For the linear correlation, the Pearson r was used with a significance level (p) of 0.05. Since the sample data were daily mean values covering several years, the sample distribution was assumed to follow a normal distribution, which was confirmed through statistical tests. Nonparametric correlation did not yield any major differences in the result, lending confidence to the use of the linear correlation model. Thus, only the results of the latter analysis will be presented here. The statistical software Statistica (Statsoft; Version 9) was primarily used for the different types of analyses discussed.

Missing data were treated by case-wise deletion and unbiased data were used, implying that outliers and extremes were included. The time period and time resolution employed in the analysis influenced the results; thus, some years showed better correlations between the variables than other years (for example, 2006/07 is such a year). Monthly mean values smooth out variations and increase the correlation compared to daily mean values.

Previous work has shown that the suspended matter in the Göta Älv mostly contains clay particles. Correlation between turbidity and suspended sediment concentration for a limited number of samples taken in the Göta Älv indicated a linear relationship ($r^2 = 0.88$) (Göransson et al., 2011), in agreement with other studies (see for example Lenhart et al., 2010; Pavanelli and Bigi, 2005a,b; Pavanelli and Pagliarani, 2002; Zonta et al., 2005). Loss on ignition indicated a content of about 2–20 % organic matter.

With regard to the variables studied, P (mm) refers to precipitation, Q ($\mathrm{m^3\,s^{-1}}$) to flow, WL (m) to water level (refers to a deviation from a reference level which corresponds mean sea level), and T (FNU) to turbidity. In the following, a brief summary of the results obtained during each step of the analysis outlined above are presented. Additional interpretations and comments to the analysis results are provided in the subsequent discussion section.

4 Results

4.1 Data time series properties

Annual averages from year 2002 to 2007 were first calculated from the data on daily mean values. These averages were then analysed with regard to the relationship between precipitation, discharge, water level, and turbidity. Table 1 summarises descriptive statistics. On an annual basis, the turbidity displays positive correlation with Q, P, and WL (about $r = 0.7$), although the statistical significance is low due to the limited number of years available. In spite of the river being regulated, correlation is expected between T and Q, as larger Q would yield more transport, both in the river and from the catchment, influencing T on an annual time scale. A strong correlation between Q and WL is observed ($r = 0.96$), simply because a higher WL is typically associated with a larger Q.

Daily mean values for the entire time series (station Lärjeholm; summary statistics given in Table 2) showed surprisingly weak, but significant, correlations for T versus P

($r = 0.12$) and T versus Q ($r = 0.18$). Analysis of daily mean values was also carried out for the shorter period 2004–2006 for both gauging stations Lärjeholm and Garn. Limiting the analysis to three year (2004–2006) when the precipitation and discharge were unusually high emphasises the dependency, yielding stronger correlation between T and Q (Lärjeholm: $r = 0.27$; Garn: $r = 0.26$).

This analysis shows the difficulty to explain turbidity variations in the river at the daily time scale from the variations in precipitation and river discharge.

4.2 Temporal dependences

The statistical analysis was repeated for a number of limited time series, or single events, to find further explanation for the variation in turbidity with runoff and flow. Eight events were chosen, five from Lärjeholm and three from Garn, each representing a particular type of precipitation or flow pattern, where either the flow, precipitation, or both, had one or several peaks. However, low correlation values were again obtained between P, Q, and T for the events studied, except in a few cases. Figure 4 illustrates one event where a marked and significant correlation was obtained between T and Q ($r = 0.78$). The figure also indicates a clear relationship between P and Q, although the response in Q is delayed, most likely because of the runoff process. With reference to the peaks, this delay is about three days, which points to a rainfall event at the catchment scale. The rapid variation at the daily time scale for Q before the rainfall event demonstrates the effect of short-term regulation in the hydropower plants, which is one factor that obscures a clear relationship between the variables studied. In another event, recorded at Lärjeholm on 3 to 22 May 2002, the peaks in Q and T clearly follow the peak in P with some time delay indicating a strong relationship. However, stronger correlations between P, Q, and T were expected for the event-based analysis, and the lack of such correlations indicates that the system is more complex with peaks in P and Q not giving immediate response in T.

Also more extreme events were investigated to see whether the correlation between turbidity and the other variables studied would increase under such conditions. Four types of events (cases) recorded at the station Garn (years 2004–2006) were selected, since the relationship between the variables seemed to be somewhat stronger at this station than at Lärjeholm, namely (1) high turbidity events ($T > 20$ FNU), (2) high discharge events (20 highest discharge events), (3) heavy rainfall events in summer (10 highest rainfall events), and (4) heavy rainfall events in winter (10 highest rainfall events).

The results indicated that extreme events do not have a clear impact on the variation in turbidity. For example in Case 1, the selection of high turbidity events only marginally improved the correlation between T, Q, and P. Overall, for the various cases investigated, the only markedly improved correlation found was between T and WL for the highest discharge events ($r = 0.60$).

As shown in Fig. 4, there is typically a delay in the flow and turbidity response to precipitation. In addition, a certain amount of rainfall is needed in order to yield sufficient runoff for producing sediment transport resulting in increased turbidity in the river water. The lag time was investigated by shifting the data on T and Q up to 11 days with respect to P, and accumulated data on P up to 13 days (days with zero rainfall included) were compared with T and Q. Delaying T with respect to P at various times steps in the correlation analysis for daily values marginally improved the coefficient values. However, a delay in the analysis of T versus Q slightly improved the correlation, still being rather low though ($r = 0.24$).

Accumulated P versus T increased the correlation with the length of the accumulation period. This increase continued up to a period of about 11 days for Lärjeholm ($r = 0.48$) and about 9 days for Garn ($r = 0.52$, Fig. 5). These results indicate that a certain amount of rainfall is needed before surface runoff and erosion takes place. Thus, rainfall events that continue over a longer period of time are needed in order to influence the turbidity in the river. The length of this period may depend on the soil conditions and the general characteristics of the catchment and the river, but the time delay obtained corresponding to the maximum correlation values indicates a typical length.

From these results it is reasonable to believe that catchment size is a significant factor. Probably, at some occasions do the catchment characteristics and size of lake Vänern govern turbidity variations in the river, whereas at other occasions are the catchment and size of river Göta Älv more important. According to the studies by Duvert et al. (2011), the percentage of time needed to carry 50 % of the annual suspended sediment flux increases with increasing catchment size. For the river Göta Älv, this means that the large catchment of lake Vänern and the lake itself evens out precipitation and flow peaks, and thereby attenuates the correlation between the variables P and Q with T.

A seasonal variation in turbidity is expected, which is also seen in Fig. 6. It was found that a slightly stronger correlation between P and T occurred during winter (December–March, $r = 0.18$) than during summer (June–August, $r = 0.06$, $p \gg 0.05$), which may be explained by a general higher discharge and less vegetation on the surface during the winter months. Vegetation stabilises the soil surface, preventing erosion and sediment transport. Decreasing the time resolution to monthly mean values improved the overall correlation ($r = 0.55$ at $p = 0.07$), but only July and November showed marked correlation for T versus P ($r = 0.89$ and $r = 0.87$, respectively).

The monthly mean values reveal a pattern with clearly higher variability in turbidity and discharge (and water level) during the winter season (wet period), which is not as evident for the precipitation. The high variability in discharge during the winter is most likely an effect of the varying energy demand, which induces short-term regulation of the river flow on a time scale of days. The high variability in turbidity during winter is partly due to the discharge, but variations in the vegetation cover and its effect on runoff and erosion may also be important.

The temporal persistence in the daily and monthly turbidity data was investigated using autocorrelation analysis (Fig. 7). Analysis based on daily data revealed strong autocorrelation for the turbidity over a time scale of weeks. Thus, events affecting the turbidity should have this typical duration, which is in agreement with the analysis for accumulated data discussed previously. Autocorrelation of monthly data on turbidity showed a typical sinusoidal shape with a period of one year that is characteristic for seasonal variations. Most of the factors influencing turbidity, such as precipitation, flow, vegetation, and temperature, have seasonal cycles producing a variation in the turbidity with a period of one year.

4.3 Spatial variations

Spatial variability in flow and turbidity can partly be attributed to contributions from tributaries. Data from the main tributaries (Grönån, Gårdaån, and Slumpån; see Fig. 1) were compiled as monthly mean values. These data included only the years 2004 to 2006, since comparisons where made with both Garn and Lärjeholm. Turbidity at Garn exhibited a strong correlation with the discharge from the tributaries in contrast to the correlation with the discharge in the main river (Table 3). This is explained by the high correlation between P and Q in the tributaries, indicating natural conditions (no regulation) and limited detention storage. The correlations between the T at Lärjeholm and Q in the tributaries were lower; however, this station is located further downstream from where the tributaries enter the river.

Sediment is supplied from surface runoff, tributaries, and erosion of the river bed and bank along this stretch (assuming most of the sediment provided to the river is not deposited). Thus, an increase in turbidity in the downstream direction from lake Vänern to the City of Göteborg is expected. The interrelationships between gauging stations along the river where hence analysed to quantify such increase. Daily data on measured discharges from the hydropower stations at Vargön (Vänersborg), Trollhättan, and Lilla Edet, and the calculated discharge for the continuation of river Göta Älv, precipitation data for Vänersborg, Garn, and Göteborg were used in the analysis, together with turbidity data from Lärjeholm and Garn (Table 4). Also, data from the other five turbidity stations were employed in the analysis. A substantial amount of data was missing from Station Gäddebäck and it was not included in the analysis.

As expected, the discharges at the three measuring stations for river flow are highly correlated, since more than 90 % of the water in the studied stretch of the Göta Älv originates from lake Vänern and the flow in the river is strongly regulated. The opening and closure of the discharge shield in the Nordre Älv, the contribution from tributaries, and effects from a varying sea water level explain the somewhat weaker correlation between Q in the Göta Älv and Q at the Vargön hydropower plant. The data also show an increase in turbidity going south from Skräcklan (lake Vänern) to Garn, a decrease from Garn to Södra Nol, and an increase from Surte to Lärjeholm. This spatial variation in turbidity indicates that the amount of material entering the river from Vänern has a large influence on the turbidity in the river. Thus, material from erosion of the river bed and banks and from surface runoff, directly or through the tributaries, only gives a minor contribution to the base level of turbidity. The river widens a few kilometres upstream Södra Nol, and the lower mean turbidity recorded in Södra Nol may indicate some sedimentation in this area.

Correlation between the turbidity measured at the different stations yielded medium to high significance, with strong relationships for turbidity measured at adjacent stations. For example, the turbidity in Lärjeholm displays strong positive and significant correlation with the two closest (upstream) stations ($r = 0.72$, $r = 0.86$), indicating that turbidity in Lärjeholm is a function of the upstream turbidity. Södra Nol exhibited medium correlation to the upstream station Garn ($r = 0.50$). Except for Skräcklan, all stations have their lowest correlation with Garn. The river is quite narrow at Garn, implying higher velocities and possibly more sediment mobilisation than for other river stretches, which may affect the turbidity.

An important result is that the turbidity base level in the river is primarily a function of the inflow from lake Vänern, whereas daily fluctuations reflect the contributions from sources along the river. The temporal variation in the turbidity of the lake varies at a slower time scale than the contribution to the turbidity from downstream sources along the river because of the size of the lake and its upstream catchment.

Next step was to analyse single series events and three types were chosen for the analysis of the spatial variation. The types were: (1) a turbidity increase for several days at Skräcklan (from ~ 4 to 10 FNU) and a slight and not as evident increase in turbidity at the other stations, (2) a distinct turbidity increase for several days at Skräcklan (from ∼ 5 to 10 FNU) and distinct and high peaks at the other stations (from < 10 to 17–23 FNU), and (3) a distinct and high turbidity increase for several days at Skräcklan (from 3 to 20 FNU) and distinct increases at Garn and Lärjeholm (from < 5 to 14–25 FNU) and Surte (from 2 to 8 FNU) (not sufficient data for Södra Nol).

The higher the turbidity, the stronger the correlation proved to be between the turbidity measured at each station. The two first type of events encompassed medium-low discharge in the Göta Älv together with low-medium rainfall; thus, the discharge in the river and/or precipitation could alone explain the large peaks in turbidity. The third type had low-medium discharge but medium-heavy rainfall. Figure 8 illustrates the temporal variation in turbidity at the stations along the river (except Gäddebäck) during the second type of event, which is a typical when the input from lake Vänern (Skräcklan) is not dominant. A distinct and high increase is displayed at all stations, except at Skräcklan that showed moderate increase, with a tendency for the mean turbidity level to increase in the downstream direction.

An explanation for the turbidity peaks, although medium-low flows prevail, may be found by looking at the tributary flows, available at a weekly basis. The much higher tributary flows for the second and third type of event, in contrast to the main river flow, is a possible explanation for the higher turbidity peaks, as well as for the stronger and more significant correlation between turbidity at the gauging stations for these two types.

4.4 ANOVA

If more than two variables are measured simultaneously, repeated measures ANOVA may be employed. This technique was utilised in the present study, where P, Q and T for the main river were analysed in terms of the variances. Instead of analysing each day or month individually, P and Q were grouped into three classes in order to investigate turbidity variances with respect to P and Q. The variables were grouped into three classes that can be categorized as no (0 mm), medium (0.1–20 mm), and heavy (20.1–60 mm) rainfall, and low (98–150 $m^3 s^{-1}$), medium, (151–200 $m^3 s^{-1}$) and high (201–258 $m^3 s^{-1}$) discharge. Subsequently, a similar analysis was done for data from Garn (0 mm, 151–350 $m^3 s^{-1}$; 0.1–20 mm, 351–650 $m^3 s^{-1}$; 20.1–45 mm, 651–977 $m^3 s^{-1}$). Both main effect and factorial ANOVA were performed (Fig. 9).

The main effect ANOVA analysis clearly shows that discharge and precipitation influence the turbidity. The chosen discharge classes generate almost equally sized 95 % confidence level for turbidity, whereas the chosen precipitation classes generate larger 95 % confidence intervals with higher classes. This is explained by the fact that the *Q*-classes represent almost equal interval steps, which is not the case for *P*. It could also be caused by the small sample size for the highest *P*-class. The results from the factorial ANOVA analysis differ somewhat between Lärjeholm and Garn, but overall they indicate the following:

- Discharge in the main river has little impact on turbidity during dry periods (situations with no rain – *P* class 1).
- Discharge in the main river starts to influence turbidity during medium rainfall. High discharge has quite large impact on turbidity during medium rainfall, whereas medium and low discharge only has minor impact.
- Discharge has great impact on turbidity during heavy rainfall. High discharge has larger impact on turbidity during high rainfall.
- During low discharge, heavy rain has only a slight influence on turbidity.
- Rain intensity influences turbidity during medium discharge, but as for low discharge, it requires heavy rainfall.
- Rain intensity has large impact on turbidity during high discharge; the more intense rainfall the larger the impact.

These results illustrate the complexity in the dependencies and relationships between the variables studied. Periods of heavy rainfall are more sensitive to discharge variations than dry periods with regard to influencing the turbidity level. Similarly, periods of high discharge are more sensitive to rainfall intensity in terms of influencing the turbidity, although the confidence intervals for heavy rainfall are quite large. Nevertheless, the combination of heavy rain and high discharge generates the highest turbidity, but with the highest variability in turbidity, whereas the opposite applies for the combination of a dry period and low discharge.

5 Discussion

The results showed that there is no simple and general relationship between P, Q, and T for the river system. The basic reason for this is the complexity of the river system, where the sediment originates from multiple sources with releases strongly varying in time and space. In addition, the river regulation, and lake Vänern acting as a huge detention storage, obscures the dependencies between variables. The discharge from Vänern is regulated at three hydropower plants that completely determine the river flow. Precipitation has mostly an indirect impact on the flow in the river through the runoff to the lake and the discharge from the tributaries. More than 90 % (in some cases 95–98 %) of the river flow downstream the lake originates from the water in the lake.

If a large part of the turbidity measured in the river would be a result of resuspension and erosion of the material in the main river (i.e. from river bed and river banks), a strong positive correlation would have been obtained between Q and T. However, the analysis shows only a weak, although significant, correlation for most cases investigated. This indicates that the material supplied from the river bed and banks is a limited portion of the sediment transport in the river and that wash load probably dominates. Taking a time delay in the response of T to Q into consideration when performing the analysis only marginally improved the correlation. Analyses of time delays between T and P, or accumulated P, indicated that a certain amount of P is needed for a response in T, and that the duration of P has larger impact on T than the intensity of P. The local precipitation does not have any significant impact on the discharge in the main river. It was expected that series of events and extremes, including high discharge, high precipitation, or high turbidity would improve the correlations. However, it was found that explaining turbidity variations using simple measures of P and Q only is difficult. If the highest discharge events observed are investigated, medium significant correlation between T and WL is found, between WL and Q, but no significant correlation between T and Q. Thus, it indicates that neither Q nor P alone governs the variation in T. There seems to be somewhat stronger relationships between the variables during the winter season, but also a larger variability in general. One explanation for the larger variability in turbidity during winter can be the higher discharge variations combined with more variable vegetation cover of the land surfaces.

A clearer pattern emerges if T is analysed with respect to the spatial variation along the river, where T at a specific location in the river influences T downstream. The larger the magnitude of the turbidity peaks is, the stronger the correlation between adjacent gauging stations. During the winter season, stronger correlations for T are obtained between the gauging stations compared to the summer season. An important contribution to the differences in T between the stations, besides the erosion from the river bed and banks, is the transport from the tributaries. Analysis of single events indicated that discharge variations in these tributaries have a significant impact on T and how it varies in space and time. Furthermore, T displays stronger correlations to the discharges in the tributaries than to the discharge in the main river. A good correlation is observed between P and the tributary Q. Thus, Q in the small streams responds directly to rainfall, which generates runoff that brings sediment and organic matter from the surfaces to the tributaries and further out into the main river.

The amount of suspended sediment in lake Vänern governs to a large degree the base level of the turbidity in the river. Contributions from surface runoff and tributaries along the river, as well as erosion of the river bed and banks, increase T in the downstream direction. Since the changes in T for Vänern is slow, the erosion processes in the river, on surfaces, and in the tributaries most likely determines the high levels and variability in T.

The strong temporal persistence in T (shown through the autocorrelation analysis) indicates a response time scale for the system concerning the sediment transport of about 10 days. Although the tributaries displayed the strongest correlation with T, there should still be influences from Q and P. However, these relationships are complex and not easy to establish through the correlation analysis performed in this study. Another approach is analysis of variance (ANOVA), which was carried out with respect to T, Q, and P. ANOVA clearly indicated that during periods of heavy rainfall T are more sensitive to flow variations than during dry periods. Similarly, T during high flow periods seems to be more sensitive to rainfall intensity, although the confidence intervals for heavy rainfall are quite large. The combination of heavy rainfall and high discharge generate high T but with the largest variability, whereas the opposite applies for the combination of dry periods and low discharge. Occasions with high discharge and heavy rainfall cause flooding of adjacent floodplains and surface runoff from adjacent land surfaces, which brings particles, organic matter, nutrients (from cropland), fecals (from pasture land) and so on, into the river. In addition to such situations, sewage overflows are common. The study by Åström (2007) clearly indicated a relationship between turbidity, precipitation, and e-coli, where e-coli was representing the release of bacteria from pasture land and sewage overflows.

Thus, in the studied river system, where the hydropower stations govern the flow, the river water mainly originates from a large lake, and local bed and bank erosion, local surface runoff, and tributary discharge governs turbidity, simple relationships between Q, P, and T can only be found at specific occasions. The study by Tena et al. (2011) of the Ebro River showed that even though the river is regulated there is a direct linear relationship between suspended sediment concentration (as one part of turbidity) and discharge. It is hence possible that the weak relationship for river Göta Älv is not an effect of the regulation but of the buffering volume of lake Vänern, making the responses very slow.

To summarise, this study contributes with an increased understanding of the variation in turbidity and its causes, especially in regulated river systems, which is of importance for the prediction of both short- and long-term impact on water quality from rainfall events. Further studies are however needed to analyse the content of the turbidity and to find relationship between turbidity and suspended sediment concentration. This is of significance for the development of forecasting models.

6 Conclusions

A stepwise statistical analysis is a useful approach to understand how processes in natural systems are affected by human activities. In a heavy regulated river with the main river water originating from a large lake (reservoir), it is probably not relevant to establish sediment rating curves for predicting suspended sediment transport, since the relationship between flow and suspended sediment concentration is not as straightforward as in natural or less disturbed river systems.

In the system under study, neither flow nor precipitation alone can explain turbidity levels and their variation. Correlation between discharge and turbidity in the river Göta Älv can only be found during specific circumstances, for example, heavy rainfall combined with high discharge that generates higher turbidity levels, or dry periods with low discharge that generates low turbidity levels. It is possible that these heavy rain–high flow events mainly cause the bed and bank erosion in Göta Älv, or, overland erosion of temporarily flooded land areas.

The turbidity in the discharged water from lake Vänern generates a base level in turbidity of the river water, whereas river bed and bank erosion, local surface runoff, and tributary flow (overland flow erosion and tributary riverbed/-bank erosion) govern the variability and high levels of turbidity in the river. Autocorrelation analysis indicated a temporal persistence for the turbidity of about 10 days. The contribution from the river bed and bank erosion is difficult to distinguish in the turbidity data.

The observed seasonal variation in turbidity is probably an effect of changes in the vegetation coverage and properties, and temperature, influencing the concentration of suspended matter, colloids, and organisms.

A significant dependence between adjacent gauging stations for the turbidity was observed, especially during the winter season, most likely due to less vegetation and more decomposed organic matter in the runoff. Large turbidity peaks yielded strong correlation between the gauging stations.

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Table 1. Daily mean, standard deviation, and correlation based on daily averages over the year at Lärjeholm (years 2002–2007; correlation values in bold are significant at $p < 0.05$).

	Mean	Std. Dev.	P GöteborgA [mm d^{-1}]	Q Göta River [$\mathrm{m}^3\,\mathrm{s}^{-1}$]	WL Lilla Edet [m]
T Lärjeholm [FNU]	6.6	0.7	0.59	0.7	0.71
P GöteborgA [mm d^{-1}]	2.6	0.45		0.44	0.62
Q Göta River [$\mathrm{m}^3\,\mathrm{s}^{-1}$]	158	11.7			**0.96**
WL Lilla Edet [m]	1.5	0.1			

Table 2. Daily mean, standard deviation, and correlation based on daily mean data at Lärjeholm (years 2002–2007; correlation values in bold are significant at $p < 0.05$).

	Mean	Std. Dev.	P GöteborgA [mm d^{-1}]	Q Göta River [m^3 s^{-1}]	WL Lilla Edet [m]
T Lärjeholm [FNU]	6.6	3.5	**0.12**	**0.17**	**0.23**
P GöteborgA [mm d^{-1}]	2.6	5.3		−0.01	**0.08**
Q Göta River [m^3 s^{-1}]	158	28.4			**0.80**
WL Lilla Edet [m]	1.5	0.4			

Table 3. Monthly mean, standard deviation, and correlation for the three main tributaries together with discharge in the main river, precipitation, and water level (years 2004–2006; correlation values in bold are significant at $p < 0.05$).

	Mean	Std. Dev.	T Lärjeholm [FNU]	Q Slumpån [m^3 s^{-1}]	Q Lilla Edet [m^3 s^{-1}]	Q Gårdaån [m^3 s^{-1}]	Q Grönån [m^3 s^{-1}]	Q Göta Älv [m^3 s^{-1}]	P Garn [mm d^{-1}]	P GöteborgA [mm d^{-1}]	WL Lilla Edet [m]
T Garn [FNU]	5.2	2.7	**0.68**	**0.70**	**0.43**	**0.71**	**0.72**	**0.48**	**0.53**	**0.61**	**0.56**
T Lärjeholm [FNU]	6.9	2.2		**0.63**	**0.45**	**0.67**	**0.68**	**0.49**	**0.34**	**0.42**	**0.60**
Q Slumpån [m^3 s^{-1}]	5.7	4.8			**0.55**	**0.97**	**0.96**	**0.59**	**0.45**	**0.44**	**0.65**
Q Lilla Edet [m^3 s^{-1}]	475	176				**0.54**	**0.55**	**0.92**	-0.07	0.04	**0.92**
Q Gårdaån [m^3 s^{-1}]	0.9	0.72					**0.99**	**0.61**	**0.51**	**0.51**	**0.69**
Q Grönån [m^3 s^{-1}]	3	2.5						**0.61**	**0.50**	**0.50**	**0.70**
Q Göta Älv [m^3 s^{-1}]	155	20							0.05	0.18	0.90
P Garn [mm d^{-1}]	2.9	1.4								**0.89**	0.15
P GöteborgA [mm d^{-1}]	2.7	1.5									0.25
WL Lilla Edet [m]	1.4	0.3									

Table 4. Mean, standard deviation, and correlation for P, Q and T along the river and based on daily mean data (years 2004–2007; correlation in bold are significant at $p < 0.05$, casewise deletion of missing data).

	Mean	Std. Dev.	T Lärjeholm [FNU]	Q Vargön [m^3 s^{-1}]	Q Trollhättan [m^3 s^{-1}]	Q Lilla Edet [m^3 s^{-1}]	Q Göta Älv [m^3 s^{-1}]	P Vänersborg [mm d^{-1}]	P Garn [mm d^{-1}]	P Göteborg A [mm d^{-1}]
T Garn [FNU]	5.8	4.2	**0.69**	**0.22**	**0.22**	**0.27**	**0.31**	**0.12**	**0.16**	**0.14**
T Lärjeholm [FNU]	7	3.5		**0.13**	**0.12**	**0.16**	**0.16**	**0.06**	**0.11**	**0.09**
Q Vargön [m^3 s^{-1}]	495	214			**1.00**	**0.99**	**0.88**	−0.05	−0.05	**−0.07**
Q Trollhättan [m^3 s^{-1}]	495	217				**0.99**	**0.87**	−0.05	−0.05	**−0.07**
Q Lilla Edet [m^3 s^{-1}]	506	222					**0.90**	−0.03	−0.03	−0.05
Q Göta Älv [m^3 s^{-1}]	160	30.2						−0.02	−0.01	−0.02
P Vänersborg [mm d^{-1}]	2.3	4.8							**0.76**	**0.62**
P Garn [mm d^{-1}]	3	6.1								**0.76**
P Göteborg A [mm d^{-1}]	2.6	5.6								

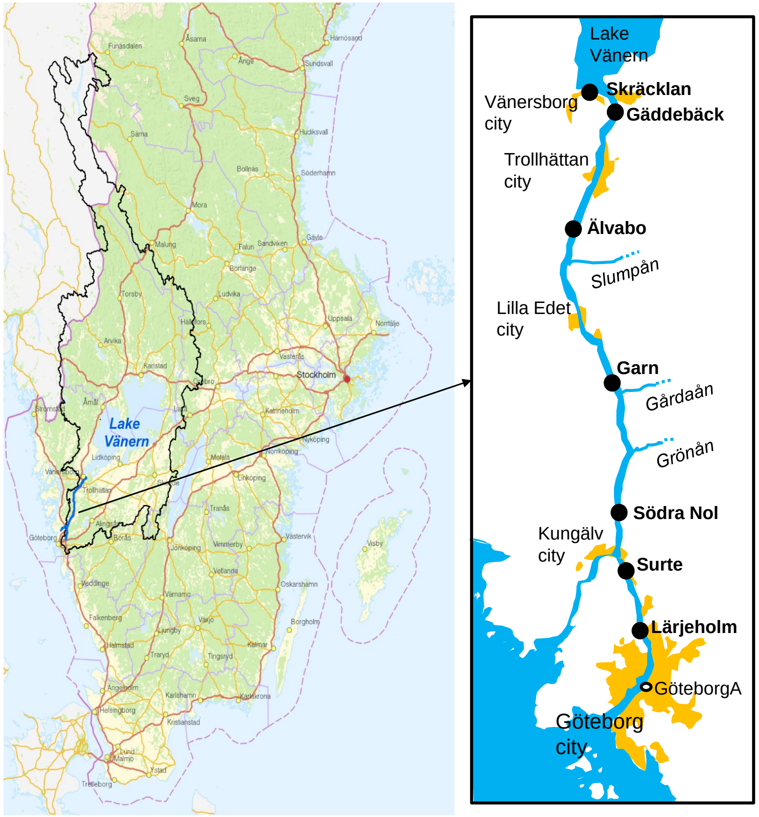

Fig. 1. The river Göta Älv catchment (left figure) and its stretch from lake Vänern to the sea, with seven stations for water quality monitoring and the outlets from three main tributaries shown (right figure). (Background map© Lantmäteriet, data from Swedish Meteorological and Hydrological Institute.)

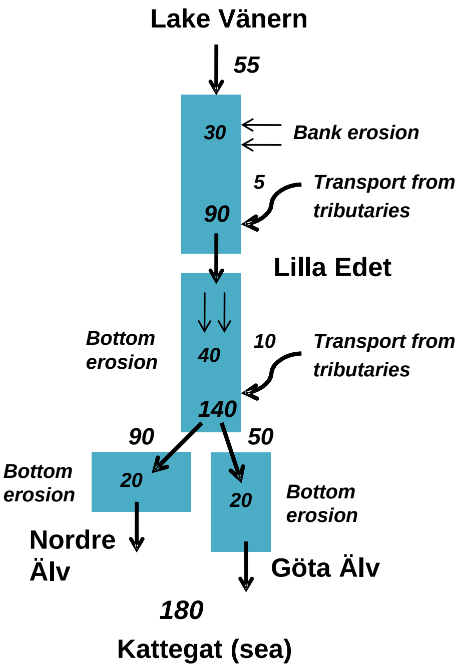

Fig. 2. Sediment budget for the river Göta Älv downstream lake Vänern (Rydell et al., 2011).

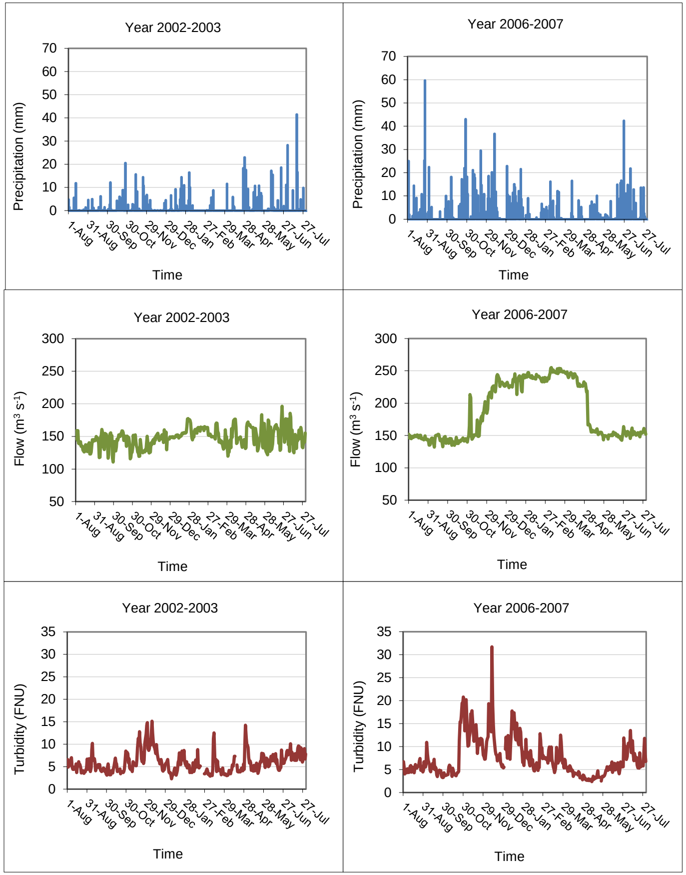

Fig. 3. Time series of precipitation, flow and turbidity in the southern branch of river Göta Älv and for the hydrologic years of 2002/3 and 2006/7.

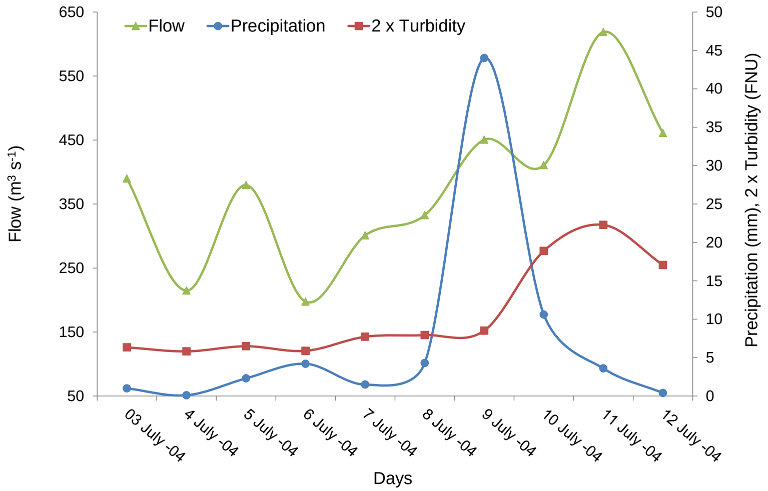

Fig. 4. Time series of daily mean values for precipitation, flow, and turbidity at Garn from 3 to 12 July 2004. Note that turbidity has been multiplied with 2 for a better resolution.

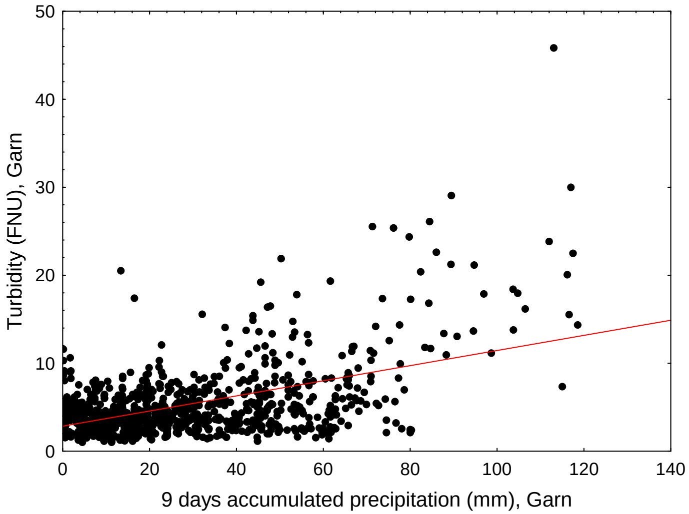

Fig. 5. Correlation between turbidity and 9 days of accumulated rain at station Garn ($r = 0.52$, $p < 0.05$), years 2004–2006.

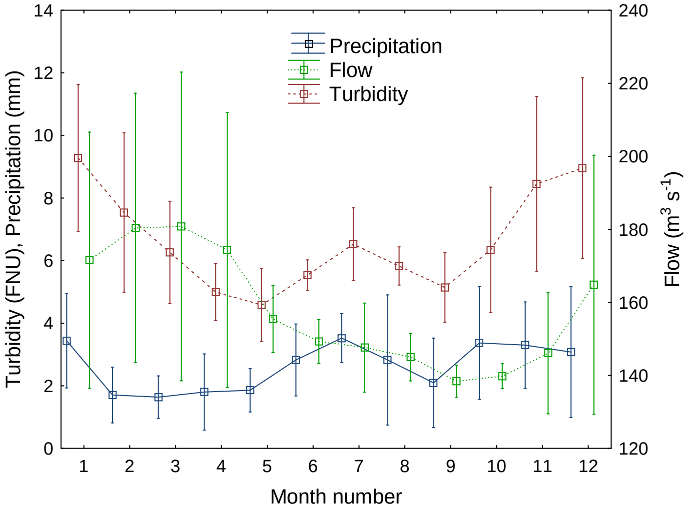

Fig. 6. Monthly mean for precipitation at station GöteborgA, flow in the river Göta Älv, the southern branch, and turbidity at station Lärjeholm, years 2002–2007.

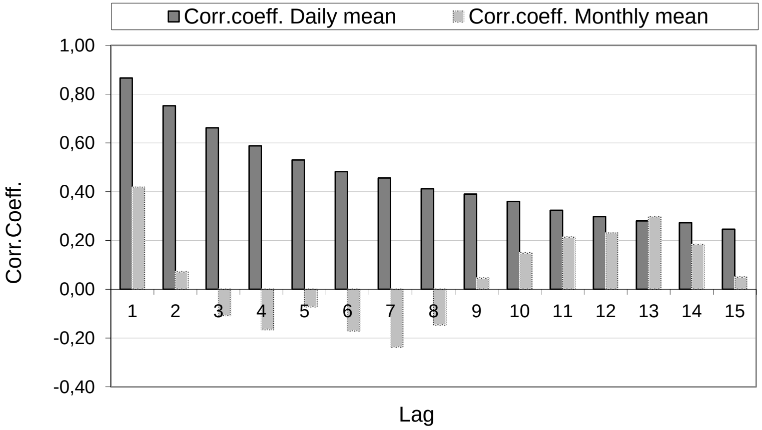

Fig. 7. Autocorrelation of turbidity at a daily and monthly basis, gauging station Lärjeholm, years 2002–2007.

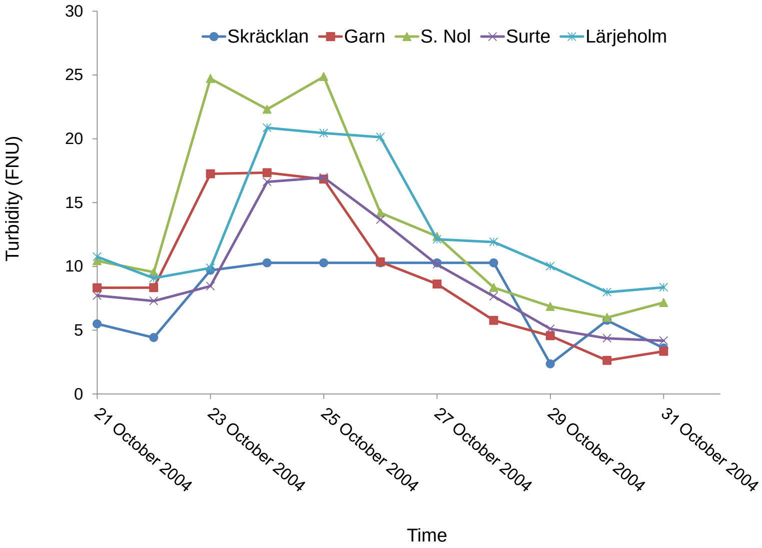

Fig. 8. Turbidity readings at five gauging stations, 21–31 October 2004. The figure illustrates the temporal variation in turbidity along the river.

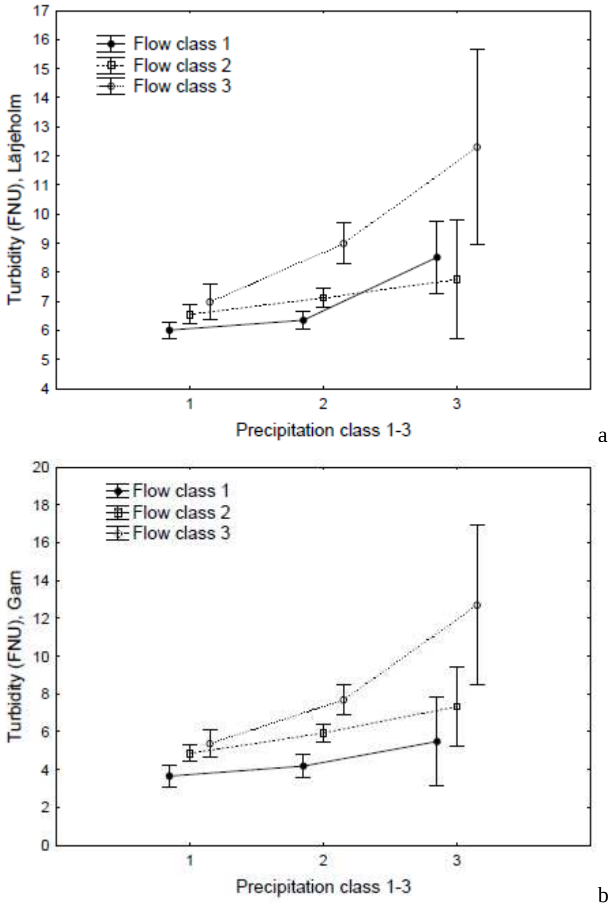

Fig. 9. Results of the ANOVA analysis for precipitation, discharge and turbidity measured at **(a)** Lärjeholm (years 2002–2007) and **(b)** at Garn (years 2004–2006); vertical bars denote 0.95 confidence intervals, $p < 0.05$.