Evaluation of the deviation from the annual natural water balance of urban areas – Proposition of a model approach

Évaluation de l'écart par rapport au bilan hydrique naturel annuel des zones urbaines - Proposition d'une approche de modélisation

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RÉSUMÉ

Le bilan hydrique des zones urbaines peut être très différent de celui des zones naturelles, comme les forêts. Cet écart peut être un indicateur des problèmes liés à l'eau dans les zones urbaines, comme les inondations, les sécheresses et le stress thermique. Pour quantifier la déviation du bilan hydrique par rapport à la référence naturel, un nouveau paramètre ΔW a été introduit pour résumer la déviation des composantes évaporation, ruissellement et infiltration. Le modèle de bilan hydrique “open source” ABIMO a été développé pour simuler ces trois composantes pour les zones urbaines. ABIMO a été appliqué à la ville de Berlin, y compris une validation réussie du modèle pour le ruissellement dans le système unitaire de Berlin. Les simulations utilisant ABIMO et les calculs de ΔW ont donné des résultats prometteurs pour Berlin, et peuvent être utilisées pour localiser les zones de forte déviation dans le bilan hydrique comme “hot spots” pour la mise en œuvre de l'infrastructure verte et bleue. Le modèle est disponible en libre accès, y compris les paquets R pour son application.

ABSTRACT

The water balance of urban areas can highly differ from natural areas, like forests. This deviation can be an indicator for water-related issues in urban areas, like floods, droughts and heat stress. To quantify the deviation of the water balance from a natural reference case, a new parameter ΔW was introduced to summarize the deviation of the components evaporation, surface runoff and infiltration. The open source water balance model ABIMO was further developed to simulate these three components for urban areas. ABIMO has been applied to the city of Berlin including a successful model validation for the surface runoff within the combined sewer system of Berlin. Simulations using ABIMO and computations of ΔW gave promising results for Berlin, and can be used to locate areas of high deviation in water balance as hotspots for the implementation of green and blue infrastructure. The model is openly available including R packages for its application.

KEYWORDS

ABIMO, AMAREX, rainwater management, urban climate, water balance

1 MOTIVATION & INTRODUCTION

The increasing frequency of extreme weather events due to climate change poses water-related issues around the world, including floods, droughts and heat stress. Urban areas are especially vulnerable to such issues due to high densities of infrastructure and impervious surfaces. Compared to natural spaces such as forests or meadows, these urban areas have a relatively low evapotranspiration, a slightly reduced ground water recharge and a high (sewered) surface runoff from precipitation (Fletcher et al., 2013; Uhl et al., 2013). In turn, this change in the natural water balance due to urbanization is closely linked to the above issues; for instance, the direct runoff leads to flooding (Fletcher et al., 2013; Zhou, 2019) and a lack in evaporative cooling leads to heat islands (Argüeso et al., 2014). Given this link, a new German technical guideline (DWA, 2022) proposes "the deviation from the natural annual water balance" as a planning criteria to minimize water related climate impacts in urban areas.

Following this intuitively correct approach, the natural and urban water balances were compared for the German city of Berlin, proposing a deviation index ΔW [%] combining the three components infiltration, evaporation and runoff. The work was performed based on the landscape water balance model ABIMO, originally developed by the German Federal Institute for Hydrology (Glugla and König, 1989) and further developed to simulate the urban water balance of Berlin. The model has been made transferable to other cities as an open source tool within the project AMAREX.

2 METHODOLOGY

2.1 Methodology of ABIMO

The model ABIMO calculates the three components of the annual local water balance based on data on precipitation and potential evaporation, land use, imperviousness, connectivity as well as soil- and groundwater specifications. In a first step real evapotranspiration is computed using the Bagrov equation (Glugla et al., 1999). In a second step the difference between the real evapotranspiration and the precipitation is split up between infiltration and surface runoff, based on soil and groundwater conditions, as well as the degree of surface imperviousness and sewer connectivity (Rachimow and Rachimow, 2009), (Goedecke et al., 2019).

All geographic input data is based on the geoportal Berlin (Senatsverwaltung für Stadtentwicklung, 2022). For precipitation and potential evaporation data monthly 1x1 km raster data by DWD (DWD, 2022) was aggregated for single years or the 30-year interval from 1991-2020.

2.2 Validation of ABIMO

ABIMO has been validated for the runoff component using annual data of waste water treatment plants (WWTP) receiving waste water and storm water from the combined sewer system (about 60 km^2 of impervious, connected area) in the city centre of Berlin. The amount of annual rainwater could be determined by subtracting the extrapolated dry weather runoff from the total runoff. In order to estimate the amount of surface runoff at the entry point of the sewer system, the combined sewer overflow volume (extrapolated from a simulation by Berliner Wasserbetriebe for an average climatic year) has been added to the rainwater that arrived at the waste water treatment plant. Data from the WWTP were available for the years from 2007 to 2021. ABIMO has been run for annual precipitation and potential evaporation data for these years and its results being compared with the manually calculated stormwater quantities.

2.3 Quantifying the water balance deviation

The deviation ΔW of the water balance of an urban area from the natural conditions was calculated as a pairwise comparison of the three water balance components (evapotranspiration, surface runoff and infiltration):

$$\Delta W = \frac{1}{2} * (|ev_{nat} - ev_{urb}| + |ri_{nat} - ri_{urb}| + |rs_{nat} - rs_{urb}|) * \frac{100\%}{precipitation}$$

where ev_{nat} and ev_{urb} are the evapotranspiration, ri_{nat} and ri_{urb} are the infiltration and rs_{nat} and rs_{urb} are the surface runoff for the natural reference as well as urban area, respectively. The new measure ΔW reduces the complexity when comparing the water balance for various areas as well as climate scenarios.

3 RESULTS AND USEABILITY

3.1 First Results

ABIMO has been used for simulating the urban water balance of Berlin since the project start of AMAREX. Apart from the validation of ABIMO, sensitivity analyses for climate scenarios and certain city structures have been conducted and ΔW was simulated for the city of Berlin.

The validation explained in Section 2.2 for the years 2007-2021 has shown a tendency of ABIMO to overestimate the surface runoff compared to the manual calculation by a MAPE of 17.7 %. This overestimation is expected, since measures of stormwater management such as green roofs or infiltration are not yet considered in the model. Moreover, two uncertain estimates of the stormwater runoff are compared. Uncertainties in the manual calculation from WWTP data are also significant, especially for the estimation of combined sewer overflow. However, a coefficient of determination R2 of 0.91 shows that both estimates show a reasonable sensitivity to annually changing climate.

Figure 1 shows a comparison between natural and current urban conditions for 25,325 blocks in Berlin (excluding surface waters). As expected, urbanization leads to an increase in runoff at the cost of evapotranspiration. Infiltration does not differ greatly. The reason are semi-permeable surfaces (e.g. cobbles stones) that allow infiltration but very little evaporation.

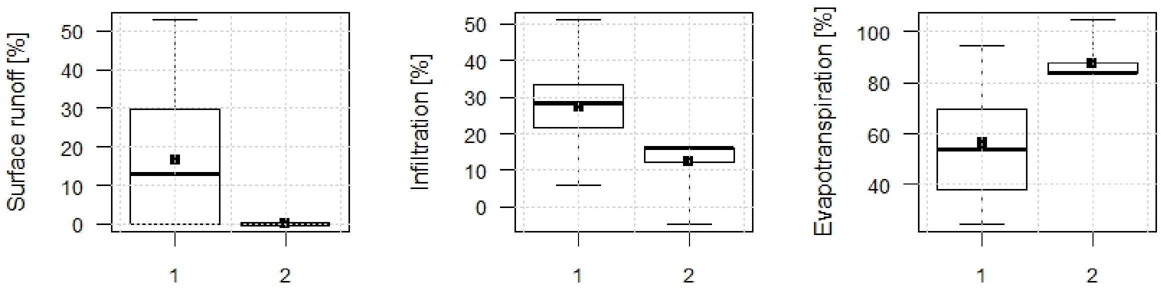

Figure 1: Comparison of the German city of Berlin (1) and a natural reference (2) for the three water balance components: surface runoff, infiltration and evapotranspiration ; boxplots represent a 30 years average from 1991 to 2020 and show a statistical distribution over 25,325 blocks in Berlin

Figure 2 presents the results of computing ΔW for a climate average of 30 years from 1990 until 2021 using ABIMO. The figure shows higher percentage values above 40 % (in red tones) for the dense and highly impervious inner city and lower values below 40 % (in blue tones) for outer districts as well as forests, parks and water bodies.

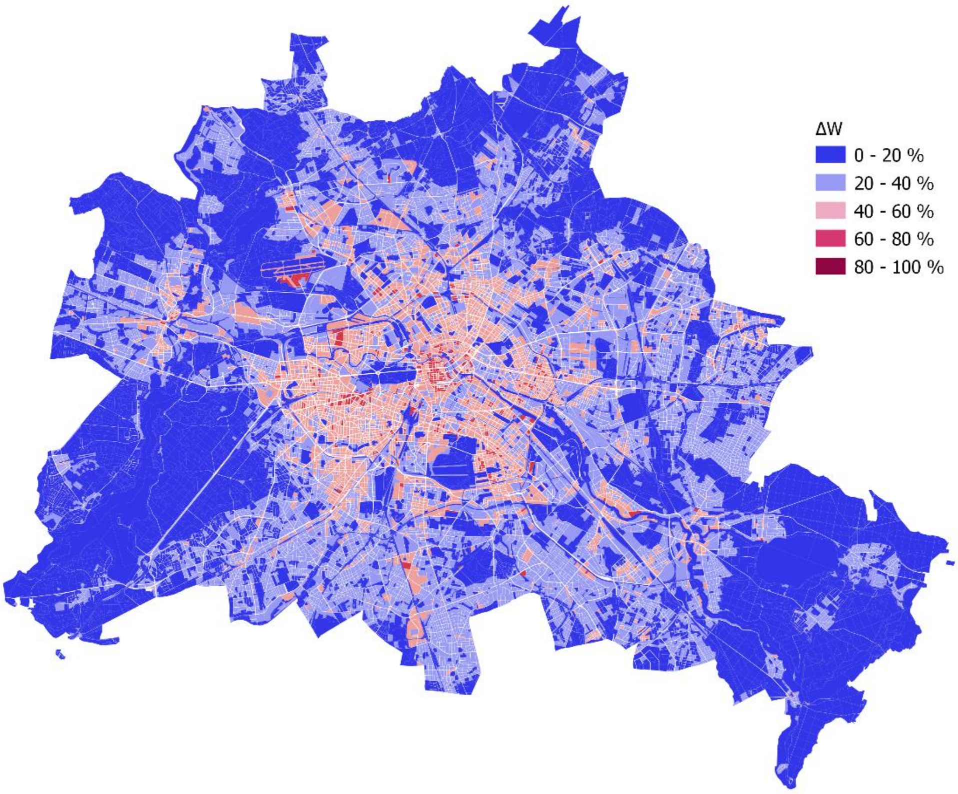

Figure 2: Deviation of water balance of each block partial area of Berlin from the natural water balance

3.2 Releases of ABIMO

The source code of the water balance model ABIMO is based on the programming language C++ and an open source project. The latest release before the start of the project AMAREX is ABIMO 3.2 and has been published on GitHub by Umweltatlas Berlin (Umweltatlas, 2022). The further development of ABIMO by KWB within the project AMAREX brought a new release of ABIMO 3.3 onto GitHub by KWB (KWB, 2022a). Compared to the previous version, ABIMO is now accessible through batch mode on Microsoft Windows command line. Additionally, KWB also released a toolbox package for ABIMO based on the programming language R on GitHub (KWB, 2022b) that contains a model wrapper to easily modify input data and to run simulations from within an R-script.

4 CONCLUSIONS AND OUTLOOK

The presented water balance model ABIMO is capable of simulating the components of the water balance for urban areas. The model was validated by comparing its results with long-term measurements of surface runoff from annual precipitation at waste water treatment plants of Berlin. Regarding the fact that stormwater management infrastructure including green covering of roofs is not considered yet within ABIMO. Hence, the slight overestimation of surface runoff with a MAPE of 17.7 % by ABIMO compared to the measured data is reasonable. First implementations of the newly introduced parameter ΔW gave promising results in representing the water balance deviation from the natural reference case. ΔW makes it possible to quantify and evaluate the total water balance deviation in only one parameter and can indicate the need for green and blue infrastructure for climate adaptation.

Major upcoming developments of ABIMO include the integration of stormwater management infrastructure into the model and making ABIMO accessible through a webtool. This will assist city planners, public authorities and citizens in making decisions about their city's stormwater management. Furthermore, ABIMO will be implemented for the city of Cologne and other cities are in the scope.

5 ACKNOWLEDGEMENTS

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