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# Incorporating insights from Time Series Analysis in groundwater modelling for the urban area of the city of Amsterdam

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## Abstract
As the public water authority of the city of Amsterdam and surrounding areas, Waternet makes use of both steady-state and transient groundwater models for a variety of purposes involving urban groundwater management. For instance when determining the effect of planned measures on the occurrence of groundwater levels that are too low or too high, potentially resulting in degradation of wooden pile foundations or mold in houses, respectively. One of the challenges we face in that modelling, is the discrepancy between the physical processes that play a part in the city, influencing groundwater measurements, and the extent to which we are able to quantify those processes in groundwater models. We addressed this discrepancy with automated Time Series Analysis (TSA). In the over 3000 time series of groundwater measurements that were analyzed, TSA often identified one or more disturbances, such as groundwater extractions and measurement error. Along with identifying disturbances and artifacts, TSA offers a way to structurally address these issues. Incorporating (automated) TSA in generating model observations also results in a uniform, reproducible approach, and the ability to evaluate enormous amounts of monitoring wells. We argue that this approach is preferable to visual inspection and evaluation of measurement series, and discuss ways to incorporate these insights into groundwater models.

## Introduction
As the public water authority of the city of Amsterdam and surrounding areas, Waternet uses both steady-state and transient groundwater models for a variety of purposes involving urban groundwater management. For instance when determining the effect of planned measures on the occurrence of groundwater levels that are too low or too high, potentially resulting in degradation of wooden pile foundations or mold in houses, respectively. Other uses include reviewing permit applications for groundwater extraction for building pits, and determining the effectiveness of climate change mitigation measures. One of the challenges we face in that modelling, is the discrepancy between the physical processes that play a part in the city, influencing groundwater measurements, and the extent to which we are able to quantify those processes in groundwater models. While this discrepancy between groundwater models and measurements can be addressed manually, we opted for automated Time Series Analysis (TSA) (Chatfield 1975; Box and Jenkins 1970). In the over 3000 time series of groundwater measurements that were analyzed, TSA often identified one or more disturbances.

## Identifying measurement disturbances and artifacts through TSA
Both measurement disturbances (a physical process which influences measurements, but is not represented in the groundwater model), and artifacts (disturbances created by human error or computational methods) can be a cause for discrepancy between groundwater models and available measurements. In the case of steady-state models, these discrepancies and their origin may be further obscured because measurements are

aggregated into a single observation. Of course, these issues can be identified manually, but visual inspection for all monitoring wells is a time-consuming, tedious and subjective process. Waternet actively measures over 3000 phreatic monitoring wells and 300 monitoring wells in deeper aquifers, any of which can be subject to one or more of these disturbances. Additionally, reproducibility of analyses and results is of increasing importance, as upcoming legislation in the Netherlands will require argumentation when excluding available measurements from analysis (Ministerie van Infrastructuur en Milieu 2017). There are many different models that can be used for TSA. In this case, we used a basic AR1-model with rainfall and evaporation series as explanatory variables (Janse and Graafstra 2015). In order to deal with the effect of unequally spaced measurements on the TSA model, innovations were incorporated (Von Asmuth and Bierkens 2005).

Disturbances and artifacts that we were able to identify using TSA, are:

D1 Groundwater extractions (figure 1).
Amsterdam has relatively high groundwater levels. Because of this, building sites that include a subsurface component make use of extraction wells to temporarily lower the groundwater table at and around the building site. At any given time, numerous groundwater extractions of varying sizes are active in the city. The details necessary to include these components in groundwater models are often not available, but their effects may influence the groundwater measurements used as observations for groundwater models.

D2 The presence of leaky sewers (figure 2A).
The sewer system of Amsterdam is mostly located below the groundwater table. When parts of the system become damaged, they can drain groundwater from their surrounding area. Oftentimes, this starts as a gradual process. As the damage progresses, or other parts of the sewer in the vicinity become damaged as well, the lowering of the groundwater table becomes more pronounced. When leaky sewers are repaired, an increase of the groundwater table can often be seen.

D3 Measurement error (figure 2B).
These errors include read-out or typing errors, and measuring the wrong monitoring well.

D4 Varying measurement frequencies or gaps in a measurement series (figure 2C).
When measurement frequencies are not constant throughout the year or the entire modelling period, a single head based on the average of available measurements can lead to bias (Hill and Tiedeman 2007). Even weighted averaging may not always resolve this problem, when measurements are unavailable over an extended period of time. Especially when paired with other disturbances, such as leaky sewers (D2), differences in the years in which measurements are carried out can lead to artifacts in generated observations. Measurement data of monitoring well A may be carried out before the sewer started leaking, while monitoring well B has data available only after the leaking started.

<u>Addressing measurement disturbances and artifacts</u>

Along with identifying disturbances and artifacts, TSA offers a way to structurally address these issues. Information obtained from TSA models can be included in the groundwater model optimization process in one of the following ways, or a combination thereof:

S1 Adjusting observation weights based on residual analysis (figure 1).
By adjusting the weight of an observation as a function of the TSA model residual, less - or zero - emphasis can be put on sections of the series where, for instance, a groundwater extraction was present. This method can also be used to subsequently derive a (weighted) observation for a steady-state groundwater model.

S2 Decreasing the time-span of measurements used to calculate an average representative head (figure 2A).
When faced with measurement series displaying trends over time, using a subset of

the measurements when calculating a representative head will allow for a better (spatial) interpretation of the presence of, for instance, leaking sewers.

S3 Incorporating TSA model outcome as input for generating observations (figure 2C). The TSA model can be used as addition to, or even replacement of, the measurements used to generate groundwater model observations. Especially when dealing with varying measurement frequencies, this technique can be used to reduce bias.

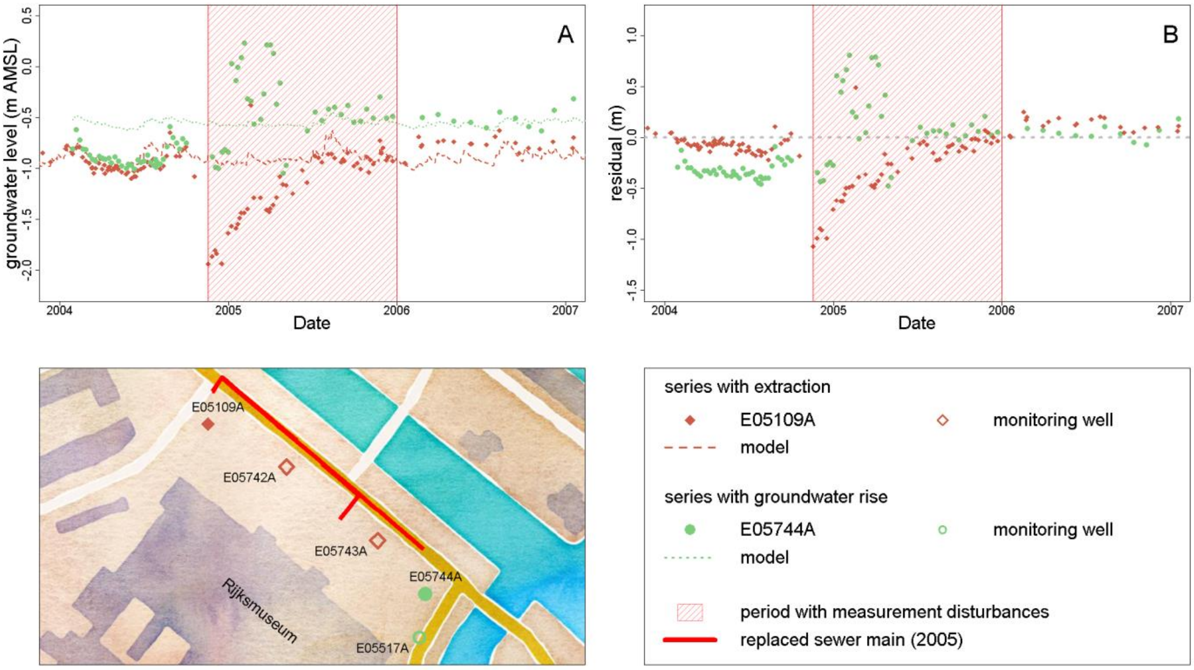


Figure 1: Identification of groundwater extractions (D1). A: Measurements and TSA model for monitoring well E05109A and E05744A. An extraction can be seen in the measurements of E05109A, while E05744 shows a rise in its groundwater table. The rise is caused by extracted water being infiltrated back into the aquifer a short distance from the site, reducing the risk of wooden foundation pile degradation. A distinct difference in groundwater level can be observed in the period before and after the extraction. B: Residuals can be used to adjust observation weights (S1). C: Five wells in an area where part of a sewer was replaced; three show a temporary lowering, and two a rise of the groundwater table.

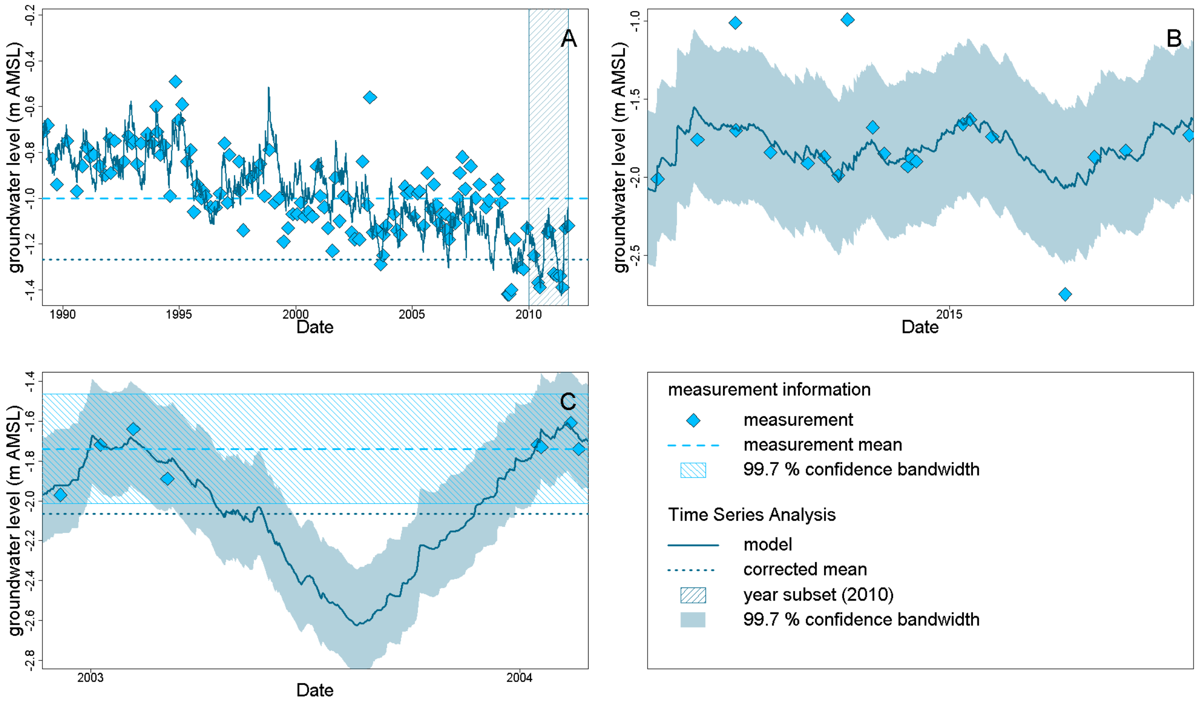


Figure 2: Identifying and addressing disturbances and artifacts. A: Identification of a leaky sewer (D2). The mean of a subset was calculated (AMSL -1.27 m in 2010), instead of the overall mean (AMSL -1.00 m). A difference of 27 cm seems minor, but the difference between too high and too low groundwater levels in Amsterdam, on average, is only 90 cm. B: Assessing the plausibility of measurements (D3). Three lie outside the 99.7 % confidence bandwidth, whose weights can be reduced or set to zero (S1). C: No measurements were available for the summer of 2003 (D4). A corrected mean of the entire series (2000-2006) was calculate (AMSL -2.07 m), instead of measurement mean (AMSL -1.74 m) (S3).

## Conclusion and discussion

Time Series Analysis (TSA) is not just a valuable tool when identifying measurement disturbances (D1-D2) and artifacts (D3-D4), but also when addressing them (S1-S3). Aside from qualitative advantages, incorporating (automated) TSA in generating model observations also results in a uniform, reproducible approach, and the ability to evaluate enormous amounts of monitoring wells. However, care must be taken in choosing the means by which to incorporate TSA when generating observations; leaning too heavily on TSA alone can polish away the capricious nature of a groundwater system, especially when the amount of measurements on which the TSA model is based, is limited.

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