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# TIME SERIES ANALYSIS OF UNEQUALLY SPACED OBSERVATIONS - WITH APPLICATIONS TO COPPER CONTAMINATION OF THE RIVER GAULA IN CENTRAL NORWAY

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**Abstract.** The upper parts of the river Gaula in Central Norway are heavily contaminated by toxic metals – particularily copper (Cu).

A monitoring program for the river was established in early 1986, and the concentration of Cu, among other variables, has been measured.

There is a fairly strong temporal component in the Cu measurements, which calls for some sort of time series model. The irregular pattern of the observation times, however, makes the usual models infeasible, as they assume equi-spaced observations.

In the paper we present a simple DLM (Dynamic Linear Model) which gives a satisfactory description of the Cu concentration series. The model is fitted to the data using a Kalman filter technique which handles the irregularly spaced observations without problems.

We have utilized the model to interpolate non-observed values, estimate the net loading and to simulate alternative patterns for the Cu series, observed values and the runoff, to obtain estimates of the extreme values and the probability that the concentration has exceeded a certain limit.

## 1. Introduction

The problem of estimating various characteristics (mean, median, etc.) of the concentration and/or loadings of various contaminants, given limited amounts of data, has been given considerable attention both from water chemists ans statisticians. The purpose of the present paper is to give a brief review of some more or less well known techniques, their advantages and their shortcomings, and to illustrate the techniques with an application from river Gaula in Central Norway.

The outline of the paper is as follows: In Section 2 we give a brief presentation of river Gaula and its surroundings. Section 3 describes the monitoring program. In Section 4 we introduce a framework for the statistical analysis, and present various approches to the estimation problems. Some results from river Gaula are shown in Section 5, while Section 6 gives a brief summary and some conclusions.

## 2. River Gaula – Some Background

This section gives a brief presentation of river Gaula and its watershed, with special emphasis on the factors that affect the contamination in the river.

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## 2.1. Geography and hydrology

River Gaula is the largest river in Central Norway when measured by the area of its watershed: 3653 $km^2$. The geographic location of the river and its watershed is shown in Figure 1. The length of the river is about 150 km, and it descends 800–900 m from source to mouth. There is approximately 6000 lakes of various sizes in the watershed. The lakes cover only 2.7% of the area, which is little compared to most rivers in Norway.

There are large variations in the runoff in Gaula, due to the climate, topography and the low percentage of lakes in the watershed. At Støren, in the lower part of the river, the mean runoff is 76.5 $m^3\ s^{-1}$, with an observed minimum of 2.2 $m^3\ s^{-1}$ and a maximum of 3060 $m^3\ s^{-1}$ during a disastrous flood in August 1940.

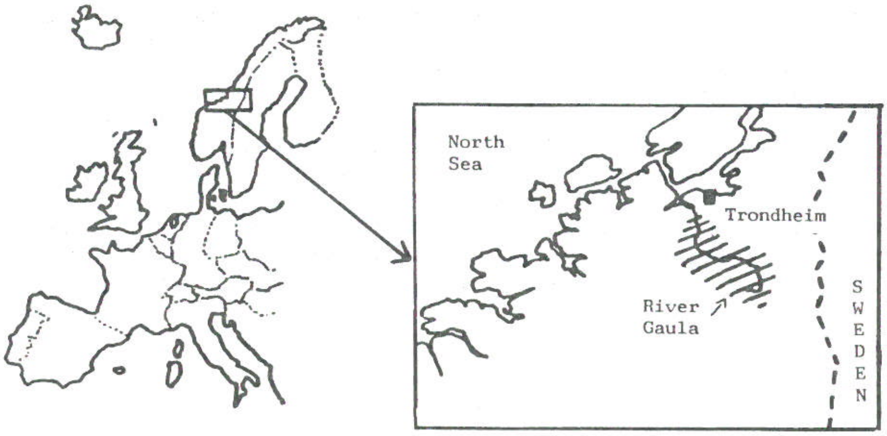


Fig. 1. Location of river Gaula and its watershed.

## 2.2. Fishing and recreation

Some of the most scenic parts of Norway may be found along Gaula. There are vast unspoiled areas of forests and mountains, and about 1500 private cabins. The lower parts of Gaula are among the most important salmon rivers in Norway, and the tributaries are excellent for trout and char. Due to the pollution from the old mines, described below, no fish can survive in the upper parts of the main river.

Due to its recreational qualities, some years ago Gaula was declared a conservation area by the Norwegian Parliament. This prohibits any further exploitation of the river for commercial purposes.

## 2.3. Mining

Kjøli and Killingdal copper mines are located near the head of the river. They were in operation for centuries, but are now closed. Kjøli has not been operating since 1941, while Killingdal was closed only recently – in 1986. The waste from the earlier production, however, still spills into the river, leading to serious contamination by heavy metals (Cu, Zn, Ca, Fe) and sulphates. No fish can survive in the most severely affected areas.

## 3. Monitoring Program

After Gaula was declared a conservation area, more concern was given to the pollution originating from the mines in the upper part as well as from human and agricultural sources further down the river. In 1986, the National Program for Pollution Monitoring thus started an investigation of Gaula. The main goal is to: "Describe the situation in the river so that the need for action may be evaluated, and to identify and quantify point source pollution, to decide where and what kind of actions that may be most effective". The investigation will be finished by the end of 1988.

The program is organized and carried out by the Norwegian Water Research Institute, in collaboration with local authorities. The Norwegian Computing Center is engaged to assist in the statistical analysis and the presentation of the results.

### 3.1. Stations, measurements and observation frequency

The measurements in the program are taken at 10 stations along the main river, and at 11 stations near the mouth of various affluent rivers. The locations of the stations on the main river are shown in Figure 2.

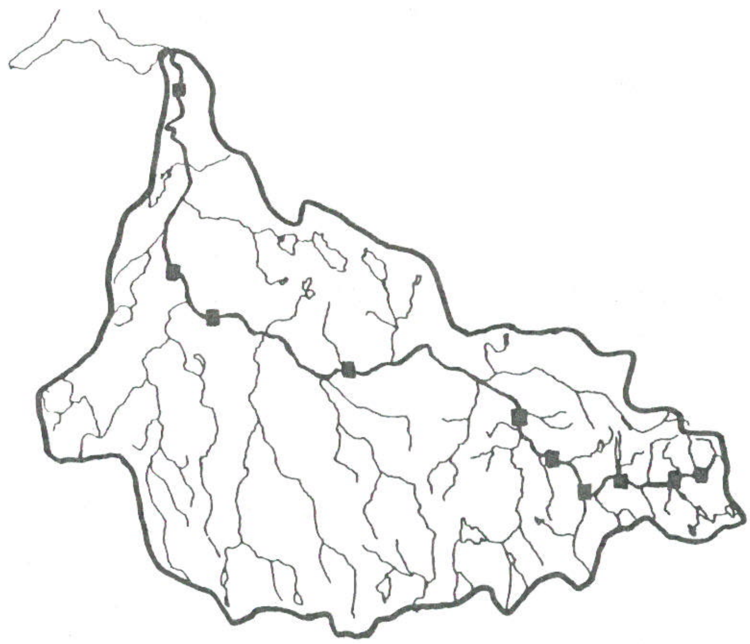

Fig. 2. Measurement stations along the main river.