TECHNISCHE UNIVERSITÄT DRESDEN

Fakultät Umweltwissenschaften, Institut für Hydrologie und Meteorologie

DEVELOPMENT OF A SEMI-AUTOMATIC APPROACH TO ESTIMATE PRE-EVENT SOIL MOISTURE FOR FLASH FLOOD GUIDANCE IN LOW MOUNTAIN RANGES (SAXONY)

Cumulative Dissertation to achieve the academic degree of

Doctor rerum naturalium (Dr.rer.nat)

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Submitted on

15.01.2022

ERKLÄRUNG DES PROMOVENDEN

Die Übereinstimmung dieses Exemplars mit dem Original der Dissertation zum Thema: „ Development of a semi-automatic approach to estimate pre-event soil moisture for Flash Flood Guidance in low mountain ranges (Saxony)."

wird hiermit bestätigt.

Tharandt,

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Abstract/Zusammenfassung/Tóm tắt

This thesis is written as a cumulative dissertation based on peer-reviewed papers and supplemented by yet unpublished results. It presents methods and results that contribute to a novel approach for estimating water storage within the soil-water-plant system at a single site or in a small catchment (< 100 km^2). The focus is on estimating the current/pre-event condition of a study area using simulated soil moisture and applying it as an indicator for flash flood forecasting. These two steps were combined in a semi-automatic framework that was used as a tool for flash flood monitoring after the Flash Flood Guidance (FFG) concept. This includes catchments for which Hydro-meteorological data and reliable site characteristics are not available. The overall objective was to demonstrate the capabilities and limitations of the regionally applicable modeling framework based on a lumped-physical model and open-source input data. The questions to be answered are: How reliable are the model outputs estimated by an uncalibrated-lumped model based on regional parameterization and forcing data? What are the potential uncertainties and limitations of such a framework? What are the potential applications of water storage in flood monitoring? The data were derived from freely available datasets. Meteorological input data can come from various sensor networks integrated in an open sensor web, mainly from the German Meteorological Service (DWD) and e.g., the forest climate stations of Sachsenforst. The model description required datasets for elevation (10 m, State Office for Environment, Agriculture and Geology-LfULG), land cover (Copernicus: Land Cover 100m), soil characteristics (BK50, LfULG) and soil profiles from the German National Forest Inventory (NFI). In addition, satellite-based soil moisture product (SMAP-L4-GPH from the National Aeronautics and Space Administration-NASA), water gauges data (LfULG) and eddy covariance flux cluster sites of the chair Meteorology at TU Dresden were used for validation.

The first publication provides the framework and elaborates on the integration of a model into the open-data platform. The BROOK90 model (R version) was embedded in an open sensor web to estimate daily water balance components for more than 6,000 (sub-) catchments in Saxony. The model performance was validated with stream gauge observations in ten selected head catchments for discharge and with SMAP-L4-GPH for evapotranspiration and soil moisture. The results indicate that the framework is able to provide reliable soil retention estimates in high resolution.

The second publication addresses the potential use of radar precipitation in this framework. Here the focus is on examining long-term radar-derived precipitation to improve water balance estimates due to its advantages in spatial coverage. The DWD's re-analysis radar product, RADKLIM, was applied and aggregated for daily model input. A comparison between radar and rain gauge precipitation was performed to evaluate the quality of the product at the study sites, including the compensation for the catch loss in precipitation using the Richter correction. The results show the satisfactory performance of the framework with radar precipitation.

The third publication demonstrates the application of model output to flood warnings. FFG was modified and applied to estimate rainfall thresholds considering the effects of antecedent soil moisture. Once rainfall threshold curves are calculated, only information on rainfall and soil moisture information is needed to issue a warning of a potential flash flood. The method was applied in the Wernersbach catchment in the Tharandt Forest and validated with historical events. The results of the contingency table show the potential of this tool for flash flood warning, but it should be tested with other rainfall runoff models and more catchments prone to flash floods.

Zusammenfassung

Die vorliegende Arbeit ist eine kumulative Dissertation, die auf begutachteten Arbeiten basiert und durch bisher unveröffentlichte Ergebnisse ergänzt wird. Sie stellt Methoden und Ergebnisse vor, die zu einem neuartigen Ansatz zur Abschätzung der Wasserspeicherung im System Boden-Wasser-Pflanze an einem einzelnen Standort oder in einem kleinen Einzugsgebiet (< 100 km^2) beitragen. Der Schwerpunkt liegt auf der Abschätzung des aktuellen/vor einem Ereignis herrschenden Zustands eines Untersuchungsgebiets unter Verwendung simulierter Bodenfeuchte und deren Anwendung als Indikator für die Vorhersage von Sturzfluten. Diese beiden Schritte wurden in einem halbautomatischen Modell zusammengefasst, das als Werkzeug für die Überwachung von Sturzfluten nach dem Konzept des Flash Flood Guidance (FFG) verwendet wird. Dies schließt Standorte/Einzugsgebiete ein, für die keine hydrometeorologischen Daten und/oder zuverlässige Standortmerkmale verfügbar sind. Das Gesamtziel bestand darin, die Fähigkeiten und Grenzen des regional anwendbaren Modells auf der Grundlage eines pauschalen physikalischen Modells und von Open-Source-Eingangsdaten zu demonstrieren. Die zu beantwortenden Fragen lauten: Wie zuverlässig sind die von einem unkalibrierten eindimensionalen Modell auf der Grundlage regionaler Parametrisierungs- und Antriebsdaten geschätzten Modellergebnisse? Was sind die potenziellen Unsicherheiten und Grenzen eines solchen Modells? Welches sind die möglichen Anwendungen der simulierten Komponenten des Wasserhaushalts bei der Überwachung von Hochwasser? Die Daten werden aus frei verfügbaren Datensätzen abgeleitet. Die meteorologischen Eingangsdaten stammen aus verschiedenen Sensornetzwerken, die in einem Open Sensor Web integriert sind, hauptsächlich vom Deutschen Wetterdienst (DWD) und z.B. den Waldklimastationen von Sachsenforst. Für die Modellbeschreibung wurden Datensätze für Geländehöhe (10 m, Landesamt für Umwelt, Landwirtschaft und Geologie - LfULG), Landbedeckung (Copernicus: Land Cover 100m), Bodeneigenschaften (BK50, LfULG) und Bodenprofile aus der Bundeswaldinventur (BWI) benötigt. Darüber hinaus werden satellitengestützte Bodenfeuchteprodukte (SMAP-L4-GPH der National Aeronautics and Space Administration-NASA), Pegeldaten (LfULG) und Eddy-Kovarianz-Flusscluster-Standorte des Lehrstuhls für Meteorologie der TU Dresden zur Validierung verwendet.

Die erste Veröffentlichung liefert den Rahmen und erläutert die Integration eines Modells in die offene Datenplattform. Das Modell BROOK90 (R-Version) wurde in ein offenes Sensornetz eingebettet, um tägliche Wasserhaushaltskomponenten für mehr als 6,000 (Teil-)Einzugsgebiete in Sachsen zu schätzen. Die Leistung des Modells wurde anhand von Pegelbeobachtungen in zehn ausgewählten Einzugsgebieten für den Abfluss und mit SMAP-L4-GPH für die Evapotranspiration und Bodenfeuchte validiert. Die Ergebnisse zeigen, dass das System in der Lage ist, zuverlässige Schätzungen der Bodenretention in hoher Auflösung zu liefern.

Die zweite Veröffentlichung befasst sich mit der möglichen Nutzung von Radarniederschlägen in diesem Rahmen. Hier liegt der Schwerpunkt auf der Untersuchung des langfristigen, vom Radar abgeleiteten Niederschlags zur Verbesserung der Wasserbilanzschätzungen aufgrund seiner Vorteile bei der räumlichen Abdeckung. Das Reanalyse-Radarprodukt des DWD, RADKLIM, wurde verwendet und für tägliche Modelleingaben aggregiert. Es wurde ein Vergleich zwischen Radar- und Regenmesser-Niederschlag durchgeführt, um die Qualität des Produkts an den Untersuchungsstandorten zu bewerten, einschließlich der Kompensation des Niederschlagsverlusts durch die Richter-Korrektur. Die Ergebnisse zeigen die zufriedenstellende Leistung des Rahmens mit Radarniederschlag.

Die dritte Veröffentlichung demonstriert die Anwendung der Modelldaten auf Hochwasserwarnungen. Der Leitfaden für Sturzflutwarnungen wurde modifiziert und zur Schätzung der Niederschlagsschwellen unter Berücksichtigung der Auswirkungen der vorherrschenden Bodenfeuchte angewandt. Sobald die Niederschlagsschwellenkurven berechnet sind, werden nur noch Informationen über Niederschlag und Bodenfeuchte benötigt, um eine Warnung vor einer möglichen Sturzflut auszusprechen. Die Methode wurde im Einzugsgebiet des Wernersbachs und im Tharandter Wald angewandt und mit historischen Ereignissen validiert. Die Ergebnisse der Kontingenztabelle zeigen das Potenzial dieses Werkzeugs für die Sturzflutwarnung, es sollte jedoch mit anderen Niederschlagsabflussmodellen und weiteren Einzugsgebieten, die für Sturzfluten anfällig sind, getestet werden.

Tóm tắt

Luận án tiến sĩ này được viết như một luận án tích lũy dựa trên các bài báo đã được bình duyệt và được bổ sung bởi các kết quả chưa được công bố. Nó trình bày các phương pháp và kết quả góp phần vào một cách tiếp cận mới để ước tính trữ lượng nước trong hệ thống đất-nước- thực vật tại một địa điểm hoặc trong một lưu vực nhỏ (<100 km^2). Trọng tâm là ước tính tình trạng hiện tại / trước sự kiện của khu vực nghiên cứu bằng cách sử dụng độ ẩm đất mô phỏng và áp dụng nó như một chỉ báo để dự báo lũ quét. Hai bước này được kết hợp trong một khuôn khổ bán tự động được sử dụng như một công cụ để giám sát lũ quét dựa theo khái niệm Hướng dẫn về lũ quét (FFG). Điều này bao gồm các địa điểm / lưu vực không có sẵn dữ liệu khí tượng thủy văn và / hoặc các đặc điểm thiếu thông tin mô tả chia tiết đáng tin cậy. Mục tiêu tổng thể là chứng minh các khả năng và hạn chế của khung mô hình áp dụng trong khu vực dựa trên một mô hình vật lý tổng hợp và dữ liệu đầu vào nguồn mở. Các câu hỏi cần được trả lời là: Các kết quả đầu ra của mô hình được ước tính bằng một mô hình gộp chưa hiệu chỉnh dựa trên tham số vùng và dữ liệu đáng tin cậy đến mức nào? Những điểm không chắc chắn và hạn chế tiềm ẩn của một khuôn khổ như vậy là gì? Các ứng dụng tiềm năng của thành phần cân bằng nước mô phỏng trong giám sát lũ lụt là gì? Dữ liệu được lấy từ các bộ dữ liệu miễn phí và có sẵn. Dữ liệu đầu vào về khí tượng đến từ các mạng cảm biến khác nhau được tích hợp trong một Open Sensor Web, chủ yếu từ Cơ quan Khí tượng Đức (DWD) và các trạm khí hậu rừng của Sachsenforst. Mô tả mô hình yêu cầu bộ dữ liệu về độ cao (10 m, Văn phòng bang về Môi trường, Nông nghiệp và Địa chất-LfULG), lớp phủ đất (Copernicus: Land Cover 100m), đặc điểm của đất (BK50, LfULG) và cấu hình đất từ Kiểm kê Rừng Quốc gia Đức (NFI). Ngoài ra, sản phẩm độ ẩm của đất dựa trên vệ tinh (SMAP-L4-GPH từ Cơ quan Hàng không và Vũ trụ Quốc gia-NASA), dữ liệu các trạm thủy văn (LfULG) và các cụm địa điểm eddy covariance được giám sát bởi khoa Khí tượng học tại TU Dresden được sử dụng để xác nhận kết quả mô hình đầu ra.

Ấn phẩm đầu tiên cung cấp khuôn khổ và trình bày chi tiết về việc tích hợp một mô hình vào nền tảng dữ liệu mở. Mô hình BROOK90 (phiên bản R) được nhúng vào một trang web cảm biến mở để ước tính các thành phần cân bằng nước hàng ngày cho hơn 6000 lưu vực (phụ) ở Sachsen. Hiệu suất của mô hình đã được xác nhận với các quan sát bằng dữ liệu dòng chảy ở mười lưu vực đầu nguồn được chọn và với SMAP-L4-GPH cho thành phần thoát hơi nước và độ ẩm của đất. Kết quả chỉ ra rằng khung có thể cung cấp các ước tính đáng tin cậy về khả năng giữ nước của đất ở độ phân giải cao.

Ấn phẩm thứ hai đề cập đến khả năng sử dụng lượng mưa radar trong khuôn khổ này. Ở đây, trọng tâm là kiểm tra lượng mưa dài hạn có nguồn gốc từ radar để cải thiện ước tính cân bằng nước do lợi thế của nó trong phạm vi bao phủ không gian. Sản phẩm radar phân tích lại của DWD, RADKLIM, đã được áp dụng và tổng hợp để nhập mô hình hàng ngày. So sánh giữa lượng mưa bằng radar và máy đo mưa đã được thực hiện để đánh giá chất lượng của sản phẩm tại các điểm nghiên cứu, bao gồm cả việc bù đắp cho lượng mưa thất thoát bằng cách sử dụng hiệu chỉnh độ Richter. Kết quả cho thấy hiệu suất khả quan của khung với lượng mưa radar.

Ấn phẩm thứ ba trình bày việc áp dụng đầu ra mô hình để cảnh báo lũ lụt. Hướng dẫn về lũ quét đã được sửa đổi và áp dụng để ước tính ngưỡng lượng mưa xem xét ảnh hưởng của độ ẩm đất trước đây. Khi đường cong ngưỡng mưa được tính toán, chỉ cần thông tin về lượng mưa và thông tin về độ ẩm của đất để đưa ra cảnh báo về khả năng xảy ra lũ quét. Phương pháp này đã được áp dụng ở lưu vực Wernersbach, trong Rừng Tharandt và được xác nhận với các sự kiện lịch sử. Kết quả của bảng dự phòng cho thấy tiềm năng của công cụ này để cảnh báo lũ quét, nhưng nó nên được thử nghiệm với các mô hình dòng chảy lượng mưa khác và các lưu vực dễ xảy ra lũ quét hơn.

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1. Introduction

1.1 Motivation and scope

The continuous warming of the atmosphere due to climate change leads to an intensification of the hydrological cycle and thus to an increased variability of future climates (Borga et al., 2011; Gebrechorkos et al., 2019; Menzel and Thieken, 2006). Therefore, a higher probability of occurrence of extreme events – such as dry periods (Andreadis and Lettenmaier, 2006; Boeing et al., 2021; Hanel et al., 2018), but also more intense precipitation events (heavy rain and hail) (Lengfeld et al., 2021; Müller et al., 2009; Schumacher, 2016) and the resulting hydrological extreme events such as flash floods (Borga et al., 2011), landslides (Kalcic et al., 2015) and mudslides must be expected in the years to come. Similar studies have already been carried out for Saxony (Görner et al., 2009; Schwarze et al., 2016) and an increase in the frequency and intensity of heavy rainfall events has been forecasted, particularly in the Ore Mountains and its low mountain ranges (Philipp et al., 2008; Wahren et al., 2007). These developments lead to increased future risks for the population and the economy such as infrastructure and the industry sector.

Several damage-intensive extreme events have already occurred in the last century (Figure 1). In Saxony, for example, there were significant flood events in 2002, 2010 and 2013, exceptionally dry periods in 2003, 2018 -2020 and repeated small-scale extreme events triggered by heavy rainfall (Marchi et al., 2010; Müller et al., 2009). Due to the high social and economic relevance, there is an increased need for research on the occurrence of these extreme events, their prediction and suitable adaptation measures, which are currently not sufficiently covered.

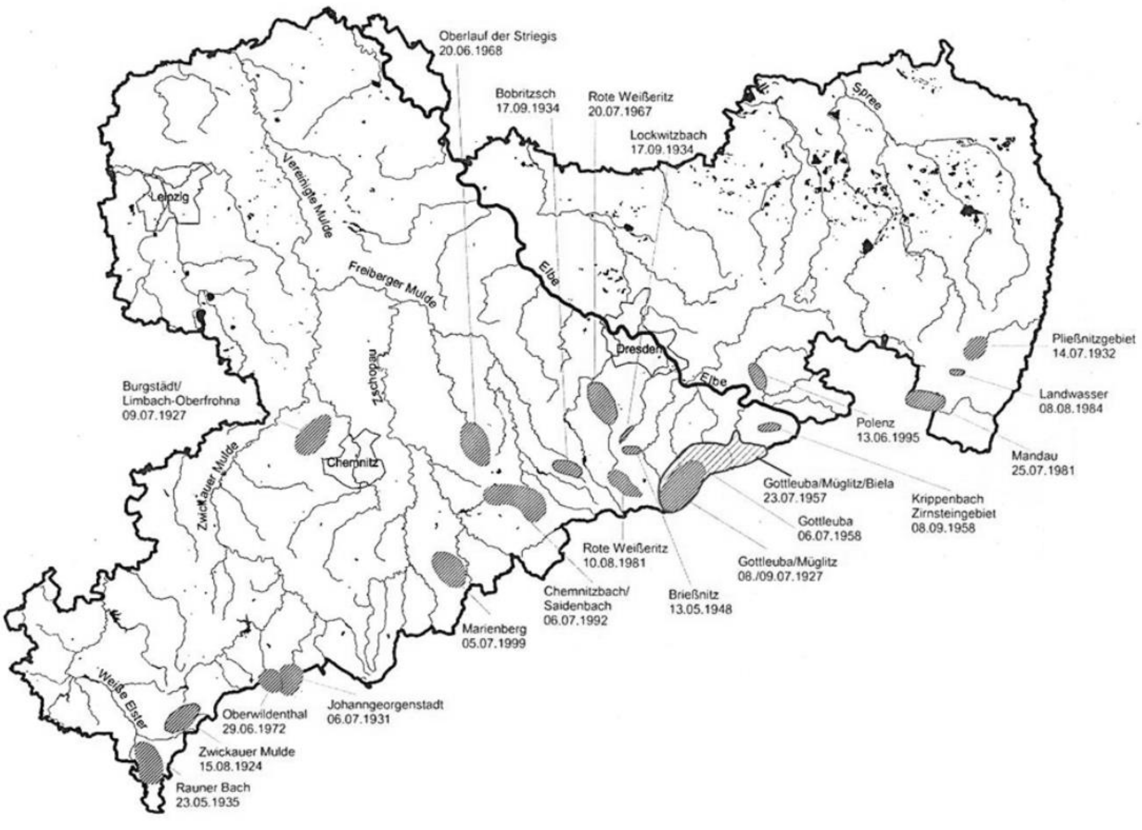

Figure 1: Overview of local summer heavy precipitation events with catastrophic effects in the 20th century in the low mountain ranges in Saxony. Published in (SMUL, 2002), taken from (Pohl, 2003).

The recent research of risk analysis and management has been often focused on extreme events in large-scale catchments (Samuels et al., 2009; Schanze et al., 2009). However, extreme hydrological events in medium- and small-scale catchments were not given adequate attention. Neither the precipitation network nor the gauge measurement network of Saxony has a sufficient measurement network density for the detection and prediction of such events (Mazzetti and Todini, 2009; Wiemann and Eltner, 2018). Furthermore, data from precipitation radar are associated with too large uncertainties (Kronenberg et al., 2012; Overeem et al., 2009), while satellite remote sensing and numerical weather prediction models are too coarsely resolved (Alfieri and Thielen, 2015; Yang et al., 2016). Thus, although Saxony has one of the most advanced early warning systems in Germany, it still lacks early warning response coverage for small-scale extreme events. As a result, recent events in small catchments in Saxony, such as the floods in the Bautzen area and Upper Lusatia (Oberlausitz) in 2010 or Adorf, Bad Elster and Oelsnitz in 2018, could only be predicted to a very limited extent, resulting in considerable economic damage in Saxony (LfULG, 2019; SMUL, 2002).

Hence, on the one hand, there is a great and urgent need for research to improve and broaden the information base, e.g., for high temporal and spatial resolution observation and analysis of small-scale, episodic extreme events. On the other hand, a simple yet efficient tool for the prediction of such events, such as Flash Flood Guidance (FFG)(Carpenter et al., 1999; Georgakakos, 2006), where flood warnings are issued based solely on pre-event soil moisture and precipitation forecasts, is required (Figure 2). FFG is an important and the most widely used concept in the world for deriving early flood warnings for small, fast-acting catchments (Georgakakos, 2006; Norbiato et al., 2009; Villarini et al., 2010). The general approach here is to determine a critical rainfall amount that will cause small water creeks to begin to overflow at some point in time in the future. In a sense, this critical rainfall amount (rainfall threshold) is pre-calculated by hydrologic modeling as a function of soil moisture (or pre-moisture condition - AMC) and snow accumulation and is spatially differentiated into time period-specific warning products in operational use. The method uses a simple comparison of cumulative (predicted) precipitation with critical precipitation thresholds in consideration of AMCs as illustrated in Figure 2.

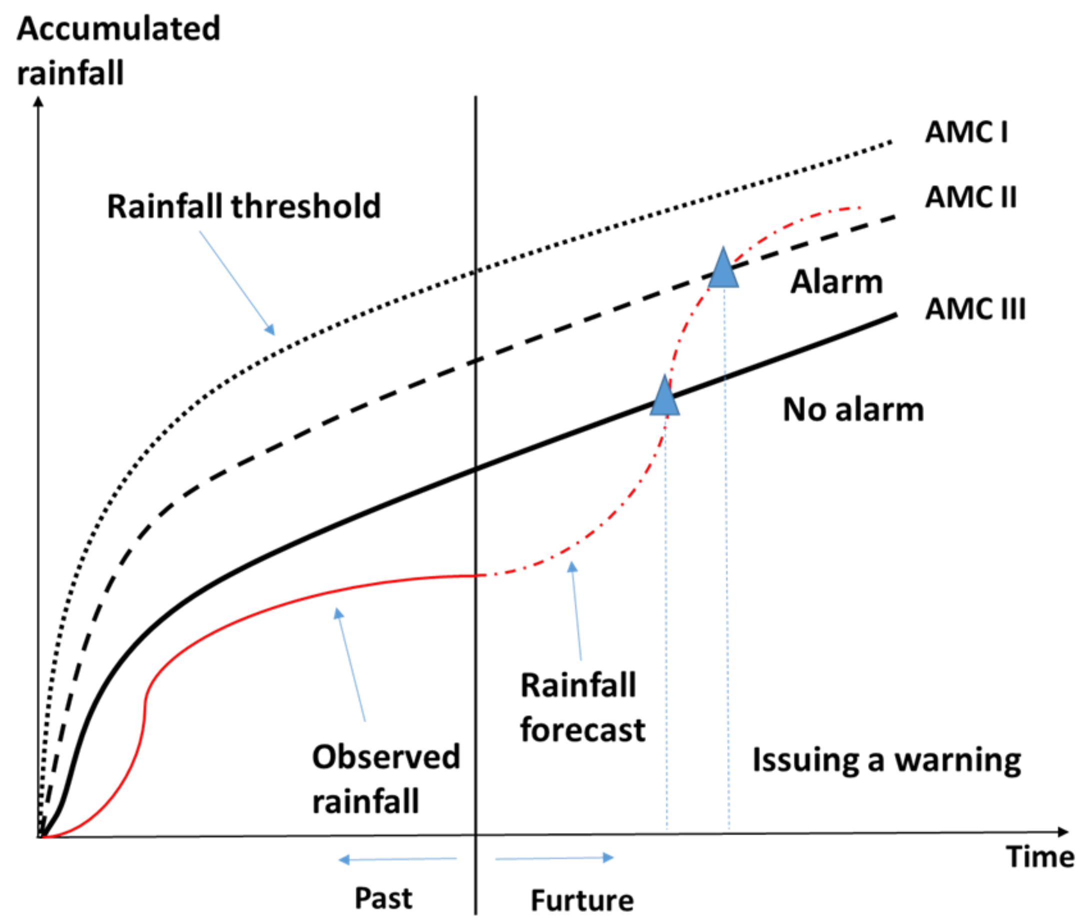

Figure 2: Example of rainfall thresholds derived for different antecedent moisture conditions (AMC) (AMC I: dry soil, AMC II: moderately saturated soil, AMC III: wet soil) as accumulated rainfall by time and their application in flash flood prediction (after Martina et al., 2008).

1.2 Problem formulation

Flash floods are known as highly destructive natural hazards due to their sudden occurrences and severe consequences (Borga et al., 2010; Georgakakos, 2006; Hapuarachchi et al., 2011). In addition to precipitation, pre-event moisture is one of the most crucial factors in determining whether particular rainfall events cause flash floods (Berthet et al., 2009; Javelle et al., 2010; Longobardi and Villani, 2003; Meyles et al., 2003; Norbiato et al., 2008), as it reflects the available natural retention in a catchment (Georgakakos, 2006; Tramblay et al., 2010). Many studies showed that initial soil moisture plays an important role in the generation of flash floods in catchments with different hydro-climatic conditions (Borga et al., 2009; Grillakis et al., 2016; Penna et al., 2011). Therefore, spatial-temporal information on soil moisture is crucial for many aspects of water management, flood forecasting and management (Samaniego et al., 2010; Schmidt-walter et al., 2020; Schütze et al., 2016; Zink et al., 2017). They serve not only to enhance our understanding on the mechanism of runoff generation but also to improve the accuracy of flash flood prediction (Marchi et al., 2010; Ravazzani et al., 2007; Tramblay et al., 2012). Additionally, flash flood events often occur in small and medium catchments of low mountain ranges, where there are limited observational data (Norbiato et al., 2008; Philipp et al., 2008). This increases the need for information on antecedent soil moisture, which tends to be underrepresented, especially at the regional scale. Therefore, the task to be solved is to develop a framework for estimating and continuously updating this variable, which is used to determine the current state of a catchment or study site.

The ability to describe the water balance sufficiently, where soil moisture can be derived, in a certain spatial and temporal scale, depends on the availability of the information and model configurations (Zink et al., 2017). While precipitation, as the main driver of the water balance, and runoff can be measured and interpolated using various methods, measurements on evapotranspiration (ET) and soil moisture are rather limited. At the regional scale, this information is not available, difficult and costly to estimate (Romano, 2014; Walker et al., 2004). As the literature and measurement technique on these components are vast and evolving so rapidly, it might be considered ambitious to present the state of research on these key variables. For instance, remote sensing can monitor soil moisture in large scale and with improved in higher spatial resolution (Entekhabi et al., 2014). The remotely derived soil moisture products of the European Space Agency (ESA), Soil Moisture and Ocean Salinity mission (SMOS, in 2009), and Soil Moisture Active/ Passive mission (SMAP) have been rapidly gaining attention in the field of hydrology due to its potential application (Massari et al., 2014; Reichle et al., 2017). However, the resolution of the above-mentioned datasets is coarse according to Wood et al. (2011), and there is a need for higher resolution data and models, e.g., for flood and drought forecasting. In addition, Bierkens et al. (2015) noted that water resource or river catchment managers prefer high-resolution data at 1-5 km resolution, which is inevitable for flash flood monitoring in low mountain ranges.

Soil moisture from in-situ measurements, on the other hand, can deliver estimations that are more reliable at point scale and feasible with various methods such as neutron scattering, gamma ray attenuation, electromagnetic techniques, tension meter and hygrometry (Romano, 2014; Walker et al., 2004). These point observations are representative of a small span of control volume of a few cubic centimeters. Even many efforts were put to establish an international database of in-situ soil moisture such as international soil moisture network (https://ismn.geo.tuwien.ac.at/en/), it is still facing limitations to cover this variable spatiotemporally on a regional scale. As for ET, a global network of micrometeorological towers is making effort to measure ET using the Eddy Covariance method for an extent of 10 to 100 meters; however, the number of these sites is limited to about 1000 worldwide. Thus, water balance models are currently a favorable option to estimate water balance conditions on different spatiotemporal scales depending on available data input as well as model features (Legates and Junghenn, 2018).

Water balance simulations are often performed only for a particular tree species or plant type (Federer et al., 2003; Wellpott et al., 2005; Ziche et al., 2021). In this area, Schmidt-Walter et al. contributed remarkably by creating water balance simulation for 8800 points in forests across Germany (Schmidt-walter et al., 2020). However, the point-based approach is constrained by its spatial distribution. Many efforts are therefore aimed at moving from point simulations to a regional-scale model or even to global scales (Reichle et al., 2017; Vorobevskii et al., 2020; Zink et al., 2017). As a result, different model setups and frameworks were constructed to simplify the workflow of producing data for larger areas and standard parameter sets (Spieler et al., 2020; Wiemann and Eltner, 2018). For instance, Schwärzel et al., introduced a GIS-based modelling approach to predict and regionalize water balance components for test plot in Tharandt Forest (Schwärzel et al., 2009). Zink et al. determined high-resolution water fluxes with a resolution of 4 km x 4 km for whole Germany (Zink et al., 2017), which is related to drought monitor product (Marx et al., 2015). However, for hydrological applications, especially for spatially distributed hydrological modeling, the resolution currently achieved is insufficient or limited. This presents a challenge for a simulation approach that can estimate water components at higher resolution and make them useful for spatially distributed models. To fill this gap, a modeling framework was developed to predict and regionalize the water storage capacity as a function of climate/weather, topography, soil type and land cover on catchment scales of hydro response unit (HRU). The overall objective is to provide a more detail description of vertical water fluxes. This study outlines the concept of the modeling framework, presents current results with two precipitation datasets from gauges and radar, and illustrates the application of simulated soil moisture as indicators for flood monitoring.

1.3 Target setting

Recent developments, especially in the so-called "physically based" hydrologic models, have not adequately solved the spatial distribution problem in most pragmatic cases, mainly due to the following reasons. First, site characteristics (both vegetation and soil) are essentially unknown or at least not well known (Blöschl et al., 2008; Merz and Blöschl, 2004), which means that any system feature will always have some spatial instability, regardless of the HRU resolution chosen for modeling. Therefore, attempting to use point-based physics at the catchment scale means that both the site and the boundary conditions should be spatially known at the scale of the simulations. As a result, an enormous amount of input data is required, which is one of the major challenges in implementing this framework. Second, modelers are forced to find "effective parameters" through calibration, since the required information is rarely available. Consequently, model selection is a key factor in overcoming this problem. The aim of this study is to create a product to estimate daily water storage in high resolution on a regional scale in Saxony. The central and overarching question is: How can a high spatial coverage with high resolution of soil moisture be obtained with an easy-to-implement automation of a simple physical-based model and make it applicable in a flood-forecasting framework like the FFG? This leads to the following detailed questions:

1. How feasible are HRU-based simulations with an automatic parameterized framework for all small and medium catchments in Saxony relying on the available data sets?

2. How reliable can a non-calibrated model provide suitable results for water balance components such as discharge, evapotranspiration and soil moisture?

3. Does water balance benefit from radar-based precipitation?

4. Can a physically based model substitute spatially distributed modeling at the regional scale?

5. How can simulated soil moisture be used as a flood indicator in FFG framework?

6. How effective is the FFG tool in flash flood forecasting?

7. What are the main drawbacks of the model framework?

1.4 Structure of the thesis

This cumulative dissertation was written in accordance with the doctoral regulations of the Faculty of Environmental Sciences at the Technische Universität Dresden.

Chapter 2 provides an overview of FF warnings with a focus on the proposed FFG framework.

Chapter 3 contains the three peer-reviewed publications.

The first publication presents an approach to simulate spatially distributed water balance components with a plot-scale model. The physically based lumped model, BROOK90, was set up for the whole state of Saxony covering more than 6,000 small and medium-sized catchments. The work was focused on the automatized implementation of land cover (CORINE 2012), soil information (BK50) and automatic retrieval of meteorological input from a sensor platform. Catchment simulations were performed by their hydro response units and compared to the observed discharge and simulated ET and soil moisture (SMAP data). The focus of the validation is on small to medium-sized head catchments, which are mostly ungauged. In these areas, data inputs are rather limited; thus, automatic data retrieval was tested to overcome this constraint.

The second paper deals with the integration of long-term radar-derived precipitation to improve water balance estimation. The idea was initiated due to the lack of spatial representation in precipitation data. Thus, quantitative precipitation estimation (QPE) using radar was applied in the framework (presented in the first publication) after a post-correction process and validated with rain gauges and water gauges. In addition, the impact of the framework structure related to data input was discussed.

The third paper introduces a method for estimating rainfall threshold for flash flood warning based on output of soil moisture. Following the FFG approach, the method was applied to the Wernersbach catchment in the Tharandt Forest. The performance was then validated with historical events using contingency table to derive statistical values such as probability of detection (POD), false-alarm rate (FAR) and critical-success index (CSI).

Chapter 4 presents the key findings, results of the individual publications, and relates them into a common context. Finally, chapter 5 provides conclusions and an outlook on the scope of the study and describes a potential application in the field of soil moisture monitoring.

2. Adjusted Flash Flood Guidance (FFG) framework

2.1 Warning based on predictions

The term “flood warning” is not always used in the same way in the context of flood risk management: in Saxony, “flood warning” according to the “Flood Information and Alarm Service” means a certain, specific product, which is produced and disseminated by the Landeshochwasserzentrum (LHWZ). However, “flood warning” is intended to be used more broadly here in the sense that it refers to all information and official activities that enable those affected to make a qualified assessment of the actual and expected flood hazard.

Due to this rather general definition of the character of a flood warning, there are potentially different ways to reach such a warning. In the simplest case, the warning is only based in the evaluation of the observed or current development of hydrologically relevant parameters, such as precipitation or runoff. In many cases, warnings are based on water level, which is operated to fulfill this task (in Saxony, the so-called “flood reporting level”), this has certain consequences. However, a flood warning does not necessarily have to be based on measured values/observations, but rather on a meteorological or hydrological forecast. Additionally, consideration of the flood attenuating effect of natural retention (soil moisture) is intrinsically important. Based on that, a new concept of (flash-) flood warning is conducted, taking into account the development of the flood hazard: either regionally or with a very concrete reference to a river course, section or cross-section.

2.2 Terminology and definitions

2.2.1 Flash flood

The term “flash” refers to the response of a drainage network in which water levels reach a critical stage within only minutes to a few (usually less than six) hours after the onset of a heavy rainfall (Borga et al., 2011; Marchi et al., 2010; Viglione et al., 2010). Typically, it often takes place in small to medium-sized catchments due to natural conditions and leaves severe damages on buildings, natural environment and human lives. The World Meteorological Organization (WMO) Manual on Flood Forecasting Warning (WMO, 2011) refers to flash floods when events of short duration are accompanied by a comparatively high peak discharge. This makes flash flood events obtain two features (short lead-time and local occurrence) which separate them from riverine flood events and indicate their higher uncertainty in forecasting.

2.2.2 Small catchment

If “small catchments“ are understood as areas of the middle to lower mesoscale (“sub-mesoscale”, this would mean an area up to 100 km^2 (Bárdossy and Lehmann, 1998). Hapuarachchi et al., (2011) define areas up to 300 km^2 and a peak rise time of up to six hours as small catchments. (Collier, 2007) cited an area size of up to 400 km^2 and again a peak rise time of six hours for the United States. The authorities responsible for flood forecasting in Baden-Württemberg and Hesse define areas up to 200 km^2 as “small”, while in Rhineland-Palatinate, the limit is set at 500 km^2. Philipp et al., (2016) described small catchments as “areas where the processes of runoff formation and runoff concentration dominate”, setting an upper limit of 200 km^2 for Saxony. Figure 3 shows empirically determined duration of the fastest runoff increase until the onset of flooding at the water bodies of Saxony with catchments not larger than 50 km^2. From this, the relevance of fast reacting areas (red lines in Figure 3) in Saxony becomes very clear, mainly focused on the low mountain ranges and the Ore Mountains.

In case of high local precipitation intensities (resulting in potential infiltration or saturation excess), there is an almost simultaneous increase in precipitation and runoff locally. The predictive benefit of a hydrologically oriented early warning product in terms of added value compared to a “classical” weather warning or other radar data based products is the lower, the more local the approach. The flood early warning strategy presented in this study is therefore focused primarily on a scale range between 5 to 150 km^2.

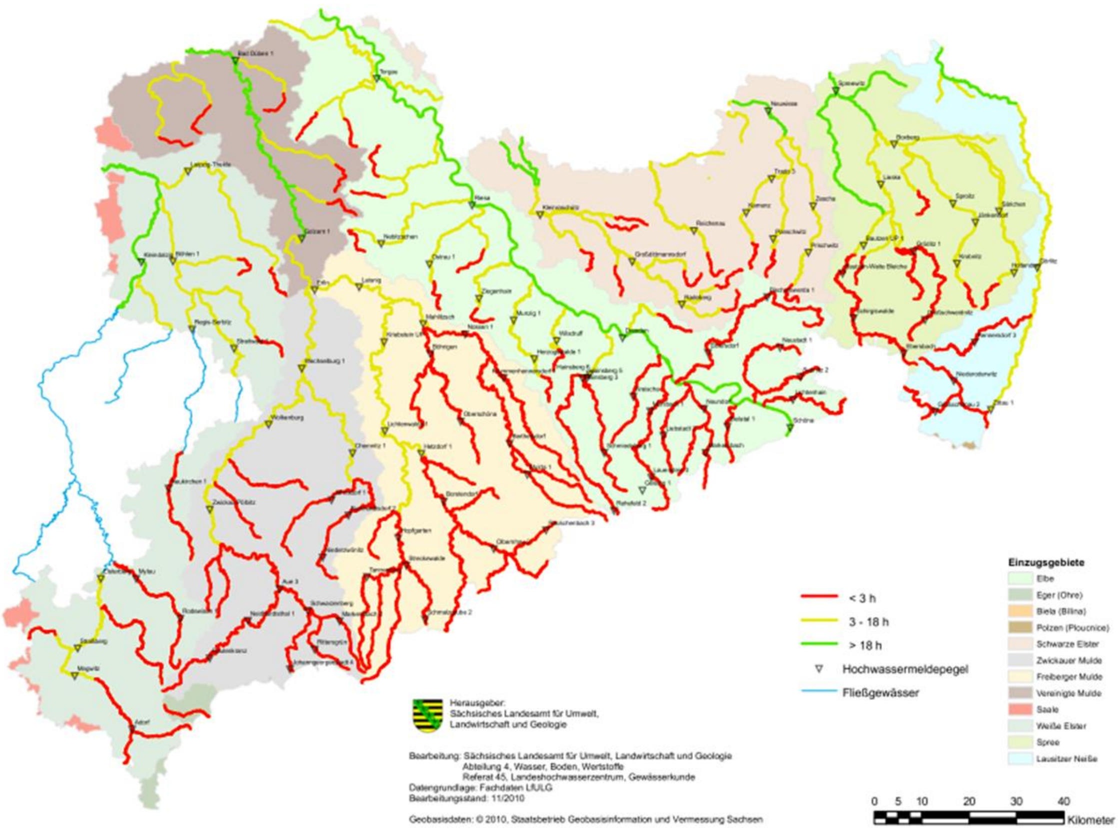

Figure 3: Duration of the fastest runoff increase until the onset of flooding at water bodies with catchment areas not larger than 50 km^2. The color red means: less than 3 hour; yellow: 3-18 hours; green: more than 18 hours (Philipp et al., 2017).

2.3 FFG concept

Based on an agreement between the WMO and various agencies of United States, the FFG concept has now been implemented for a number of countries worldwide, including seven countries in Central America, four in the Mekong River basin, Haiti and Dominican Republic, Pakistan, eight countries in the Black Sea/Middle East region, seven in South Africa and Mexico (Seo et al., 2013; Summary, 2009). The U.S. National Weather Service has routinely relied on FFG calculations (Figure 4) when issuing flash flood warnings since 1970s (Georgakakos, 2006). In addition to its extensive application in the U.S and Central America (Georgakakos, 2004), in Europe the FLOODSite integrated project (http://www.floodsite.net), among others, it aims to evaluate the benefits of the precipitation threshold approach as a substitution to classical approaches in flash flood events. Conceptually, FFG or rainfall threshold is the amount of rainfall of a given duration, assumed to be uniform in space and time for a given catchment, that flash flood may occur. However, a method used to derive rainfall thresholds may differ depending on the hypothesis adopted, such as probabilistic or deterministic (Luca and Versace, 2017). For instance, the rainfall threshold, calculated by inverting a lumped hydrologic model, is compared to either real-time observed or predicted rainfall of the same duration and catchment area. If the predicted or forecast precipitation amount is larger than the FFG, the cross-section is assumed to be inundated.

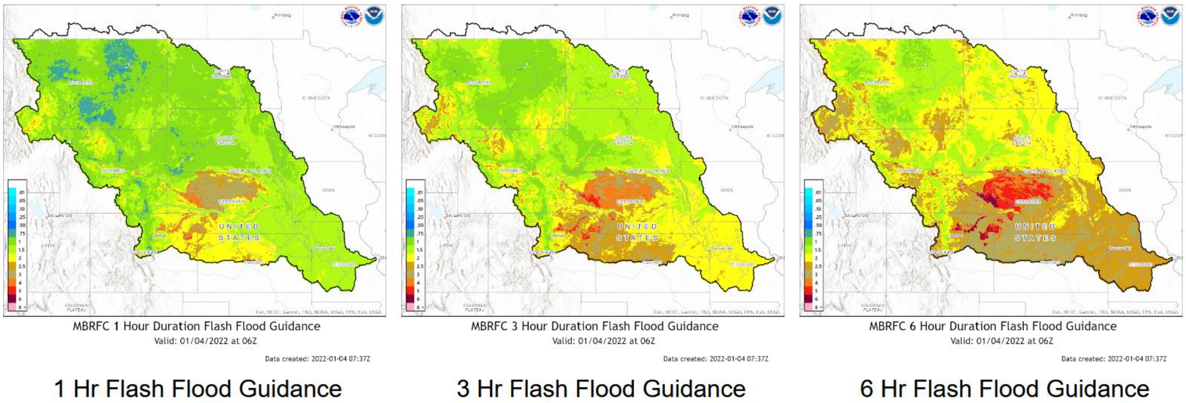

Figure 4: Flash Flood Guidance for the U.S for an one-hour, three-hour and six-hour duration; precipitation amounts are in inches (source: https://www.weather.gov/mbrfc/ffg).

In recent years, innovations have been proposed for the FFG that generally benefit from the development of spatial distributed hydrologic models (Blöschl et al., 2008; Borga et al., 2009; Reed et al., 2007). However, development of the FFG concept is still work-in-progress. It is generally accepted that the FFG concept is a useful tool that enhances communication about the hydrologic status of catchments between hydrologists and meteorologists, and that it represents a potential reference standard for further development and comparison. Thus, the objective here is to conduct a framework based on FFG concept, considering a wide range of physiographic conditions in Saxony and focusing on the temporal variation of the state of the soil moisture before a flood event.

2.4 Adjusted FFG framework

In this thesis, the FFG approach according to WMO and the U.S agencies was adapted to incorporate pre-event moisture in real time forecast with the ESF EXTRUSO project (Wiemann et al., 2017). In order to estimate pre-event soil moisture for the complete area of the low mountain ranges of Saxony with flash flood potential (Figure 1 and 3), a widely applicable, accurate but yet simple approach was needed. Radar-based and gauge precipitation as input time series; detail orographic, land-use and soil information and a lumped parameter model are used to estimate the total soil moisture and potential retention in the catchment. The concept of the workflow is presented in Figure 5. The main effort was put into the establishment of a semi-automatic framework, which integrates the high quality of regional datasets for model parameterization and meteorological data inputs, to derive current state of a catchment. Combined with precipitation forecasts and their inherent uncertainty, the approach allows the determination of when precipitation exceeds the retention potential of the catchment area. Spatially distributed and complex hydrologic modeling and additional measurements can then be initiated. Assuming reasonable precipitation forecast of 24 to 48 hours, this part can begin up to two days before the actual event.

The estimation of antecedent soil moisture of the adjusted FFG framework is also published as a part of "xtruso"package developed under the EXTRUSO project, freely available on Github (https://github.com/GeoinformationSystems/xtruso_R). The workflow is transparent through code updates, bug fixing and development steps documented in the Github platform. The Incorporation of a sensor network, so-called Open Sensor Web (https://www.opensensorweb.de/de/), which fetches daily meteorological data from various networks Saxony-wide, allows the framework to provide up-to-date estimates of soil moisture. The framework operates in a semi-automatic mode that allows integration of data download, pre-processing, modeling, and post-processing. After selecting a catchment of interest, the program retrieves all the catchment-related data such as digital elevation model, soil properties, land use and meteorological variables. The framework handles the data, configures the identification of the HRUs, and assigns the parameters required to run the model. It then runs the model for each HRU, estimates the weighted average for the catchment, and saves the model output in various formats (Figure 5). From there, the current retention of the catchment can be derived for further estimation of rainfall thresholds and in FFG operation.

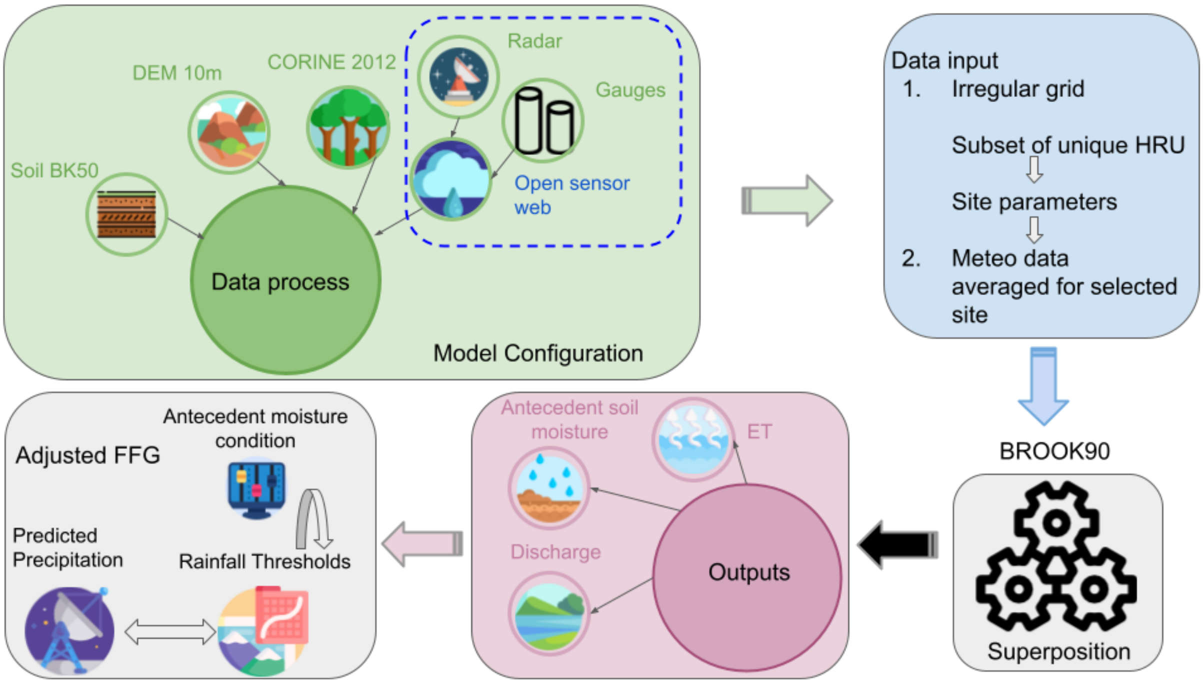

Figure 5: An overview of the adjusted FFG framework (modified after Vorobevskii et al., 2020).

3. Core publications of the PhD thesis

The originally submitted cumulative dissertation included all peer-reviewed publications in Chapter 3, which are merely mentioned below. This study outlines the concept of the modeling framework, presents recent results with two rain gauge and radar precipitation datasets, and illustrates the application of simulated soil moisture as an indicator for flood monitoring. Detailed texts are attached in the appendixes.

3.1 Pseudo-Spatially-Distributed Modeling of Water Balance Components in the Free State of Saxony

Luong T.T., Pöschmann J, Vorobevskii I, Wiemann S, Kronenberg R, Bernhofer C. Pseudo-Spatially-Distributed Modeling of Water Balance Components in the Free State of Saxony. *Hydrology*. 2020; 7(4):84. https://doi.org/10.3390/hydrology7040084

3.2 The Integration of Long-term Radar-derived Precipitation to Improve Water Balance Estimation: A Case Study in Multiple Catchments in Saxony, Germany

Luong T.T., Vorobevskii I, Pöschmann J,Kronenberg R, Bernhofer C. The Integration of Long-term Radar-derived Precipitation to Improve Water Balance Estimation: A Case Study in Multiple Catchments in Saxony, Germany. *Hydrology Research*. (to be submitted)

3.3 Rainfall Threshold for Flash Flood Warning Based on Model Output of Soil Moisture: Case Study Wernersbach

Luong T.T., Pöschmann J, Kronenberg R, Bernhofer C. Rainfall Threshold for Flash Flood Warning Based on Model Output of Soil Moisture: Case Study Wernersbach, Germany. *Water*. 2021; 13(8):1061. https://doi.org/10.3390/w13081061

4. Major findings

The work is divided into three sections that can be found in three publications. An overview for the entire structure of the study is shown in Figure 5. In the first section, a framework is created to integrate model and data inputs into a platform for conducting simulations. The next step tested the potential use of long-term precipitation derived from radar for estimating water balance processes. For the application, the simulated soil moisture was used to estimate rainfall thresholds. This follows the concept of Flash Flood Guidance (FFG), where flood warnings are issued based solely on pre-event soil moisture conditions and rainfall forecasts. The method was originally developed and implemented by the United States National Weather Service in the 1970s and is used in several countries (Georgakakos, 2006; Norbiato et al., 2008; Reed et al., 2007). In this study, we propose a modified FFG method to examine a wide range of soil moisture from dry to wet as input to a rainfall-runoff model. Here, the major findings of the publications are summarized following the questions listed in the target setting section (chapter 1.3).

1. How feasible are HRU simulations based on automatic parameterization for all small and medium catchments in Saxony relying on the available data sets?

Three main datasets are integrated into the framework. They supply the required meteorological, vegetation and soil input data for the BROOK90 model. The network of DWD stations in Saxony is used as meteorological driver. The following variables are retrieved: 2 m air temperature (°C), surface net solar radiation (J m^{-2}), humidity (%), wind speed (ms^{-1}) and precipitation (mm). It contains a total of more than 400 stations in the study area embedded in the Open sensor web for automatic data generation. We used the inverse weighted distance method to interpolate the data for a study site. It is also possible to extend the meteorological data networks available in the Open Sensor Web to the forestry climate stations or agriculture meteorological stations. The soil map BK50 provides detailed standard information about soil properties on a regional scale with a spatial resolution of 50 m. The following information about soil is extracted: soil classes, soil layers, thickness and stone fraction. A major innovation of this map is that essential parameters for all leading soil profiles were determined by laboratory analysis and a comparison between filed and laboratory data was made for the validation. The CORINE 2012 land cover map dataset was published in 2016 and disseminated by the Copernicus Global Land Service. It contains more than 32 discrete classes in the study area, including various types of forests, shrubs, herbaceous vegetation, grasslands, wetlands, croplands, urban/ settlement areas, infrastructures, open waters and no data. Due to limited literature on model parameters, land covers were simplified to five classes, namely, coniferous forest, deciduous forest, grassland, agriculture site and others, while retaining the main characteristics of water balance components. Additionally, a digital elevation model (DEM 10 m) is used for the calculation of orographic features namely, mean slope and aspect. These are needed to derive solar radiation and subsequently evapotranspiration and snowmelt. By overlaying the maps, a method called superposition was applied to derive hydrological response units (HRUs) that represent homogeneous features of a site in term of topography, soil and vegetation. As a result, more than 100,000 HRUs were derived for more than 6,000 catchments in Saxony. Thus, a catchment contains an average of 18 HRUs and a maximum of 136 HRUs. The procedures of processing data, retrieving model parameters, modelling and post-processing of model outputs were automatized and wrapped up in an R-package “xtruso”. The methodology is presented in the publication 3.1 “Pseudo-Spatially-Distributed Modeling of Water Balance Components in the Free State of Saxony”.

2. How reliable can an uncalibrated model provide suitable results for water balance components such as discharge, evapotranspiration and soil moisture?

To evaluate the performance of the framework, the model outputs of ten selected catchments were compared to the observed discharge and simulated ET and soil moisture from SMAP_L4_GPH product. Validation was performed for different spatial and temporal resolutions in the period 2005-2019. The simulated discharge was compared with daily and monthly time series of data from water gauges. Since observed ET and soil moisture data are not spatially available, thus the satellite-based SMAP, with a spatiotemporal resolution of 9 km x 9 km and 3-hour intervals, was selected. To make values compatible, all grid cells that are partly or fully covering the considered catchment were extracted, area-weighted and aggregated to daily resolution. The mean values of the selected skill scores for daily discharge are 0.63 (KGE), 0.72 (R), indicating acceptable performance of the model. An improvement can be observed in the monthly scale (KGE = 0.75, R = 0.88). While high values of KGE confirm the plausibility of the approach, ratios of standard deviation (alpha) and mean (beta) greater than one show an overall overestimation of discharge. This may be associated with the neglect of bypass flow and groundwater recharge processes from the simulation, which is also confirmed in the study of Vorobevskii et al., 2020. In addition, soil moisture was well captured (KGE > 0.75 and R > 0.85 for both daily and monthly scale). Unlike discharge, the values alpha and beta of soil moisture are less than one, indicating an underestimation of soil moisture from the model compared to SMAP data. This can be explained by various factors related to the spatial scales, the method used, the data input and the parameterization of the two products. Last but not least, the skill scores of ET of the two datasets showed a good agreement on both daily and monthly scales (KGE >0.6 and R >0.8). Similar to soil moisture, an underestimation of ET was also found in the “xtruso” framework compared to SMAP (alpha = 0.86, beta = 0.7). The reasons for this can be identified with those above-mentioned from soil moisture, despite the fact that ET from the two products is estimated by the Penman-Monteith equation (Allen G et al., 1998). Nevertheless, the results of the validation show that a non-calibrated model with the proposed model setup can deliver reliable water balance components. This also highlights that the automatic parameterization approach works reliably with the available information at the study sites. Detailed evaluation of the model output can be found in the publication 3.1 “Pseudo-Spatially-Distributed Modeling of Water Balance Components in the Free State of Saxony”.

3. Does water balance benefit from radar-based precipitation?

Precipitation is an important factor influencing water balance, with errors in precipitation affecting subsequent stages of water quantity analysis. Thus, this step aims to use the spatial coverage of a radar-based product, particularly at the regional scale, to investigate whether radar precipitation improves water balance performance compared to rain gauge data. The DWD’s 2017 RADKLIM-RW re-analysis radar product was used for this purpose. The data provides a largely homogeneous, spatially and temporally highly resolved radar-based precipitation time series. It covers the entire federal territory with a high resolution of 1 km * 1 km. and hourly from 2001. This makes it a very interesting and promising dataset for various application, e.g., in the water balance in our study case. The raw data were processed and converted in the netCDF (Network Common Data Form) format before being integrated into the framework. This step is crucial to reduce to the computational time required to extract the data for a study area. Data are extracted for each sub-catchment and aggregated from hourly to daily for mode input. A comparison between gauges and radar at different spatial and temporal scales was performed for selected catchments in the study area. To compensate for the underestimation of precipitation measurements, the Richter correction method was applied, taking into account different precipitation types and the degree of shielding of the measurements. Subsequently, both datasets were used in the framework to estimate water balance fluxes, holding other model inputs constant. Simulated discharges with both gauge and radar precipitation were compared with observed discharge to evaluate accuracy. Such a procedure is presented in the publication 3.2, "The integration of long-term radar derived precipitation to improve water balance estimations: A case study in multiple catchments in Saxony, Germany". As a result, RADKLIM-RW provided reliable simulations of discharge and showed potential for optimizing precipitation to model input (KGE = 0.53 and 0.7 at daily and monthly resolution, respectively). However, a clear improvement of radar precipitation toward gauge precipitation in water balance simulation cannot be observed in the selected catchments. The difference in the model performance is rather arbitrary and further studies are required considering difference frameworks and study areas. Additionally, a simple compensation like the Richter method with conventional precipitation should be used with caution.

4. Can a physically-based model substitute spatially-distributed modeling at the regional scale?

This study proposes a new approach to simulate water balance components at high spatial resolution in catchment scale using the BROOK90 model. A data platform developed in the EXTRUSO project facilitates the inputs of spatial data into the model. Even though it is merely a "plot-scale" model with parameters derived by detailed orographic, land use and soil information, simulations using the HRU approach were applicable for more than 80% of Saxony. Despite the fact that the model is not calibrated, this approach is feasible, as most of the parameters own a physical meaning, which can be measured and/or transferred to similar study sites. The validation results in publication 3.1 and 3.2 assure the plausibility of the framework. However, focusing on describing vertical fluxes movement, the later water flow from adjacent areas in the model is neglected. In other words, the model has no routing mode, which makes the approach not fully distributed. Hence, the estimation of discharge and its partitioning should be handled with care, particularly if it is not a "site" description.

5. How can simulated soil moisture be used as a flood indicator in FFG framework?

Soil moisture information can be derived from the simulation framework mentioned above. Since antecedent soil moisture varies, it plays an important role in the runoff generation in a catchment. A storm event is considered irrelevant in a dry period; however, it can cause flooding in a wet period when the soil is already saturated. Thus, rainfall thresholds need to be determined, considering various moisture conditions. The use of synthetic precipitation with different intensities and duration also allows a more holistic evaluation of flooding cases. Rainfall thresholds were estimated for durations of 1 to 24h, by running the BROOK90 model in "inverse" mode and determining the rainfall values that result in an exceedance of critical discharge (fixed value) for each duration. Discharge is considered critical when inundation starts, exceeding the so-call bank-full flow. This value is usually defined as the 2-year recurrence interval of simulated long-term runoff in the case of an ungauged catchment; other methods derive it from available historical discharge data and the hydraulic geometry of the study site. Identifying critical rainfall values requires a large sample of different rainfall events and their corresponding runoff to test the physical boundary when the river is full of water under different initial catchment conditions. It results in tremendous computation effort and data input. However, it is a "one-time-job" that can be easily applied to flash flood warning. The procedure of this method is described in the publication 3.3 “Rainfall threshold for flash flood warning based on model output of soil moisture: case study Wernersbach, Germany”.

6. How effective is the FFG tool in flash flood forecasting?

The rainfall threshold estimates were validated using the contingency table with recorded historical events in the Wernersbach catchment. The results showed a very high probability of detection (91%) for the 40 extracted flood events during the period 1996-2010. Nevertheless, the high false-alarm rate (56%) that leads to low critical-success index (42%) suggests that the method should be further improved by using other rainfall-runoff models and applying it to more study cases. This study has highlighted the importance of soil moisture as an indicator for flood warning and has shown the potential of the proposed adjusted FFG as a reliable tool for flash flood prediction. The FFG tool can be further developed by considering different rainfall runoff models, the method for estimating critical discharge and different precipitation products such as radar or numerical weather prediction models. Particularly, the computed discharge could be improved by a spatially distributed model and better temporal resolution of data inputs. Then an antecedent soil moisture derived from the BROOK90 model could serve as the starting condition for running a more complex hydrological model that in turn checks for the alarm level. A detail of FFG performance is presented in the publication 3. 3.

7. What are the main drawbacks of the model framework?

The performance of the model is constrained by various errors in the data and methods. The largest uncertainty lies obviously in the core of the framework- the regional parameterization. Simplification of the land cover parameters could result in the same parameter set for completely different plant species assigned to one vegetation class, e.g., pine and spruce (coniferous forest), birch, oak and beech (deciduous forest). Likewise, assigning soil hydraulic characteristics based on texture class using parameters from local USA studies may result in a discrepancy when applied to the German soil map. In addition, issues with spatial coverage of the meteorological datasets should be considered. The DWD station network does provide very high quality and consistent long-term meteorological measurement -series. Nevertheless, the coverage of this network is still coarse in the border area near Poland and Czech Republic. Thus, an expended sensor network can reduce some of these uncertainties, such as forest climate stations or meteorological agriculture measurement stations.

Additionally, the model is limited by the fact that non-green leaves, which intercept precipitation and radiation, but do not transpire in the meantime, are not considered. Since canopy parameters are assumed to be constant, tree/plant phenology or growth (e.g. crop rotation in agriculture sites, tree height development, etc.) and particularly LAI dynamics are not included in the framework.

While other parameters such as location, vegetation and soil can be derived from data inputs or literature, the model’s flow parameters are rather empirical. This requires the experience of the modelers and their knowledge of a study site or a systematic calibration framework. Due to limited computation resources and concept of the framework, no calibration was performed. Thus, a pragmatic solution was chosen for all sites using “top-down” flow recommended by Federer, where preferential flows and ground water flows are neglected and only the amount of discharge is considered as model output.

Calibration was not performed for several reasons. There is no data for calibration at the sites/ catchments for which measurements are not available. If a calibration is carried out, that would lead to the limitation on the extent of the study areas. Thus, a physically based model was chosen to address this issue by deriving model parameters from literatures and available measurements at similar sites. In addition, the model should be able to run with limited data input, which can be easily obtained from accessible and reliable datasets. To achieve high resolution of water fluxes, the model is run at a point or in an area with homogeneous characteristics, resulting in an enormous numbers of simulations to cover the spatial distribution. Hence, the calibration for the study area requires a large amount of computational resources.

5. Conclusions and outlook

A new approach is presented that integrates the lumped physical balance model BROOK90 and open-source datasets into a semi-automatic framework to estimate antecedent soil moisture and its related rainfall thresholds according to the FFG concept. The main highlight is to produce a soil moisture map at HRU scale for more than 6,000 small and medium-sized catchments in Saxony. The study showed that the adapted FFG method is an efficient support for the prediction of flash floods. Particularly, the operation is based only on precipitation forecasts and soil moisture information. The obtained results are satisfactory; however, missing alarms can potentially be improved, through which an appropriate rainfall runoff model is a key factor. This FFG method should be further tested in more flood-prone catchments in Saxony.

Although the results have already been validated with different observations and methods and in different catchments/sites in Saxony, further validations, particularly with in-situ soil moisture measurements are advisable. To improve the model performance, an extended database on dynamic vegetation height and LAI should be integrated into the framework. The results of this work can be used to establish a monitoring system for water fluxes from point to regional scale. This monitoring tool can be used as operational mode or forecasting, depending on meteorological data input. The framework was established for flood warning of small catchments with regional applicability; however, it can be extended to soil drought monitoring and water management in agriculture or forestry.

Since the establishment of the framework in 2019, it has contributed to several study projects and a master thesis. In addition, Forest Soil Monitoring Department in Competence Center Forest and Forestry of Sachsenforst was interested in implementing the framework as an operational mode for forest soil in Saxony. As a result, a project to develop an online soil moisture monitor for different forest sites in Saxony (die Bodenfeuchteampel- BFA) was launched in October 2020. Although the BFA is currently in the test phase, it has provided information on the actual water content of exemplary soils at forest sites in Saxony since June 2021. This is also a new part of the Regional Climate Information System "ReKIS" (https://life.hydro.tu-dresden.de/BoFeAm/dist/index.html). A publication on the extension of the framework in the field of soil moisture monitoring on forest sites is under preparation. New ideas for further development of the framework could be:

- Prediction of soil moisture by integrating available numerical weather prediction models, which can provide soil information one week to one month in advance.
- Apply climate scenario projection to study soil moisture climatology.
- Investigate the effects of climate change on site Information.

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List of Abbreviations

Abbreviation	**Description**
AMC	Antecedent moisture condition
BFA	Bodenfeuchteampel – *“Soil moisture traffic light”*
BK50	Bodenkarte 50 – “Soil map 50”
CORINE	Coordination of information on the environment
CSI	Critical success index
DWD	Deutscher Wetterdienst – „*German Meteorological Service*“
ET	Evapotranspiration
EXTRUSO	Extremereignisse in kleinen und mittleren Einzugsgebieten “*Extreme events in small and medium catchments*”
FAR	False alarm rate
FFG	Flash Flood Guidance
LfULG	State Office for Environment, Agriculture and Geology
LHWZ	Landeshochwasserzentrum
POD	Probability of detection
QPE	Quantitative precipitation estimation
SMAP	Soil moisture active passive
WMO	World Meteorological Organization
ReKIS	Regional Climate Information System
netCDF	Network Common Data Form
RADKLIM-RW	Radarklimatologie – „*Radar climatology*“

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Figure 1: Overview of local summer heavy precipitation events with catastrophic effects in the 20th century in the low mountain ranges in Saxony. Published in (SMUL, 2002), taken from (Pohl, 2003).

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Figure 4: Flash Flood Guidance for the U.S for an one-hour, three-hour and six-hour duration; precipitation amounts are in inches (source: https://www.weather.gov/mbrfc/ffg).

Figure 5: An overview of the adjusted FFG framework (modified from Vorobevskii et al., 2020)

List of the author's publication

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(1) Molina, O.; Luong, T.T.; Bernhofer, C. Projected Changes in the Water Budget for Eastern Colombia Due to Climate Change. *Water* 2020, *12*, 65. https://doi.org/10.3390/w12010065

(2) Luong, T.T.; Pöschmann, J.; Vorobevskii, I.; Wiemann, S.; Kronenberg, R.; Bernhofer, C. Pseudo-Spatially-Distributed Modelling of Water Balance Components in the Free State of Saxony. **Hydrology** 2020, 7, 84. https//doi.org/10.3390/hydrology7040084

(3) Luong, T.T.; Pöschmann, J.; Kronenberg, R.; Bernhofer, C. Rainfall Threshold for Flash Flood Warning Based on Model Output of Soil Moisture : Case Study Wernersbach, Germany. *Water* 2021, 13, 1061. https://doi.org/10.3390/w13081061

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(5) Vorobevskii, I.; Luong, T.T.; Kronbenberg, R.; Grünwald, T.; Bernhofer, C. Modelling Evaporation with Local, Regional and Global BROOK90 Frameworks: Importance of Parameterization and Forcing. *Hydrology and Earth System Sciences* hess 2021-602 (submitted)

(6) Wiemann, S.; Janabi, F.A.; Eltner, A.; Krüger, R.; Luong, T.T.; Sardemann, H.; Singer, T.; Spieler, D.; Kronenberg, R. Entwicklung eines Informationssytems zur Analyse und Vorhersage hydro-meteorologischer Extremereignisse in mittleren und kleinen Einzugsgebieten. Forum für Hydrologie und Wasserbewirtschaftung 2018, Heft 39.

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(1) Luong, T.T.; Kronenberg, R.; Spank, U.; Grünwald, T.; Modorow, U.; Janabi, F.A.; Schütze, N.; Bernhofer, C. Comparative Estimation and Assessement of Initial Soil Moisture Conditions for Flash Flood Warning in Saxony. EGU General Assembly 2017, Wien.

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(3) Luong, T.T.; Lorenz, J.; Kronenberg, R.; Bernhofer, C. Evaluation of Rainfall Thresholds for Flash Flood Warning Derived from Antecedent Soil Moisture Conditions with a Physical Process-based Model: Case Study Wernersbach, Germany. EGU General Assembly 2018, Wien.

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(7) Kronenberg, R.; Oehschlägel, L.M.; Bernhofer, C; Luong, T.T. Introducing an Implementation of BROOK90 in R. Saxony. EGU General Assembly 2019, Wien

Acknowledgements

Glory and praise be to God, my heavenly Father, for His grace and kindness that have enabled me to finish this work. I thank You for Your faithfulness and steadfast love!

Hereby, I would like to express my sincere gratitude to the people who played a major role in this dissertation.

First and foremost, I would like to express my gratitude to Prof. Christian Bernhofer, my PhD advisor, for giving me the opportunity to write this study and for all his support, supervision and encouragements that made this work possible. Thank you for being my "father" during my doctoral process.

I would like to thank Rico, my co-supervisor, who kept me focused and my head above the water despite the challenges arose during the process.

I am grateful to Judith, my dear sister in faith, friend and office colleague, for all kinds of support and encouragement.

Thanks to Ivan for the fruitful discussions about the work and for staying by my side to finish this project together and most importantly for your great friendship.

Thanks to the chair of Meteorology in Tharandt, to all my all dear Colleagues – Sylke, Heiko, Uwe S., Uwe E., Thomas G., Thomas P., Majana, Gesa, Markus, Philipp, Daniel and Sabine; for all the help in the administrative, technical things and precious lunch breaks together.

I would like to express my sincere gratitude to Christine Ong for being available to proofread this work in English.

I would like to acknowledge the funding institutions that supported me- to DAAD for giving me opportunity to study in Germany, to the EXTRUSO project for providing a platform to develop my skills and knowledge, to Ground watch for the financial support on the last mile.

I express my warmest thanks "Schulhaus" community in Borlas, Charlotte, Sylvio, Andrea and Dominik - for being my family in Germany and for your unconditional love, 24/7 availability.

Special thanks to all brothers and sisters in Church here and there elsewhere in the world, particularly the Köhler family, for your support and prayers

Thanks to the Grießbach family, who not only provide me with a place to stay but also as my close "Borlasers".

Thanks to countless encounters, who I cannot list here or remember now, which have given me strength and encouragement.

Last but not least I am so grateful to my family in Vietnam, who are far but always in my heart.

Thank You so much for all the love the Father has given me!

Appendixes including the core publications

hydrology

MDPI

Article

Pseudo-Spatially-Distributed Modeling of Water Balance Components in the Free State of Saxony

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Received: 16 October 2020; Accepted: 9 November 2020; Published: 9 November 2020

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Abstract: Highly-resolved data on water balance components (such as runoff or storage) are crucial to improve water management, for example, in drought or flood situations. As regional observations of these components cannot be acquired adequately, a feasible solution is to apply water balance models. We developed an innovative approach using the physically-based lumped-parameter water balance model BROOK90 (R version) integrated into a sensor network platform to derive daily water budget components for catchments in the Free State of Saxony. The model is not calibrated, but rather uses available information on soil, land use, and precipitation only. We applied the hydro response units (HRUs) approach for 6175 small and medium-sized catchments. For the evaluation, model output was cross-evaluated in ten selected head catchments in a low mountain range in Saxony. The mean values of Kling–Gupta efficiency (KGE) for the period 2005–2019 to these catchments are 0.63 and 0.75, for daily and monthly discharge simulations, respectively. The simulated evapotranspiration and soil wetness are in good agreement with the SMAP_L4_GPH product in April 2015–2018. The study can be enhanced by using different data platforms as well as available information on study sites.

Keywords: water balance components; soil moisture simulation; hydro response unit; BROOK90; SMAP soil moisture data

1. Introduction

Spatiotemporal information of water balance components is important for many aspects of water management, hydrological modeling, and forest management [1–3]. It often serves as the initial information used by hydrological models to describe discharge generation processes [4,5] and, thus, can be applied in the impact assessment of flood events. However, information on precipitation, evapotranspiration (ET), and soil moisture (SM) on a regional scale are increasingly important for assessing droughts as well [6–8]. This is especially the case in Europe, which has suffered in various economic and social sectors in recent years due to ongoing droughts, even though it is considered a water-rich continent [9,10]. With the increasing effects of climate change, the need for regional hydrological information becomes more relevant because of the high intensity of the increase of all kinds of water-related extreme events [11,12].

The ability to describe the water balance on a regional level thoroughly is linked to the information availability of its components. While precipitation, main driver of the water balance, and discharge (Q) can both be measured and interpolated via different methods, information on ET and SM are rather limited. On a regional scale, it is not feasible to measure such components due to the high-cost demand for logistics and technical devices [13,14]. Despite the growth of in-situ measurement networks, for instance, the International Soil Moisture Network [15], SM data is still scarcely available [1]. Besides, information from these sources are point-scale observations, which are representative over only a volume of a few centimeters [14,16]. Regarding ET, a global network of micrometeorological tower sites are putting effort to capture ET using the eddy covariance technique, for footprints of 10 to 100 m; however, the number of these sites is still limited to around 1000 worldwide [17].

To compensate for the spatial limitations of in-situ measurements, remote sensing products are gaining rapid attention, especially in hydrological modeling [18,19]. Recent common products are soil moisture active passive data (SMAP) at 9 km × 9 km resolution from a National Aeronautics and Space Administration NASA mission [20,21], and soil moisture and ocean salinity data (SMOS) at 25 km × 25 km from a European Space Agency (ESA) mission [22]. Both have been assimilated in various hydrological models to improve Q prediction [23,24], and have also been applied in deriving SM deficit for drought monitoring in India [25]. However, the resolutions of these products are still too coarse for regional-scale applications [5], and the laser penetration of these satellites are rather shallow and confined to surface measurements (e.g., 5 cm) [26]. Due to the limitations of both in-situ measurements and remote sensing techniques to capture water balance components at high resolution, water-balance models are often considered a good alternative to derive spatially and temporally consistent water balance components.

There are numerous studies available on simulating water balance components in various spatial and temporal resolutions. At point scales, a water balance simulation is often carried out only for a specific tree species or crop type [27–29]. In this field, Schmidt-Walter et al. [3] contributed a remarkable work by establishing water budget simulations for 8800 inventory clusters in forests across Germany. However, the point scale approach is limited by its spatial distribution. Many efforts, hence, endeavor to upscale from point simulation to a regional scale models. For instance, Schwärzel et al. [2] applied a GIS-based modeling approach for predicting and regionalizing water balance components at a 2 km × 2 km testing area in a forest site. Zink et al. [1] established highly-resolved water fluxes at a 4 km × 4 km resolution for the entirety of Germany. Last, but not least, Vorobevskii et al. [30] upscaled it globally using global data sets. Even though the regional simulation approach can provide water balance components spatially, the current achieved resolution is not adequate or limited for hydrological applications, particularly in spatially-distributed hydrological modeling. Thus, this raises a challenge for a simulation approach to estimate water balance components at high resolution, particularly make them applicable to spatially-distributed hydrological models.

This study presents an approach to simulate spatially distributed water balance components with a plot-scale model. The physically-based lumped model, BROOK90, is set up for the whole Free State of Saxony (Germany) with automatized implementation of land cover (CORINE (2012)) and soil information (BK50), as well as automatic retrieval of meteorological input from a sensor platform. We took advantage of the EXTRUSO project as a web-based information system providing all necessary data [31]. We performed the catchment simulations based on their hydro response units (HRUs) for the whole region and compared the model results to the observed discharge and simulated ET and SM (SMAP data [20]). The focus of the validation is on small to medium-sized and headwater catchments, which are mostly ungauged [32]. In these areas, data inputs are rather unavailable; thus, automatic data retrieval is tested to overcome this limitation.

With this approach, we will clarify (1) if the automatic parameterization of HRUs works reliably throughout the whole region of Saxony based on given datasets, (2) how reliable an uncalibrated model version gives suitable results for Q and ET/SM, and, thus, can show (3) if a physically-based lumped model can substitute spatially-distributed modeling on a regional scale.

2. Materials and Methods

2.1. Study Area

The German federal state Free State of Saxony is located in the moderate climate zone of Central Europe but shows a more continental climate than the West and North of Germany [33]. Within Saxony, regional climate differences can be observed. The average annual temperature (1991–2005) in the northern flat and central hilly part (Figure 1) was between 8.5 °C and 10 °C, the low mountain ranges were between 6 °C and 7.5 °C, and Fichtelberg was the coldest region, at about 4 °C [34]. Average annual precipitation in the lowlands was 500 to 800 mm and about 900 to 1200 mm in the low mountain ranges for the same period. From the hydrological perspective, the most important and largest river is the Elbe, which flows through Saxony from southeast to northwest. The other main rivers Mulde, Weißeritz, Zschopau, and Weiße Elster, which originate from Ore Mountains, contribute to the Elbe river system from the southern direction (Figure 1). The most common land-use in the whole region are agriculture and forestry, with additional urban areas and open water bodies spread over Saxony. The soil varies from loamy soils and sandy soils in the central and northern part of Saxony, to soils with high stone fractions in the low mountain ranges [35,36].

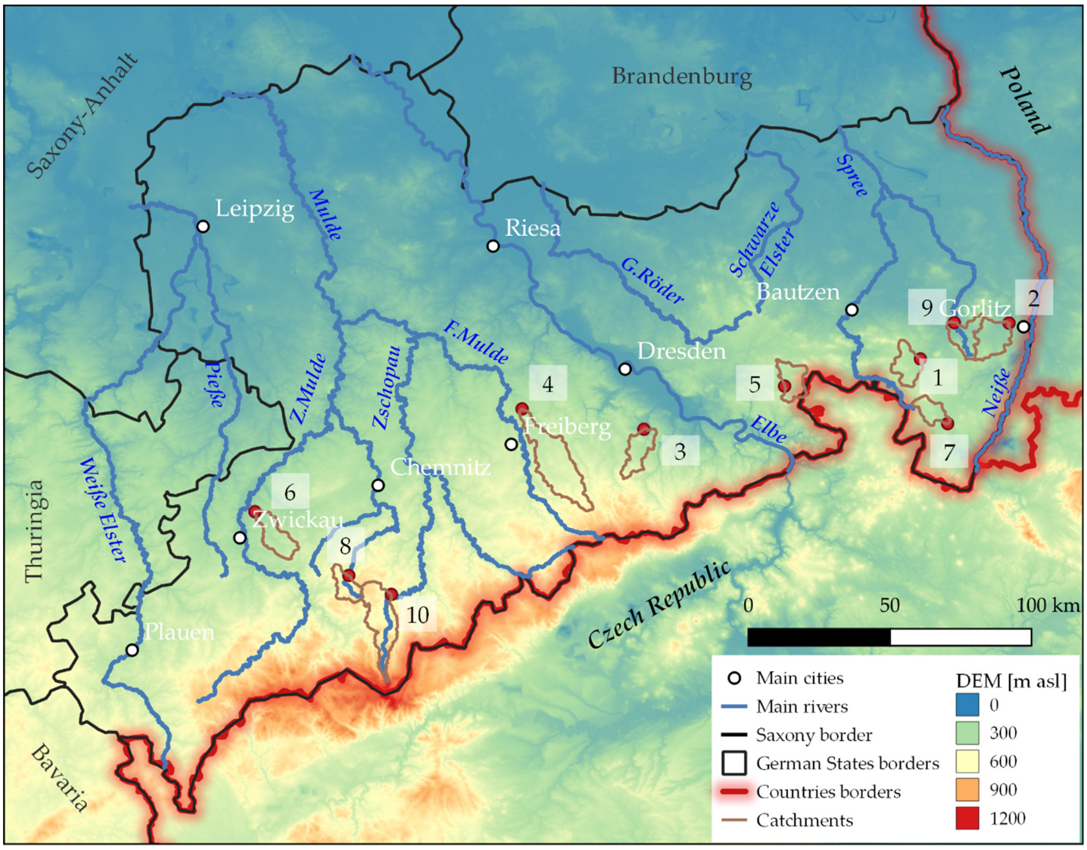

Figure 1. An overview of ten selected catchments for validation (WGS-84 Pseudo-Mercator projection) with a background from a digital elevation model (DEM) based on SRTM30. The ID numbers of the catchments can be referred to in Table 1.

The validation of the model performance was carried out based on ten selected catchments according to the following criteria: (1) small to medium catchment size (<200 km^2), (2) variance in area and elevation, and (3) no proven human activities (dam, reservoir, the domination of urban areas) based on satellite images. The selected catchments are shown in Figure 1. They have an area from 30 to 130 km^2 and are located between 124 to 660 m.a.s.l. The main characteristics of the selected catchments are summarized in Table 1.

Table 1. Summary of important characteristics of selected catchments.

Catchment/ID		Area (km^2)	Average Elevation (m.a.s.l.)	HRU/Km^2	Land Use [%]				
					Agriculture	Grass Land	Deciduous Forest	Evergreen Forest	Other
Großschweidnitz	1	41.44	239.66	7.2	47	21	2	18	12
Holtendorf	2	54.17	269.29	3.4	65	13	2	13	7
Kreischa	3	43.88	384.91	11.2	44	25	4	22	5
Krummenhenners-dorf	4	130.92	476.96	4.0	57	29	0	5	9
Neustadt	5	40.18	386.16	7.7	30	24	4	28	14
Niedermuelsen	6	49.58	355.61	9.7	47	21	1	18	13
Niederoderwitz	7	28.87	123.80	3.1	53	18	2	4	23
Niederzwoenitz	8	31.36	600.58	2.8	29	16	0	44	11
Reichenbach-Oberlausitz	9	42.51	266.05	6.2	64	18	3	6	9
Tannenberg	10	91.48	662.02	4.3	24	23	1	42	10

2.2. Model Setup

2.2.1. BROOK90

The BROOK90 model is a physical lumped-parameter water budget model designed for small, uniform catchments. It is widely applied to estimate daily water fluxes at the soil-plant-atmosphere interface [2,29,37], especially due to its good representation of ET. ET is considered in BROOK90 by applying the well-known Penman–Monteith equation twice: once for the canopy and once for the soil surface [38]. Soil water movement is described by multiple soil layers with saturated and unsaturated matrix flow and macrospore flow using Richard's equation. Soil water retention and hydraulic conductivity in the soil profile is described by applying a modification of the Campbell expressions [39], with near saturation interpolation of Clapp and Hornberger [40]. The model can operate with different levels of meteorological data input, from a minimum input of daily data of precipitation and minimum and maximum temperature (Tmin and Tmax) up to daily values for precipitation, Tmin and Tmax, solar radiation, vapor pressure, and wind speed.

This study uses an identical translation of the original BROOK90 model [38] in the R environment (BR90-R), documented and available via GitHub (https://github.com/rkronen/Brook90_R). BR90-R enables not only to enhance the operation of the model in a sensor network but also to run the model in parallel modes for a large number of simulations.

2.2.2. Land Cover Parameterization

The land cover (in BROOK90: canopy) parameters, such as leaf area index (LAI), canopy height, albedo, maximum canopy conductance, a fraction of resistance, maximum leaf conductance, and relative root density are needed as model input. The land covers in this study were derived from the CORINE 2012 map (European Environment Agency), which contains 31 different categories of land cover types at high resolution (100 m). The categories are static; in other words, land cover aging is neglected. To date, there is no common way of translating land use characteristics into the mentioned parameters [30,41,42]. We simplified the 31 land cover categories into the five most common (dominated types in the study area) to reduce the associated uncertainties when considering more types. We thereby could take advantage of the well-documented canopy parameter choices by Federer et al. [38], with further adjustment from the extensive measurements in the Tharandt forest of Bernhofer et al. [43] and profound literature studies of Peters et al. and Schwärzel et al. [28,44]. Table 2 shows an overview of the simplification and the area percentage of the re-categorized land covers in Saxony. Each category of land cover was assigned a specific set of parameters. In the study sites, the coniferous and mixed forests have similar characteristics to evergreen forests and the broad-leaved forest's characteristics are similar to the deciduous forest. Thus, we arranged them accordingly (Table 2). Due to the lack of information from specific tree species, the spruce tree was chosen as representative for the evergreen forest, and the deciduous forest, we selected the beech tree as representative. Since BROOK90 is not meant to apply in urban areas and open water bodies, those areas were parameterized and treated as missing information in the modeling approach.

Table 2. Overview of simplified land uses derived from the CORINE map applying for Saxony.

Simplified Land Used	Percentage (%)	Categories in CORINE Map
Evergreen Forest	14.0	Coniferous and mixed forest
Deciduous Forest	23.0	Broad-leaved forest
Agriculture/Cultivated Land	47.0	Land principally occupied by agriculture, significant areas of natural vegetation, complex cultivation patterns, fruit tree and berry plantations, non-irrigated arable land, agricultural farms.
Grassland/Meadows	3.2	Natural grassland, pasture, meadows and other permanent grasslands under agricultural use
Urban Infrastructure/Others	12.8	Continuous urban fabric, road and rail networks, and associated land, mineral extraction sites, airports, watercourses.

2.2.3. Soil Parameterization

The soil parameterization in BROOK90 requires information of matric potential, soil water content at saturation and field capacity, exponent in the Brooks and Corey equation as given by Clapp and Hornberger [40], hydraulic conductivity at field capacity, and wetness at the dry end of the near-saturation range for a soil layer for each layer of a soil profile. This soil information for whole Saxony can be derived from the BK50 with a 50 m resolution. The BK50 contains specific properties for each soil types, which are classified into 31 soil classes (Figure 2, in black) based on the soil textural properties (percentage of sand, loam, and clay), according to soil science mapping guide (Bodenkundlichen Kartieranleitung, version 5, table 76) [45]. In Saxony, the BK50 in total encloses approximately 1000 soil profiles. They are extended to a maximum of 2.7 m soil depth, if not limited by bedrock.

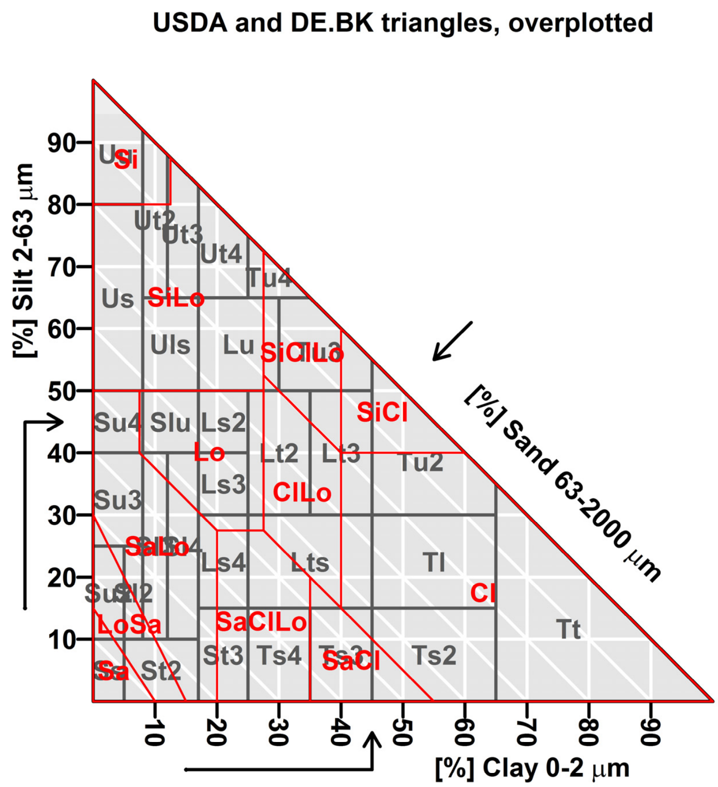

Figure 2. Over plotted soil types classified after the American system USDA (in red) and the German system (in black). The abbreviations of the soil types in the two systems are well documented in the "soiltexture" package.

BK50's physical properties of soil (bulk density, soil textures of sandy loam and clay) with the help of pedotransfer, can be used to describe soil hydraulic properties, such as soil water retention and hydraulic conductivity functions [3,46]. As suggested by Federer et al. [38], the Clapp and Hornberger hydraulic parameters [40] were applied to describe water movement in soils. However, the parameters sets are available for 12 different soil types (Figure 2, in red), classified according to the American system, USDA [47]. To take advantage of these detailed soil parametrization, we translated the 31 BK50 soil types of the German system into 12 USDA ones using soil texture information, particularly the percentage of sand, silt and clay provided in the associated table of the BK50 (Figure 2). Details can be found in the documentation of the R-package "soiltexture" (https://github.com/julienmoeys/soiltexture).

2.2.4. Spatial Realization

The spatial realization of the model is done with hydro response units (HRUs), also known as hydrotopes. An HRU is defined as a unique combination of topography, land cover, and soil profile. The characteristics required for model parametrization are derived from a 10 m digital elevation model (DEM) and a digitalized soil map at 50 m resolution (BK50), which are provided by LfULG (Sächsisches Landesamt für Umwelt, Landwirtschaft und Geologie, Datenportal für Sachsen), as well as a land cover map at 100 m resolution (CORINE 2012). Fixed parameters were set with default values, as suggested by Federer et al. [38].

HRUs are defined by uniform areas within the catchment according to soil and land-use via superposition. As a result, the Free State of Saxony is split into 115578 HRUs with areas ranging from 2.53×10^{-10} km^2 to 31 km^2 (median value at 0.037 km^2). Water balance processes are simulated at the HRU scale for all catchments meaning: Each HRU is considered a homogeneous area that allows a plot-scale simulation. BR90-R is thus run for each HRU to estimate water fluxes. The area-weighted average of all HRUs inside the catchment border estimates the final catchment fluxes. Small catchments can already contain up to 100 HRUs or more depending on their location and the resolution of the underlying information of land use and soil. A high number of HRUs considers the variability of the land surface in a catchment; however, this requires high computational effort to use in models.

Since the scope of the study is to represent the water balance on a small to medium catchment scale, Saxony was simulated based on catchments with areas ranging from 0.001 to 115 km^2 (with a median value of 3 km^2). LfULG provides the shapefiles of all 6175 catchments in Saxony. Border catchments with the German States Bavaria, Thuringia, Saxony-Anhalt, and Brandenburg, as well as the Czech Republic or Poland, are included in the simulations only if a minimum of 75% of the area is within the territory of Saxony. In these cases, the external area is not considered in the model and the information from within Saxony is used as a representative for the whole catchment. This setup is due to data availability, which is "State-based" within Germany.

An example of the described approach is given with the Niedermuelsen catchment, as shown in Figure 3. The simplified land use map (b) was intersected with the transformed soil map (c) to derive the combination of HRUs (d). Thus, approximately 500 HRUs are found in the area of 50 km^2 within the catchment.

Note that the model structure does not allow water exchange between the HRUs, thus, no water flow (routing) within a catchment. The modeling is not fully distributed, but a rather pseudo-spatial representation of water balance components for a catchment. Furthermore, the groundwater recharge process associated with flow parameters in the model is not considered in this study. The evaluation of bypass flow and groundwater flows to the model performance, which requires a systematic calibration, is worth to be a topic on its own. Thus, we focus on an uncalibrated model approach to evaluate the performance of the physically-based parameters. In addition, the meteorological data input is generated for the catchment only, not for each HRU.

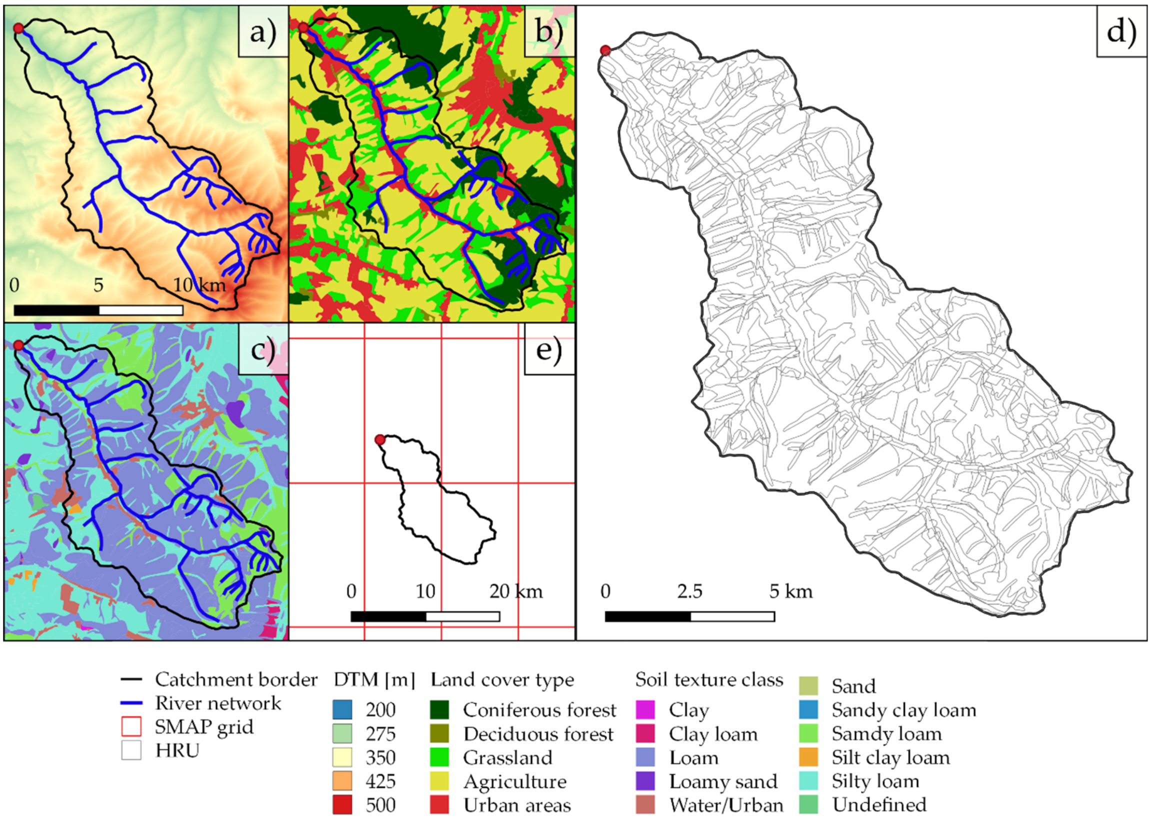

Figure 3. An overview of the input datasets (WG-S 84 projection), exemplary for the Niedermuelsen catchment: (**a**) digital elevation model (DEM) based on 10 m, (**b**) land use map simplified from CORINE 2012, (**c**) soil map converted from USDA soil classes and simplified from BK50, (**d**) hydro response units (HRUs): intersecting between simplified CORINE and BK50 and (**e**) SMAP_L4_GPH grid tiles.

2.2.5. Meteorological Data Input

BR90-R requires meteorological measurement information as data input. This data is obtained from the web-based information system described in Wiemann [48], which was developed as part of the EXTRUSO project (https://extruso.bu.tu-dresden.de) at TU Dresden. The platform automatically retrieves and integrates data from various in-situ sensor networks on an hourly basis. This data can be subsequently accessed, processed and downloaded, e.g., for a certain study site. For the area of Saxony, data from more than 2000 hydrological and meteorological sensors are made available. The R-based xtruso package (https://github.com/GeoinformationSystems/xtruso_R) was developed to facilitate the integration of this data for meteorological and hydrological modeling. By using this package in combination with the aforementioned sensor information system, input for the BROOK90 model is generated as follows:

1. Selection of a catchment by using catchment ID number integrated with the package;
2. Automated extraction of relevant catchment information, i.e., elevation, soil profiles and land covers;
3. Automated search for in-situ measurement stations in the surrounding of the catchment (maximum ten stations with a maximum height difference of 200 m to avoid elevation effects);
4. Automated extraction and daily aggregation of measurement time series for the identified in-situ stations.

The final input values at the catchment location are estimated from the surrounding measurements by the inverse distance weighting method, widely applied for interpolating climate variables [49–51]. The model input requirements are fulfilled by the following daily statistics:

- Mean global radiation;
- Maximum/minimum temperature;
- Mean vapor pressure deficit derived from the mean temperature and the mean relative humidity based on the Magnus equation;
- Mean wind speed; and
- Precipitation sum.

The generated time series serve as data input for all HRUs of the corresponding catchment.

2.3. Model Application and Validation

2.3.1. Model Applicability Test

Implementing the model approach for the whole Free State of Saxony requires a lot of computational time and effort. Each catchment simulation will use the automatic retrieval of meteorological data input, making the simulation of the whole region very time-consuming, even though a parallel mode was integrated into the code. To reduce time, we did a pre-screening of the region by applying the same meteorological data input for six years to all HRUs to test the general possibility of spatial water balance simulation. As a result, around 80% of the area of Saxony was able to be simulated (Figure 4, green color). In particular, this area covers the catchments in the mountainous areas, which have more flooding potential and are where it is difficult to acquire the water fluxes in high resolution. The model did not work for the remaining 20% (also presented in Figure 4). Most errors are caused by translating soil profiles from BK50 into BR90-R (black color). Another error was associated in areas with shallow soil in the upper layers (brown color). During periods of drought, the simulated amount of ET will exceed the simulated amount of water contained in the soil, which will cause the model to stop. Urban areas (red color) are too heterogeneous to model for BR90-R; thus, no reliable parameters are available for this category of land cover. Finally, areas of large water bodies such as rivers, lakes or reservoirs (blue color) are not considered as the BK50 does not provide any soil profile information in these areas.

2.3.2. Validation

The calibration of parameters was not the scope of this paper since we were interested in the raw results of using meaningful physical parameters in BR90-R. Thus, the model performance was directly evaluated against Q, ET, as well as SM data at different spatial and temporal resolutions. The simulation period is 2005–2019, which resulted from a limitation caused by the platform's data storage capacity. Note that evaluating the model outputs requires excluding a three-month spin up period at the start of each BROOK90 model run to allow the SM to reach a point of equilibrium to avoid its effect on hydrological processes.

A. Q: simulated Q was compared with daily and monthly time series of data from flow gauges for the whole simulation period of 2005–2019. The observed Q data for the selected catchments is available in an hourly resolution and unit m^3/s provided by LfULG. To use the data in BR90-R, all values were converted to mm/d by considering the catchment area and aggregating Q to daily values.

B. ET: since observed ET from direct measurements is not spatially available in general, we chose to take data from the satellite-based SMAP product, which is based on the Catchment land surface model (LSM) of the NASA Goddard Earth Observing System version 5 (GEOS-5) modeling and assimilation framework [20,52]. ET is taken from SMAP's Level 4 surface and root-zone soil moisture product (SMAP_L4_GPH) with a spatiotemporal resolution of 9 km × 9 km and 3 hour intervals [20,21]. An illustration of SMAP_L4_GPH grid cells with the example of the Niedermülsen catchment can be seen in Figure 3e. ET data of the product was extracted from all grid cells that are partly or fully covering the considered catchment, area-weighted averages applied and aggregated to daily resolution for validation. Due to data availability, the validation period for ET was chosen from April 2015 to 2018.

C. SM: SM data were retrieved from SMAP_L4_GPH similar to ET with the following additional step: SM from BR90-R was divided into the soil profile porosity (BK50) to derive SM wetness, which is comparable with SM from SMAP. The same validation period as ET was chosen. Note that both described, SM and ET are not considered true observations, rather additional sources to cross-check the model performance. Still, both assimilated values are based on observations by the satellite.

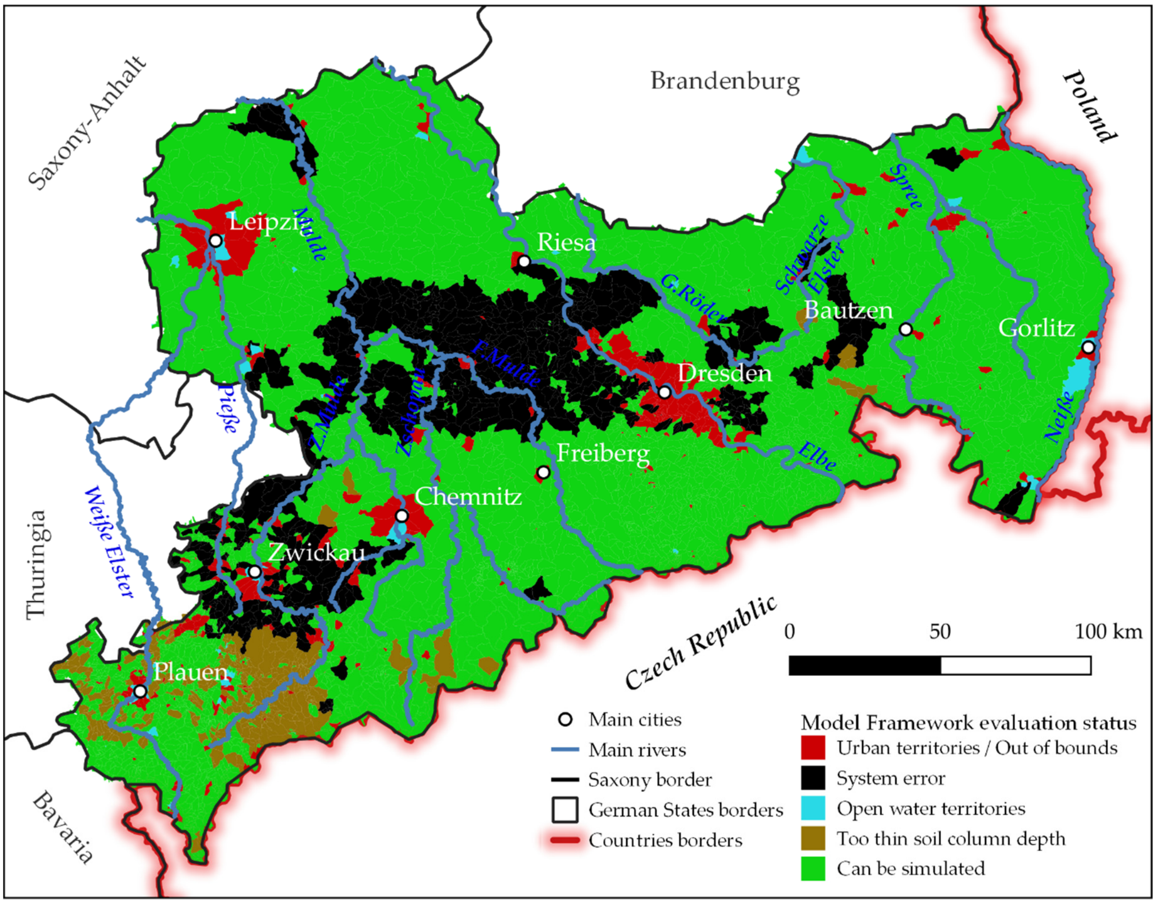

Figure 4. Overview of the approach performance in the Free State of Saxony.

As commonly done in hydrological research and other disciplines [22,53], the skill score Kling–Gupta efficiency (KGE) [54] and its decomposition components (correlation, mean bias, and variability bias) were chosen to quantify the model results with the following Equation (1):

$$KGE = 1 - \sqrt{(R-1)^2 + (\alpha - 1)^2 + (\beta - 1)^2} \quad (1)$$

With R being the correlation coefficient, $\alpha = \sigma_{sim}/\sigma_{obs}$ the standard deviations σ of simulations and observations, and $\beta = \mu_{sim}/\mu_{obs}$ being the ratio of the simulated and observed means μ. KGE will equal 1 for a perfect fit of the simulation when R, α and β are all at their optimal value 1. One of the advantages of using KGE is the consideration of multiple aspects in the comparison. However, according to [55], the KGE value at-0.41 shows that the model performance is as good as the observed mean flow.

3. Results and Discussions

3.1. Variation between HRUs

The comparison of simulated and observed water balance components are shown with the example of Krummenhennersdorf catchment in Figure 5.

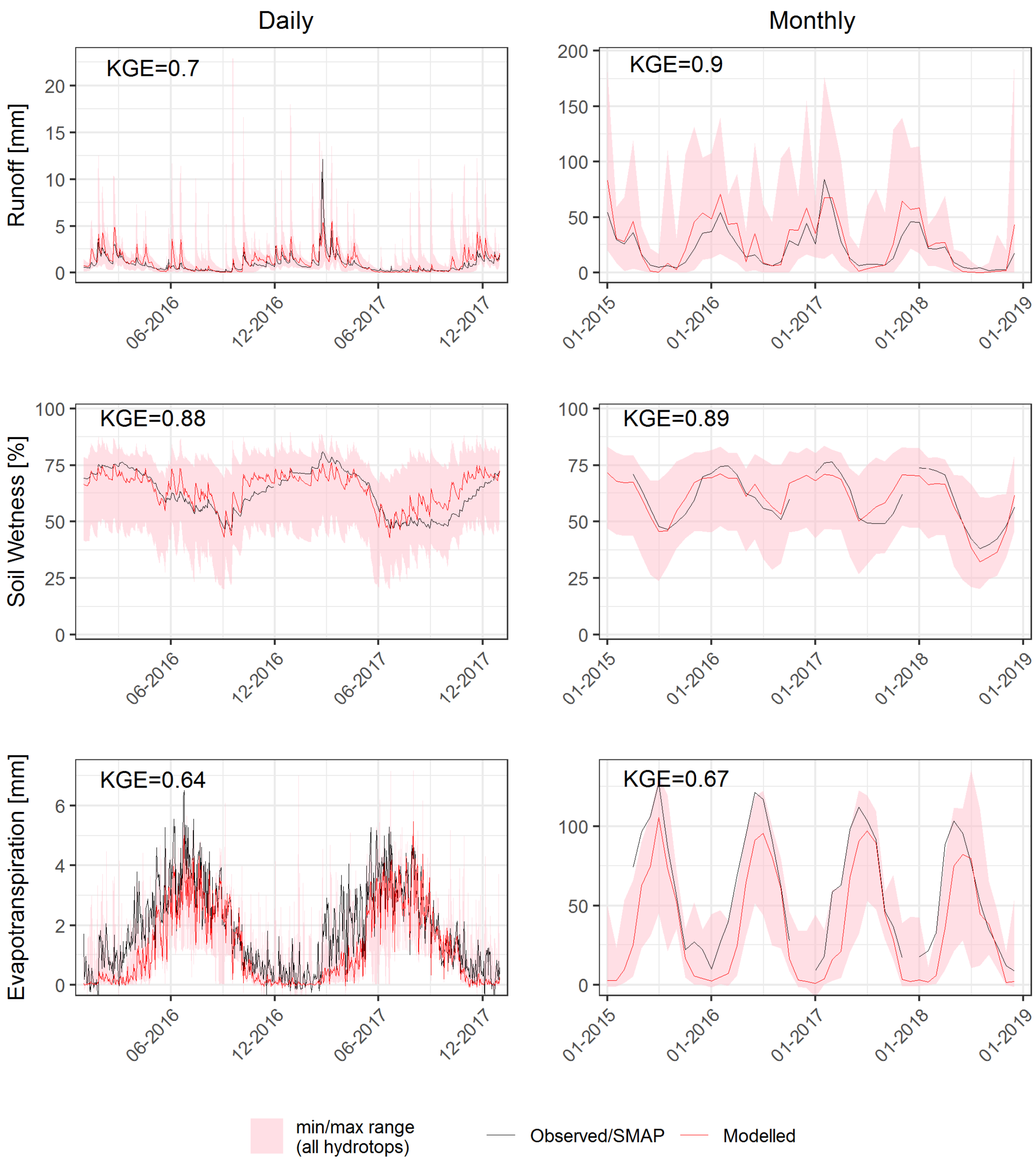

Figure 5. Daily and monthly time series of simulated (weighted mean and maximum/minimum range from all hydrotops) runoff, soil wetness, and evapotranspiration (ET) compared with observations for the Krummenhennersdorf catchment (4) as exemplary. The data gaps of monthly soil moisture (SM) and ET (observed/ soil moisture active passive data (SMAP)) are caused by missing values in SMAP_L4_GPH product, thus, are not considered in the validation.

Figures for other catchments can be found in the Supplementary Materials. For a better display, daily values (left column) are shown from January 2015 to December 2016 (2 years), and monthly values (right column) are shown from January 2015 to December 2018. Modeled and observed Q values matched well on the seasonal dynamics of water flow, namely high Q in the spring months due to snowmelt and low in summer months due to the high rate of ET. Generally, good agreements are seen in both temporal scales. Particularly, the long duration of low flow conditions in the year 2018 (and, not shown in Figure 5: 2019) due to the drought situation in Germany was captured well. The simulated peak flows are overestimated on a daily scale; however, they are improved on a monthly scale. The seasonal pattern of SM and ET are visible on daily and monthly scales with wet soils in winter months and dry soils in summer months, as a consequence of ET response to inter-annual radiation pattern. This behavior was observed in all selected catchments. Interestingly, the drought from 2018 (whole Germany) via SM was clearly shown in the simulation results.

Generally, the selected catchments show no distinct difference in the behavior of the water components itself since they are located in the same climate zone. Within one catchment, there is a large range between minimum and maximum values of the corresponding hydrotopes for all water balance components, indicating the great variety of possible catchment responses. Due to the general higher variability of flow values, the range of simulated discharge values is higher than for ET and SM. From the first impression, it seems that the average values of simulated SM especially fits well with the SMAP observations and that there is a good representation of the ET pattern while the ET values of SMAP seem to be a bit replaced, especially for summer months. One interesting observation was that the range of SM values between the HRUs is similarly high for all catchments, independent of their area sizes. These variations show the high spatial heterogeneity of SM and, thus, emphasizes the importance of representing SM at a high resolution [16,56].

3.2. Skill Score

3.2.1. Catchments Average

In this section, we present a quantitative evaluation via selected skill scores for simulated water balance components. The area-weighted mean values of the considered variables Q, SM, and ET (red lines in Figure 5) were used as representatives for the catchments for comparing the simulations with observations. The mean values of the skill scores for all ten catchments are displayed in Table 3. On a daily scale, the mean values for daily Q are 0.63 (KGE), 0.72 (R), 1.04 and 1.04 (ratios of standard deviation (α) respectively mean (β)), which indicate an acceptable performance of the model. A slight improvement of the Q simulation was observed on a monthly scale (0.75 (KGE), 0.88 (R), 1.16 and 1.04 (α and β)). While high values of KGE and R confirm a good performance of the model approach, the values of α and β greater than one shows an overall overestimation of Q. This issue is likely caused by excluding bypass flow and groundwater recharge processes from the simulation. Thus, water, which is lost to an aquifer, is eventually accumulated at the catchment outlet. A similar conclusion was drawn by Vorobevskii et al. [30], which also applied a similar approach.

Table 3. Average skill score of all catchments (KGE: Kling Gupta efficiency, R: Pearson correlation, α: standard deviation ratio, β mean ratio between BROOK90 model outputs and "observation") for discharge (Q), SM and ET.

Variable	Validation Period	Daily Resolution				Monthly Resolution			
		KGE	R	α	β	KGE	R	α	β
Mean Q	2005–2019	0.63	0.72	1.04	1.04	0.75	0.88	1.16	1.04
Mean SM	2015–2018	0.76	0.86	0.79	0.94	0.76	0.87	0.76	0.94
Mean ET	2015–2018	0.62	0.83	0.86	0.70	0.65	0.92	0.87	0.71

The skill scores of SM between the two datasets of BR90-R and LSM from SMAP products show an overall good correspondence on a daily scale and a monthly scale. The values for both scales are almost identical. High KGE (KGE > 0.75) and correlation (R > 0.85) was observed in the validation period. However, α (<0.8) and β (=0.94) indicate, in general, an underestimation of soil wetness derived from

BR90-R compared to LSM. This result arises because of the differences in the model setups, e.g., due to model structure, data input, land cover map, soil map, parameterization approach as well as resolution. Additionally, the pedotransfer function applied in the LSM was derived from Wösten et al. [46] and updated by De Lannoy et al. [57], which has a different approach compared to the Br90-R [38]. Last but not least, the non-representative of 9 km × 9 km model grid cell of SMAP for the area-weighted mean of the HRUs approach can be accountable for this underestimation.

Similarto the SM results, the skill scores of ET for the two products show a good agreement on both scales. While KGE > 0.6 and R > 0.8 exhibits a relatively good correlation of ET, $\alpha = 0.86$ and $\beta = 0.70$ indicate the underestimation of ET from the BR90-R compared to ET from LSM. Even though both models use the Penman-Monteith equation [58] to describe ET processes, approximately 20% of ET of the BR90-R was less than the one from LSM, which is due to the abovementioned reasons relating to the model setups and miscalling issue.

More detail can be seen in the analyses for individual catchment and seasonal variability in the next section.

3.2.2. Catchment and Seasonal Variation

The evaluation based on skill cores for the simulations and observations varied from catchment to catchment as well as to water balance components (Figure 6). Note that the catchment names can be found via catchment IDs in Table 1. Overall, the water balance components dynamics of ten selected catchments are satisfactorily captured by the model in the study period. The ranges of KGEs for Q corresponding to the ten selected catchments are 0.42 to 0.85 on a daily scale and 0.56 to 0.9 on a monthly scale. The spread of KGEs for the monthly Q is slightly narrower compared to daily flows. This pattern is also applied to R and α values. As expected, the high temporal variability of daily Q is flattened when averaging over a longer (monthly) period, which leads to an overall better agreement between observed and simulated Q. The best model performances were found at Krummenhennersdorf (KGE > 0.85) and Niederzwoenitz (KGE > 0.78), where the differences between daily scale and monthly were minor. A relatively lower model skill in simulating the Q dynamics was observed at Grossschweidnitz, Holtendorf, Niederoderwitz, and Reichenbach Oberlausitz (numbers 1, 2, 7, and 9 in Figures 1 and 6), which are located at the farthest East from Saxony, namely the Oberlausitz region. These results could be attributed to the lack of information on meteorological data input due to a sparse network of sensor measurements. Additionally, sensors data from the neighboring countries, such as the Czech Republic and Poland, are not available, thus, not integrated into this study. Nevertheless, the model performances of the four abovementioned catchments are considered acceptable comparing to those found by previous studies, such as [30,37,59]. Thus, we conclude that the uncalibrated version of the BROOK90 model can capture the Q dynamics in the ten selected catchments.

In addition, evaluating the skill scores for SM and ET between the BR90-R model and the LSM in the study period confirms a good correspondence in all catchments. The ranges of KGEs are 0.6 to 0.89 and 0.55 to 0.69 for SM and ET, respectively (Figure 6). Unlike the Q dynamics, the model performances of SM and ET were consistent on both scales in all catchments. A clear pattern can be observed is that SM and ET from the BR90-R were estimated as lower than from the LSM reveal by the ranges of α (0.54 to 0.94 for SM and 0.71 to 0.96 for ET) and the ranges of β (0.82 to 1.21 for SM and 0.67 to 0.74 for ET). An exception was found at the catchment Neustadt (number 5 in Figures 1 and 6), where soil wetness derived from the BR90-R is wetter than the LSM. This could be attributed to the soil profiles derived from the two maps applied in the models, which accidentally caused the overestimation of SM in the catchment. We observed further the relationships between model performance and the characteristics of the selected catchments (e.g., topography, land cover, area, as well as the density of HRUs, as listed in Table 1). We could not see any correlation. In contrast, the studies of Newman et al. [60] or Mc Millan et al. [61] exhibited a clear dependency between model performance to characteristics, such as the catchment area. Thus, the observation from the ten catchments might suggest the validity of the approach for the regional scale.

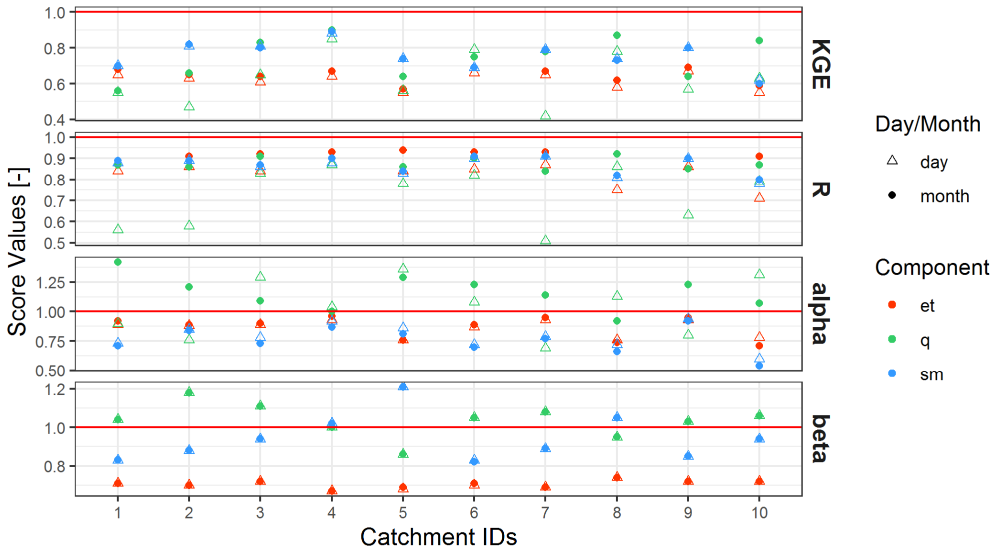

Figure 6. Skill scores of water balance components (ET = et, Q = q, SM = sm) for ten selected catchments on a daily and monthly scale.

The model simulations were further evaluated for the seasonal variability as our study sites are located in a temperate region, which is significantly characterized by seasons. We considered only Q and estimated the selected skill scores in the study period on both daily and monthly scales (Figure 7). The average KGEs on a monthly scale of ten selected catchments is 0.62, 0.70, 0.53, and 0.70 for spring, summer, autumn, and winter, respectively. The highest variation in terms of β (0.6 to 1.6) was observed during spring, when the snowmelt process takes place, and the lowest in winter, in which the loss of ET is lowest among seasons. In addition, we observed very high and consistent correlations in all catchments on a monthly scale in summer, although most of the high precipitation events due to convective rainfall occur during this time. Hence, we can assume that the sensor measurements from the platform can capture such events well. Last, but not least, the consistent values of α and β values reveal outperformance in winter comparing to other seasons. This can be attributed to saturated SM in winter, which supports surface flow processes quickly after a rainfall event. Thus, the impact of the infiltration process is reduced, and the model can well capture the Q dynamics.

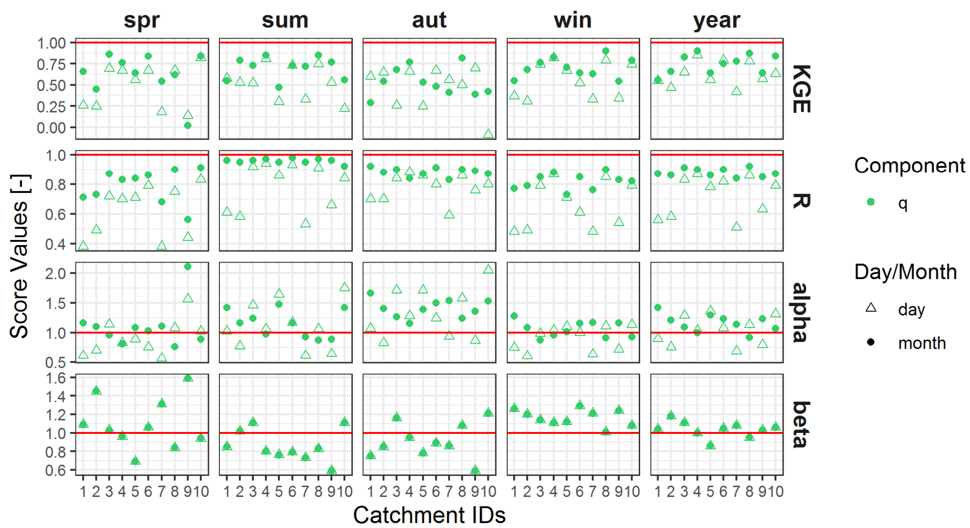

Figure 7. Skill scores of the seasonal variation for Q for ten selected catchments on a daily and monthly scale. The seasons are defined as spring (spr) March to May, summer (sum) June to August, autumn (aut) September to November, and winter (win) December to February.

4. Conclusions and Outlook

In this study, we present a new approach to simulate water balance components at a high spatial resolution using the BROOK90 model integrated into the data platform developed in the EXTRUSO project. The model is not calibrated and its parameters are derived merely by detailed orographic, land use, and soil information, as well as available literature. It is feasible as most of the parameters of the model have physical meanings, which can be measured and/or transferred from similar study sites. The simulations were followed by the HRU approach and applicable for more than 80% area of Saxony. The validation in ten selected head catchments in a low mountain range showed a reliable model performance. Thus, our results underline that the automatic parametrization approach performed assuredly with available information in the study site. Additionally, the uncalibrated model version revealed itself to be able to deliver reasonably distributed water balance components. The study provides a feasible way to consider the changing climate conditions and shows that a physically-based lumped model can substitute for a spatially distributed one on a regional scale. Nevertheless, numerous drawbacks are resulting from the model structure, parameterization approach, modeling concept, and validation data, which will be considered in our ongoing work.

- The lack of routing mode in the model structure causes the estimation of the discharge to be mere as the water remaining after ET, SM, and groundwater processes. Thus, the simulated Q has rather a meaning of an amount of accumulated water than its temporal distribution characteristics [2]. It can be seen at the daily scale of the validation of the ten catchments. Integrating an additional routing mode may solve this problem and would approach fully distributed. It can be implemented as the BR90-R version allows for coupling external modules in its structure; however, this step can cause more computational time and loosen the characteristics of HRUs.
- The evaluation regarding discharge for individual catchments revealed an uncertainty of the model performance in the border region, namely the Oberlausitz at the farthest east of the state. It may be caused by the limitation of the density of climate stations in the region, which makes it difficult to capture the climate conditions representatively. Thus, a high spatial resolution climate dataset such as precipitation from radar data can overcome this issue.
- The 20% areas, where the model cannot be implemented, can be adjusted by modifying the soil profiles. For instance, soils with shallow surface horizons can be fixed by combining several thin layers into one with which we can obtain a new soil profile with similar soil hydraulic properties. For urban areas out of the scope of the application of the model, pre-event SM derivation for an area, the curve number method (also called the Soil Conservation Service or SCS) [62–64] can be applied as a good alternative. The areas that caused system errors were found to be associated with lacking soil profile information from the BK50, which prevents the simulation in the sub-soil-process of the model. Thus, an updated, more precise soil map, is needed.
- The suggested approach to derive parameters from the soil and land use maps is a good practice to translate the characteristics of the catchments to the model. Nevertheless, the parameterization is still limited due to the simplification of land cover classes to one species and the transformation of soil systems. A systematic calibration for all of the catchments might improve or compensate for such discrepancies. In other words, a spatial parameter derivation is needed.
- SMAP_L4_GPH is a valuable data source to validate model outputs, particularly at a regional scale. However, a direct comparison with in situ measurements is a better choice to prove the plausibility of the ET and SM.

Supplementary Materials: The following are available online at https://zenodo.org/record/4095208#.X6K9P7sxmCo, Figures S1–9: Daily and monthly time series of simulated (weighted mean and max/min range from all hydrotops) runoff, soil wetness and ET compared with observations for the selected catchment (IDs from 1–3 and 5–10).

Author Contributions: All authors made a significant contribution to the final version of the manuscript. Conceptualization, T.T.L., J.P., and C.B.; data and materials, T.T.L., R.K., and S.W.; methodology, T.T.L. and J.P.; technical implementation, S.W.; validation, T.T.L., I.V., and J.P.; writing—original draft preparation, T.T.L.;

writing—review and editing, all authors. All authors have read and agreed to the published version of the manuscript.

Funding: The research was supported in the framework of the EXTRUSO project funded by the European Social Fund (ESF) under award number 100270097.

Acknowledgments: We thank all colleagues at the Chair of Meteorology in Tharandt for their support as well as Aaron Semmling for his contribution via his master thesis. We are also grateful for the comments and materials of Rolf Reichle und Gabrielle J. M. De Lannoy regarding the SMAP_L4_GPH products. Special thanks goes to Michael Wagner for providing his contribution to the soil map BK50.

Conflicts of Interest: The authors declare no conflict of interest.

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The second article of this dissertation, “Integration of Long-term Radar-derived Precipitation to Improve Water Balance Estimations: A Case Study for Multiple Catchments in Saxony, Germany”, cannot be republished here (at this point) due to conflicting publication rights.

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Rainfall Threshold for Flash Flood Warning Based on Model Output of Soil Moisture: Case Study Wernersbach, Germany

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Abstract: Convective rainfall can cause dangerous flash floods within less than six hours. Thus, simple approaches are required for issuing quick warnings. The flash flood guidance (FFG) approach pre-calculates rainfall levels (thresholds) potentially causing critical water levels for a specific catchment. Afterwards, only rainfall and soil moisture information are required to issue warnings. This study applied the principle of FFG to the Wernersbach Catchment (Germany) with excellent data coverage using the BROOK90 water budget model. The rainfall thresholds were determined for durations of 1 to 24 h, by running BROOK90 in "inverse" mode, identifying rainfall values for each duration that led to exceedance of critical discharge (fixed value). After calibrating the model based on its runoff, we ran it in hourly mode with four precipitation types and various levels of initial soil moisture for the period 1996–2010. The rainfall threshold curves showed a very high probability of detection (POD) of 91% for the 40 extracted flash flood events in the study period, however, the false alarm rate (FAR) of 56% and the critical success index (CSI) of 42% should be improved in further studies. The proposed adjusted FFG approach has the potential to provide reliable support in flash flood forecasting.

Keywords: rainfall threshold; flash flood warning; antecedent soil moisture; BROOK90 model; EXTRUSO project

Citation: Luong, T.T.; Pöschmann, J.; Kronenberg, R.; Bernhofer, C. Rainfall Threshold for Flash Flood Warning Based on Model Output of Soil Moisture: Case Study Wernersbach, Germany. *Water* **2021**, *13*, 1061. https://doi.org/10.3390/w13081061

Academic Editor: Yurui Fan

Received: 4 March 2021
Accepted: 9 April 2021
Published: 12 April 2021

1. Introduction

Flash floods (FF) are considered one of the most dangerous flood types due to their sudden occurrence and potentially severe impacts. The term "flash" reflects the rapid reaction of a drainage network with water levels reaching a critical stage within only minutes to a few (usually less than six) hours after the onset of a heavy rainfall event [1–3]. This leaves an extremely short flood warning time which can cause tremendous socio-economic damage [4,5]. Typical consequences of such events include local flooding, soil erosion, debris and destruction of buildings and infrastructure, which are potentially dangerous for human life [6,7]. The majority of flash floods take place in small to medium-sized and often ungauged catchments. In the near future, these events are likely to increase in frequency and intensity with the impact of climate change [8].

Flash flood conditions are usually difficult to model, monitor and forecast [3,9]. Due to the fast rise in discharge and water level, a flood warning based on the evaluation of measured precipitation or stream gauges would be often too late to prevent a serious impact. Instead, the flood or hazard potential must be estimated from meteorological or hydrological forecasts. One commonly used approach for flash flood warning is so-called flash flood guidance (FFG), where flood warnings are issued solely based on pre-event soil moisture conditions and rainfall forecast information. The method uses a simple comparison of accumulated (forecasted) rainfall with critical values of rainfall [1,2]. These rainfall thresholds are estimated once based on catchment characteristics and flood warnings are issued when they are exceeded for the specific rain forecast. The method was originally designed and implemented by the US National Weather Service in the 1970s and has been operated in several countries [2,4,10]. However, a method for deriving rainfall thresholds for early warning of precipitation-related flooding may differ depending on the hypothesis adopted, such as probabilistic or deterministic [11]. De Luca and Versace (2017) discussed in detail various schemes that can be used for rainfall thresholds and suggested careful consideration for selecting a scheme for rainfall threshold estimation to avoid confusion in its use in early warning.

This study used a relatively simple and flexible model that can be later applied to gauged as well as ungauged catchments. BROOK90 delivers soil moisture based on the water balance, indicating the pre-event catchment state in the case of FF. Most recent studies on flash flood warnings based on the FFG approach used only rainfall-runoff models for single events, as flash floods often happen under extremely heavy rainfall events with short durations; hence, only a limited number of events are available [12,13]. Pre-event soil moisture was taken into account in the calibration and validation processes [14,15]. However, the boundary conditions of a catchment for different durations and seasons were neglected. Rainfall thresholds derived from a single-event approach might be unrepresentative and have limitations in statistical analysis. Given that antecedent soil moisture differs, it plays an important role in the runoff generation in a catchment. A storm event is considered irrelevant in a dry period; however, it can cause flooding in a wet period when the soil is already saturated [16,17]. This is why rainfall thresholds need to be determined under several soil moisture conditions.

When long historical records are available, statistical means of precipitation data before the event can be applied for warning thresholds. However, such long-term records are rare, especially in flash flood-prone catchments. An approach based on synthesis hyetographs with different shapes and durations as values of rainfall producing a critical discharge was proposed to overcome the limitation of historical records [12]. This approach requires assumptions regarding both the temporal evolution of the designed rainfall and pre-event catchment conditions. However, the main drawback of these approaches is the use of an event-based model.

Here, we propose an adjusted method of FFG that takes the limitations of previous studies into account and overcomes the associated drawbacks. Instead of considering the pre-wet condition of individual events for flood development, we examine a wide range of soil moisture from dry to wet as an input to run a rainfall-runoff model. The use of synthetic precipitation with different intensities and durations also allows us to evaluate FF cases more holistically and overcome the statistical problem due to the rare occurrence of such an event.The FFG approach was applied to the Wernersbach catchment within the Tharandt Forest as a test case to i) take advantage of the reliable and multifold long-term data available for the catchment, and ii) investigate the potential use of the BROOK90 model as a tool for FFG.

2. Materials and Methods

2.1. Catchment Characteristics

The study area is a small forested catchment of 4.6 km^2 in Tharandt Forest south of Dresden in eastern Germany (Figure 1), which has been part of many studies [18,19]. The slope is relatively flat with an average grade of 3% and an elevation ranging from 322 to 424 m.a.s.l. The catchment is dominantly covered with coniferous (spruce) trees (>80%) and contains soil dominated by loamy silt, Dystric Cambisols, Podsols and Stagosols [20]. A more detailed presentation of the geologic and land use characteristics is provided in [21]. This catchment was selected due to (a) well-monitored experimental catchment with long term hydrological and meteorological data records (more than 50 years), (b) reference measurements to derive vegetation parameters, and (c) numerous studies and expert knowledge are available.

Floods occur mostly in summer partly caused by very intense rainfall. For instance, the extreme flood event in 2002 with a total daily sum of 312 mm between August 12th and

13th measured at Zinnwald-Georgenfeld set a new record in Germany [22]. The maximum discharge during this event was 10 m^3/s, 280 times greater than the mean runoff. Soils in the catchment are able to store a large amount of rain water before surface flow starts occurring [23,24].

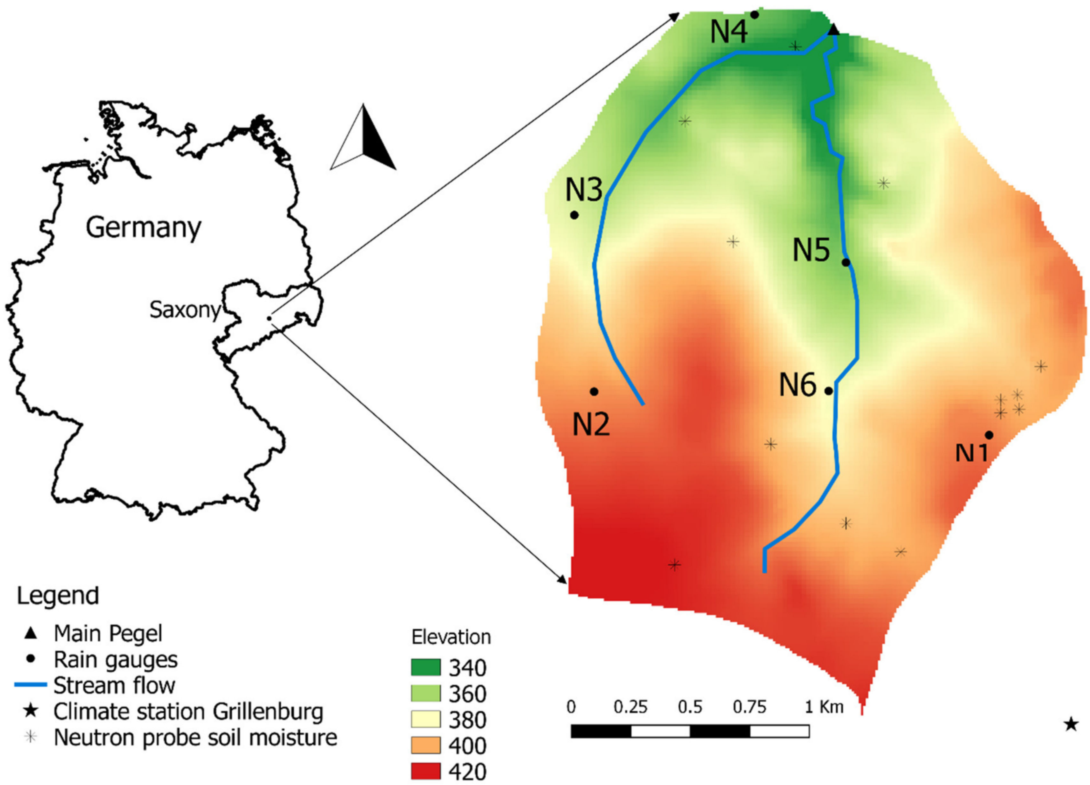

Figure 1. Overview of the study sites in Tharandt Forest, Saxony (Germany). The unit of elevation is m.a.s.l.

2.2. Data Sets and Model

2.2.1. Data Sets

Long-term measurements are used in this study, based on the monitoring of this research and education catchment of TU Dresden (Chair of Meteorology). Meteorological variables with daily resolution (precipitation, Tmin, Tmax, solar radiation, vapor pressure and wind speed) are available since end of 1967. Soil, land use and site parameters are adapted from the literature [21,23,25] to run BROOK90. For deriving soil moisture state, the above-mentioned climate variable data from 1970 to 2016 are used. Rainfall data are averaged over six rain gauges spatially distributed within the catchment from 350 m a.s.l. (N4) to 420 m a.s.l. (N2) as shown in Figure 1. The average annual rainfall amount varies from 605 mm (2003) to 1287 mm (2010) with an average of 930 mm. Most of the precipitation occurs during the summer months especially in July (101 mm) and August (103 mm).

The discharge records used in this study are for discharge at the catchment outlet. Discharge is calculated by empirical equations for two stage-discharge relationships, one for low base flow with water stages lower than 331 mm and one for high base flow with water stages higher than 331 mm. The parameters of the empirical curves are validated twice a year with flow measurement devices. During the extreme flood events in 1980 and 2002, discharge data are derived from interpolated data from surrounding states since the gauge weir was overtopped.

2.2.2. Short Model Description

The BROOK90 model is a lumped-parameter water budget model designed for small, uniform catchments. It produces a good representation of evapotranspiration (ET) and soil moisture by applying the well-known Penman–Monteith equation twice: once for the canopy and once for the soil surface [26]. To describe soil movement, the model applies Richard's equation and near-saturation interpolation of the scheme of Clapp and Hornberger, (1978) [27]. The model requires daily data for precipitation, Tmin, Tmax, solar radiation, vapor pressure and wind speed. However, it can also be operated with reduced daily inputs of precipitation and min/max temperature, while other input values are generated by the model. Thus, it is widely applied to estimate water fluxes at the soil plant atmosphere interface on a daily basis [21,23,28]. Nevertheless, the input of precipitation at higher temporal resolutions, such as hourly resolution, is possible, potentially improving the representation of fast components of the water budget, such as interception or interflow. A detailed chart can be found in [26].

Discharge is generated with different flow paths, such as vertical bypass, seepage, surface flow and lateral subsurface flow. Most of the flow parameters are empirical and are set according to the general understanding of the modeler. However, the model cannot accommodate lateral transfer of water downstream. The lack of a routing mode limits the application to catchments, in which flow is generated locally. To address some heterogeneity in larger catchments (up to 100 km^2), we allow the model to run for various combinations of land use and soil characteristics. The catchment response is then derived from the superpositioning of individual runs weighted according to their spatial contribution to the catchment area. This allows the introduction of a kind of hydrological response unit (HRU) but contributes additional uncertainty.

While the BROOK90 model is not recommended for direct flood modelling, we apply it for the partitioning of precipitation into ET, storage change and discharge. The simulated discharge is merely used as an indicator to evaluate the critical flooding stage as outlined below.

2.3. Flash Flood Guidance Setup

FFG is an effective flood warning system for small or medium-sized mountainous catchments with the potential danger of intense and destructive flooding with a short warning time. It does not intend to predict the timing of flooding, but tries to identify potential flood occurrence. The method compares rainfall forecasts with so-called rainfall thresholds for different antecedent soil moisture conditions (AMCs). Rainfall thresholds are rainfall intensities that lead to critical discharge in the catchment. A flood warning is issued if the corresponding thresholds are exceeded. Rainfall thresholds are derived with the following three steps as described in Figure 2.

Step 1: Estimation and classification of antecedent soil moisture

Following [16,29,30], the soil moisture in the catchment is grouped into values corresponding to "wet", "moderately saturated", or "dry" conditions to account for different AMCs. For this process, the BROOK90 hydrological model was used to simulate the catchment's water balance from 1970 to 2016, identifying the daily moisture conditions. The model performs well under different data input conditions, and detailed model setup and performance validation are described in [24].

The 0.33 and 0.66 percentiles are derived from the historical soil moisture value distribution to categorize the three aforementioned classes. Each class, namely, AMC I (dry soil), AMC II (moderately saturated soil), and AMC III (wet soil), is defined as the wetness condition at the beginning of a rain event. This step is referred to as the current catchment state in Figure 2.

Step 2: Runoff threshold identification

Runoff is considered critical when flooding starts, exceeding the so-called bank-full flow. A method commonly used to identify this value uses a 2-year discharge return interval [10]; other methods derive it from available historical data and hydraulic geometry using, for example, stage-discharge curves of the considered riverbed. In the case of the Wernersbach catchment, statistical values give very small and implausible discharge values, explainable by the small catchment size. Values based on hydraulic geometry are larger, leading to a very small sample size. The critical water stage (Qs) was therefore defined as 50 cm, equivalent to the average high discharge, which is considered representative of flood events in this specific catchment. This value (Qs, in Figure 2) was compared with the simulated discharge (q, in Figure 2) after a model run to identify the rainfall threshold.

Step 3: Rainfall threshold estimation

Identifying critical rainfall values that can potentially cause a flood requires a large sample of different rainfall events and their corresponding runoff to test the physical boundary when the river is full of water under different initial catchment conditions. We increased the sample size by running the BROOK90 model for the summer months from April to September for the study period 1996–2010 with synthetic rainfall inputs and different rainfall intensity distributions, namely, step, triangle, decreasing and increasing (Figure 2). These designed rainfalls are also called hyetotypes [12]. Only summer months were included in the analysis since flash flood events are mainly caused by convective rainfall, which mostly takes place during the summer, particularly in Germany [7]. The study site was parameterized by deriving from available measurements and literature. As mentioned above, the BROOK90 model is primarily based on physical laws. Thus, soil properties (density, grain size distribution, humus content of soil horizons) are combined with site properties (slope, exposure) and meteorological measurements (air temperature, humidity, radiation, wind speed, precipitation) to form explicitly site-specific conditions. The model's flow parameters, which have no physical meaning, were estimated empirically by the daily discharge measurements using the Parameter ESTimation program [31]. The Nash–Sutcliffe efficiency (NSE) for the calibration period (1970–1990) and the validation period (1991–2016) are 0.61 and 0.82, respectively. For each day with its corresponding original catchment conditions (taken from the water balance calculations in Step 1), rainfall of different durations from 1 to 24 h and different configurations (step, triangular, decreasing and increasing) was fed into the model (Figure 2), taking temporal variations in rain events into account. A maximum of 24 h was chosen since critical discharge in flash flood situations is usually reached sooner than six hours after the rain begins. For each rain configuration and duration, the amount of rainfall was increased until the model output reached or exceeded the critical discharge value within the corresponding duration (when $q > Qs$). The sample was divided into three pre-event soil moisture conditions (AMCs), and three final curves for each AMC category were established. The R version of the BROOK90 model (freely available at https://github.com/rkronen/Brook90_R (accessed on 25 January 2018) was used for the derivation since it is much more flexible than the original version concerning data input and adaptation of the model to the user's needs.

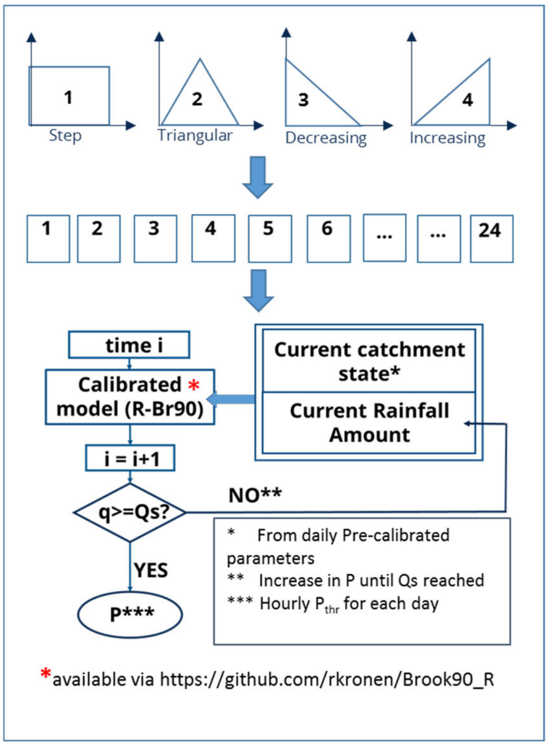

Figure 2. Different rainfall designs used as model input (hyetotypes and durations) and flow chart of inverse hydrological modelling for rainfall threshold estimation.

2.4. Validation of the Flash Flood Guidance Approach

2.4.1. Flash Flood Events in the Catchment

To validate the FFG approach, rainfall-runoff events with flash flood characteristics must be identified from rain and runoff data, and the FFG approach must be applied to them. Rain is considered one relevant event when rain sequences are separated by a minimum of 3 h of no rain and when the precipitation sum exceeds 20 mm (Psum $\geq$ 20 mm). We adapted the methodology of Marchi et al., 2010; Tarolli et al., 2012 and Amponsah et al., 2018 [32–35], considering the hydro-climatic settings and catchment size of our study area. Discharge data were considered to reflect a potential flood event when the critical value was exceeded within the first 48 h after the relevant rain event started. This methodology is similar to that used by [34], where the storm duration was defined for an integrated high-resolution dataset of high-intensity European and Mediterranean flash floods. The identified relevant rainfall-runoff events are then classified into AMC categories according to the soil conditions at the beginning of the rain event (just before the rain started).

A total of 40 summertime events between 1996 and 2010 were extracted from the discharge and precipitation series (Table 1). The total event precipitation ranged between 21 mm and 272.3 mm. The maximum hourly precipitation values (Pmax) ranged from 3 mm to 41 mm.

Table 1. Selected rainfall event characteristics with Psum ≥ 20 mm (AMC = antecedent soil moisture condition categorized into three classes, with I indicating wet and III indicating dry; Pduration = rainfall event duration; Pmax = precipitation peak; AS = antecedent soil moisture as an absolute value in mm).

Date	*AMC*	*Pduration* [h]	*Psum* [mm]	*Pmax* [mm]	*AS* [mm]	*Intensity* [mm/h]
1997-06-14	I	6	22	11.5	163	3.7
1998-06-12	I	7	24.5	10.3	148.2	3.5
1998-06-21	I	4	22.6	6.5	172.5	5.7
1998-07-27	II	3	27	19.6	190.6	9
1998-08-02	II	12	39.8	29.1	187.5	3.3
1999-06-18	I	32	60	6.1	173.8	1.9
1999-07-06	III	19	35.6	19.8	233.4	1.9
1999-07-20	II	6	21.7	12.4	217	3.6
1999-09-18	I	7	21.7	21.5	153.2	3.1
2001-07-07	II	6	44.3	34.1	199.3	7.4
2002-07-16	I	5	23	12.5	153.7	4.6
2002-08-08	II	2	34.7	34.5	181.6	17.4
2002-08-11	II	51	272.3	23.7	181.2	5.3
2002-08-31	II	11	66	40.9	192.2	6
2002-09-26	II	14	22.2	5.9	214.2	1.6
2003-05-08	I	13	24	9.2	160.9	1.8
2004-05-06	II	5	25.3	12.7	201.1	5.1
2004-05-10	II	14	31.8	13.3	216	2.3
2004-07-22	II	8	44.4	21.7	209	5.5
2005-07-05	I	14	23.2	2.9	170.8	1.7
2006-06-27	I	2	46.6	38.6	150.3	23.3
2006-08-05	I	49	78.9	9	136.3	1.6
2007-05-07	I	11	25.3	13.8	134.1	2.3
2007-05-14	I	5	23.1	13.8	160.4	4.6
2007-05-27	II	2	20.8	20.5	182.6	10.4
2007-05-28	II	11	21.1	9.8	184.2	1.9
2007-06-15	I	1	21.7	21.7	171.5	21.7
2007-06-21	I	3	25.1	10.5	174.9	8.4
2007-08-20	I	15	40.5	14.6	177.3	2.7
2007-08-31	II	9	27.1	9.2	188.4	3
2008-07-03	I	1	23.6	23.6	155.8	23.6
2008-08-08	I	7	31.7	31	164.3	4.5
2008-08-11	I	6	20.9	10.2	170.1	3.5
2009-05-26	I	18	33.1	9.4	154.3	1.8
2009-08-02	I	16	52.6	31.1	173	3.3
2009-08-26	I	6	40.6	24.9	168.3	6.8
2010-06-02	III	19	49.2	16.6	242.3	2.6
2010-07-22	I	19	28.8	5.5	144.9	1.5
2010-08-03	II	16	38.8	10.6	183.3	2.4
2010-08-15	II	3	27.6	16.4	219.2	9.2
Mean		11.5	39.1	17.2	191	5.8
S.D.		11.1	40.2	9.8	25.7	5.8

2.4.2. Application of Flash Flood Guidance

After estimating rainfall thresholds for the individual catchment and soil moisture states, the FFG approach can be applied to rainfall events. Once it starts raining or once rain is forecasted, all rain is accumulated until the rain event is over. Soil moisture at hour "0" (just before the rain starts) is classified as AMC I–III to choose the correct threshold curve. The rain information is updated from the rain forecast.

Examples of selected events from Table 1 are illustrated in Figure 3 to demonstrate how rainfall thresholds and different pre-event soil moisture conditions and rainfall intensities are linked. Depending on the characteristics of an event, the consequences can be very different. In the example of Figure 3a, the rainfall (red curve) does not exceed the rainfall threshold curve (i.e., there were not "enough" rain during this event); hence, no warning would be issued. In Figure 3b the accumulated rainfall exceeds the corresponding AMC III curve, and a warning is issued. Note that in this example, the rain would also exceed the curves if the initial wetness state were different. However, even though accumulated rainfall exceeds the rainfall thresholds in the case of wet and moderate soil moisture states (Figure 3c), no warning is issued as the catchment is dry and can hold more water. The situation shown in Figure 3d would lead to a warning because the accumulated rainfall exceeds the AMC III curve. For a drier catchment (AMC I), no warning would be issued for the same accumulated rainfall.

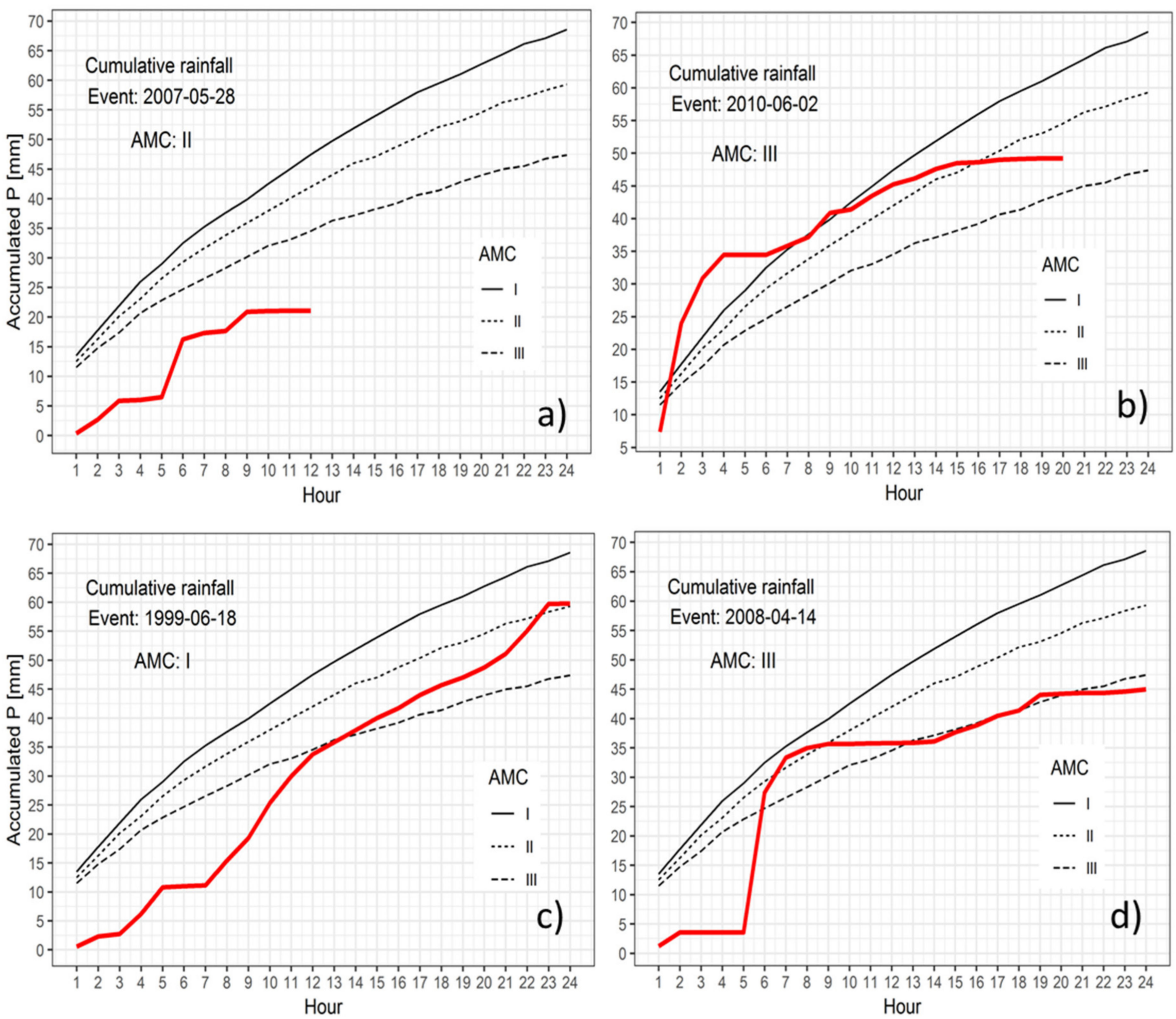

Figure 3. Application and validation of rainfall thresholds, with examples shown for four selected events with different pre-event soil moisture conditions (indicated in each sub-figure) and rain and discharge characteristics. The red lines are accumulated forecasted rainfall of the events. (**a**) Missing alarm; (**b**) correct alarm; (**c**) correct missing alarm and (**d**) correct alarm due to information on antecedent soil moisture. The categories are summarized in Table 2. The characteristics of the four selected events are listed in Table 1. The events were selected on purpose to illustrate the differences in issuing an alarm. The false alarm is not illustrated here.

2.4.3. Validation of FFG

The discharge for both events in Figure 3a–c, in fact, exceeds the critical discharge value in both cases; hence, a warning should have also been issued for the left examples. This shows that the operational mode of the FFG approach requires careful validation. For this validation, the method is tested on the historical events that were previously defined in Table 1. The rainfall information is cumulative, as shown in Figure 3, as if it were forecast information. If a flood warning is issued (the rainfall threshold is exceeded), we count it as a correct alarm (CA, see Table 2). If the rainfall threshold is not exceeded, it is a so-called missing alarm (MA) since the discharge exceeds the critical value. For a complete evaluation, we also evaluated all other rainfall events from the period 1997–2010. A rain event was defined as previously described, and the cumulative value was compared with the rainfall thresholds. If the critical rainfall level was not reached as expected, the event was counted as a correct missing alarm (CMA). The cases in which a warning is issued based on rainfall but without precedent high discharge were classified as false alarms (FAs). Obviously, MAs are potentially dangerous and should be avoided if possible.

Table 2. Two-by-two contingency table.

		Qobs > Qthreshold	
		Yes	No
Pobs > Pthreshold	Yes	CORRECT Alarm (CA)	FALSE Alarm (FA)
	No	MISSING Alarm (MA)	CORRECT Missing Alarm (CMA)

However, if we reduce the MA frequency to 0 (which is theoretically possible by setting the rainfall thresholds very low), the FAs will naturally increase to a very high level since a warning will be issued almost every time it rains. This modification would decrease the quality of FFG and would make the approach obsolete and unnecessary. Hence, the quality of prediction can be evaluated by using the hit alarm rate or the probability of detection (POD) and the false alarm rate (FAR) and the critical success index (CSI). The POD is determined by comparing the correctly predicted events with the events actually observed. The FAR establishes a comparison between incorrectly forecast events and all observed events. Adapting the concept of Schaeffer, (1990) [36], CSI presents the ratio of correctly predicted events to the total number of predicted events. The three statistics are defined as follows:

$$\mathrm{POD} = \frac{\mathrm{CA}}{\mathrm{CA} + \mathrm{MA}} \tag{1}$$

$$\mathrm{FAR} = \frac{\mathrm{FA}}{\mathrm{FA} + \mathrm{CA}} \tag{2}$$

$$\mathrm{CSI} = \frac{\mathrm{CA}}{\mathrm{CA} + \mathrm{MA} + \mathrm{FA}} \tag{3}$$

FFG performs well if the forecast system has a POD of 1 and a FAR of 0. Consequently, CSI will obtain a value of 1 as the derivation of POD and FAR. This evaluation method is a comprehensive approach that can cover all potential cases and improves the estimation accuracy of the FFG approach for our study catchment.

3. Results

3.1. Rainfall Thresholds

This approach results in more than 241,000 model runs, covering the wide range of pre-event condition states in the catchment, including almost drought to almost saturated conditions, as shown in Figure 4. The high number of the simulations resulted from the combination of 2340 days in the study period with 24 durations and four different rainfall shapes. This process requires a tremendous computation effort as each simulation is involved by "a reverse mode" to detect a rainfall threshold. Each point in Figure 4 displays a rainfall threshold value that caused simulated discharge within its duration to exceed the discharge threshold as defined in step 2 in the guidelines. Figure 4a–c shows a range of rainfall thresholds for durations from 1 to 24 h. At first glance, the amount of rainfall increases exponentially as the event duration increases. For instance, critical rainfall increased for 1 to 24 h of step rainfall in the range of 5–130 mm in the case of dry soil condition. Classifying these values according to AMCs reveals an interesting distribution. Specifically, the higher the pre-event soil moisture is, the smaller the potential rainfall intensity causing potential flooding is. It is also observed that wetter soil has a smaller range between the upper boundary and lower boundary of the rainfall thresholds (Figure 4c).

Under wet conditions, the Wernersbach catchment required only 11.5 to 13.5 mm of precipitation in one hour to reach the flooding stage. On average, dry soil requires more rainfall input to cause critical discharge, regardless of the type of designed rainfall. Furthermore, the rainfall threshold values are also variable and depend on the hyetotypes and antecedent soil moisture. The median values of critical rainfall were extracted as representatives for further evaluation (Figure 4d–f). We see that almost 50 mm is estimated for the difference in rainfall amount in 24 h depending on the hyetotype. Comparing critical rainfall among the hyetotypes, the threshold decreased in the following order: decreasing-triangular-step-increasing. This result is due to the increasing rainfall intensity of the hyetotypes in the same order.

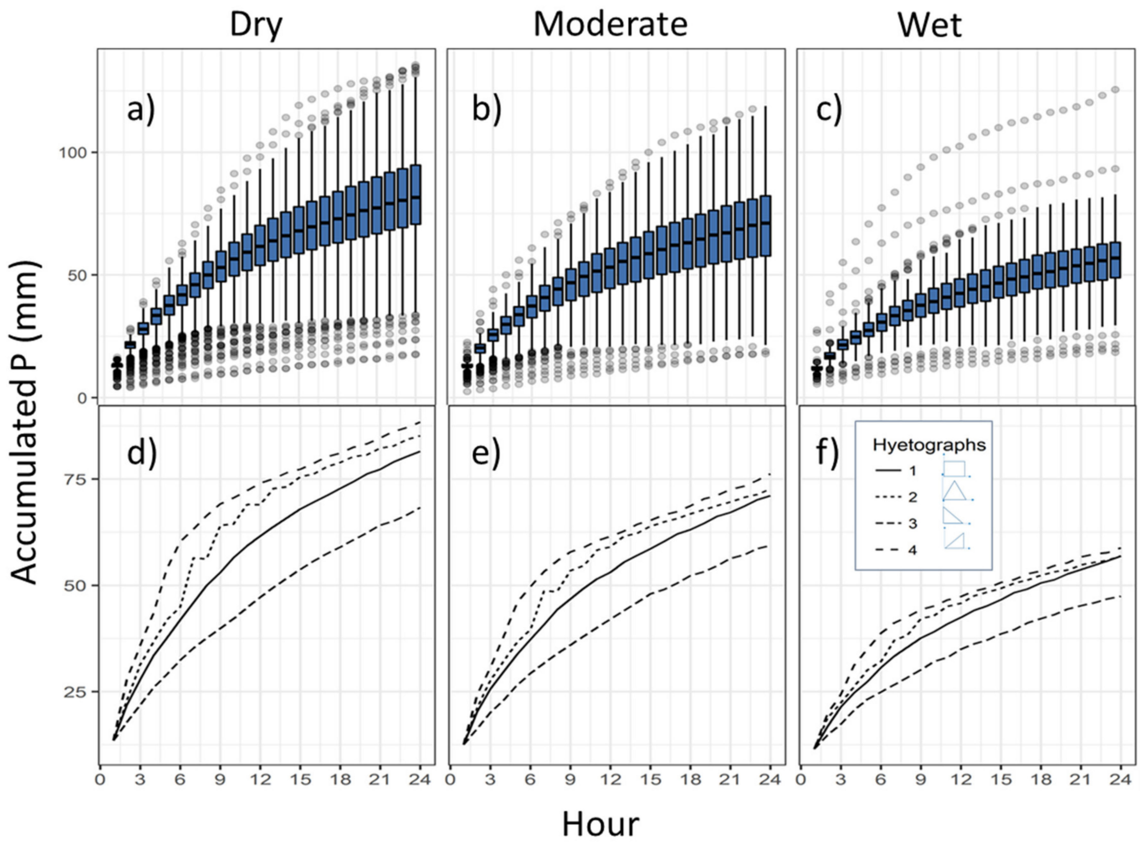

Figure 4. Rainfall threshold for different AMCs and hyetotypes: (**a**–**c**) Threshold ranges of the study period for different AMC types exemplary of hyetotype 1; (**d**–**f**) rainfall threshold (median values) for different AMCs because of the different P configurations (1–4).

By grouping critical rainfall events (median values of rainfall thresholds) according to soil moisture classes for the hyetotypes (Figure 5), we can clearly see the impact of antecedent soil moisture. In all hyetographs, the pattern remained consistent, as the drier soil required more precipitation than the wetter soil. However, the differences among rainfall thresholds in soil classes varied in the hyetographs. For instance, for a duration of 24 h, the ranges of rainfall thresholds between wet soil and dry soil were 25, 29, 21, and 30 mm for the increasing, step, triangular and decreasing hyetotypes, respectively. In operational application of the proposed framework, Figure 5 can be used as a practical tool for decision-making. When the temporal distributions of storm moisture and pre-event soil moisture are estimated, corresponding curves can be chosen for comparison with the accumulated rainfall.

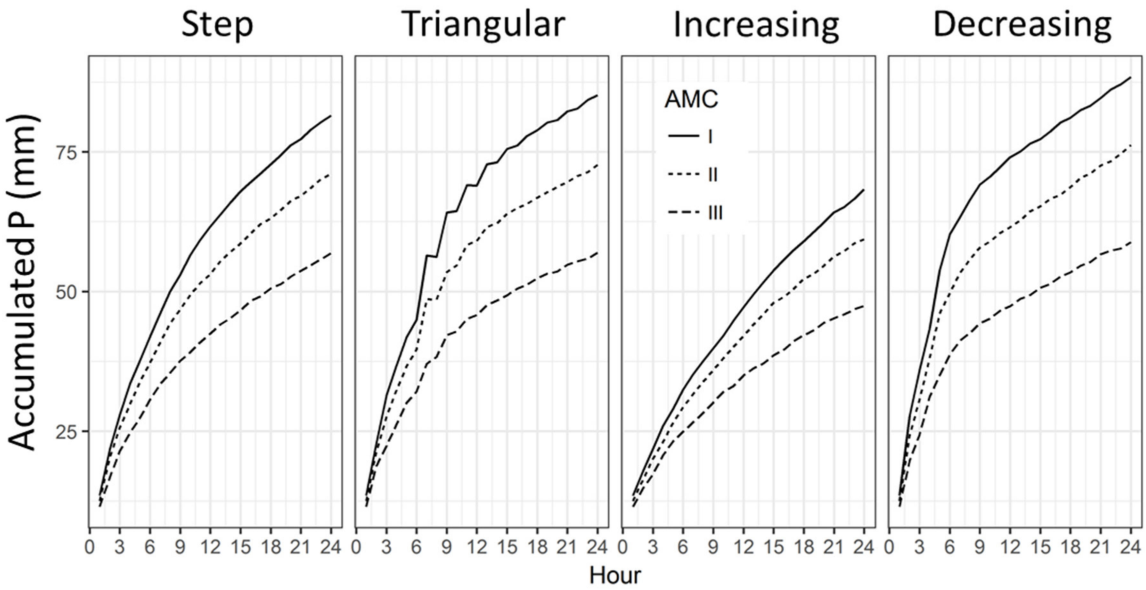

Figure 5. Rainfall thresholds sorted according to different hyetographs for all soil moisture classes.

3.2. Performance Evaluation

Table 3 shows the results of validation and summarizes the categories of CA, MA and FA for different pre-event soil moisture and rainfall configurations. Since we noticed that most rain events decreased in intensity, we focused on the results for the corresponding hyetotype H3, as highlighted. We can see that 11 events were correctly forecast, 1 event was forecasted as an MA, 14 events were forecasted as FAs, and 11 events had CA. These results led to the evaluation criteria of a POD of 91.7% and an FAR of 56% and an CSI of 42.3%, which is comparable with similar studies [37,38]. Based on this result, for the rain gauge data, the threshold-based forecasting system seems to have reliable performance. On the other hand, the FAR is not as low as desired. The main cause of the high FAR is the number of long low-intensity events in the validation. Montesarchio, Lombardo and Napolitano, 2009 also obtained an FAR of 75% in their study and found the same reason in a catchment in North Italy. This study also pointed out an interesting result that FA events took place only under dry to moderate AMCs. This result can be explained by the fact that most rainfall infiltrated the soil due to low intensity and did not generate surface runoff. However, the model was not able to describe this process, which is shown in Figure 6 and discussed in the next section.

The correctly forecasted events were those with high discharge values and those with generally large rainfall amounts. An important characteristic was that most of the events had preceding rain that started with peak rain.

Table 3. Rain gauge events evaluation with rainfall thresholds derived from the flash flood guidance (FFG) method.

	Correct Alarm				Missing Alarm				False Alarm				Correct Missing Alarm			
Hyetotype	**H1**	**H2**	**H3**	**H4**	**H1**	**H2**	**H3**	**H4**	**H1**	**H2**	**H3**	**H4**	**H1**	**H2**	**H3**	**H4**
AMCI	1	1	2	1	1	1	0	1	7	7	9	7	13	13	11	13
AMCII	5	4	7	4	3	4	1	4	4	4	5	4	4	4	3	4
AMCIII	2	2	2	2	0	0	0	0	0	0	0	0	0	0	0	0
∑	8	7	11	7	4	5	1	5	11	11	14	11	17	17	14	17
	H1	**H2**	**H3**	**H4**												
POD (%)	66.7	58.3	91.7	58.3												
FAR (%)	57.9	61.1	56	61.1												
CSI (%)	34.8	30.4	42.3	30.4												

3.3. Role of Discharge Simulation

As briefly mentioned above, the routing process in the BROOK90 model has been omitted to focus on the details of the factors controlling evaporation [26]. An apparently weak point of the model is a missing delay in discharge, which should be expected for the concentration time for simulated discharge. Therefore, the model responded quickly, which resulted in peak discharge immediately after rainfall, which is not the case in reality. The peak discharge in the catchment often occurs much later after sub-surface flow processes occur. This causes the peak discharge to be not well captured temporally; thus, even if the cumulative rainfall exceeds the reference threshold, the observed discharge is still under, even if the cumulative rainfall critical value. This discrepancy can be clearly seen in Figure 6 (left side), as the peak discharge in the simulation appeared 3 h earlier than the observed peak discharge. The concentration time was longer, which led to the discharge curve being rather flat during the rainfall event. Hence, the threshold discharge was already exceeded by the simulated discharge, while the observed discharge was still under the threshold. In addition, the discrepancies were particularly significant under dry soil conditions, where infiltration mainly dominated the hydrological process. The results in Table 3 illustrate that among 14 FAs, 9 were found in AMC I (dry soil class). The results clearly demonstrate the role of soil moisture conditions in the prediction skill for flash flood events.

Figure 6 (right side) shows an interesting result for the extreme event in 2002. A large rainfall amount seems to overcome the problem of simulating discharge. This finding indicates that this approach will work considerably well for extreme events. Moreover, in ungauged catchments, neither hydraulic geometry nor hydraulic data are available, which makes it more difficult to estimate the critical discharge. Thus, output from the BROOK90 model can be used a reference source of discharge information. When the data input is sufficiently long, a critical discharge value can be estimated using the return period method. Thus, this method enables more robust application in poorly gauged catchments.

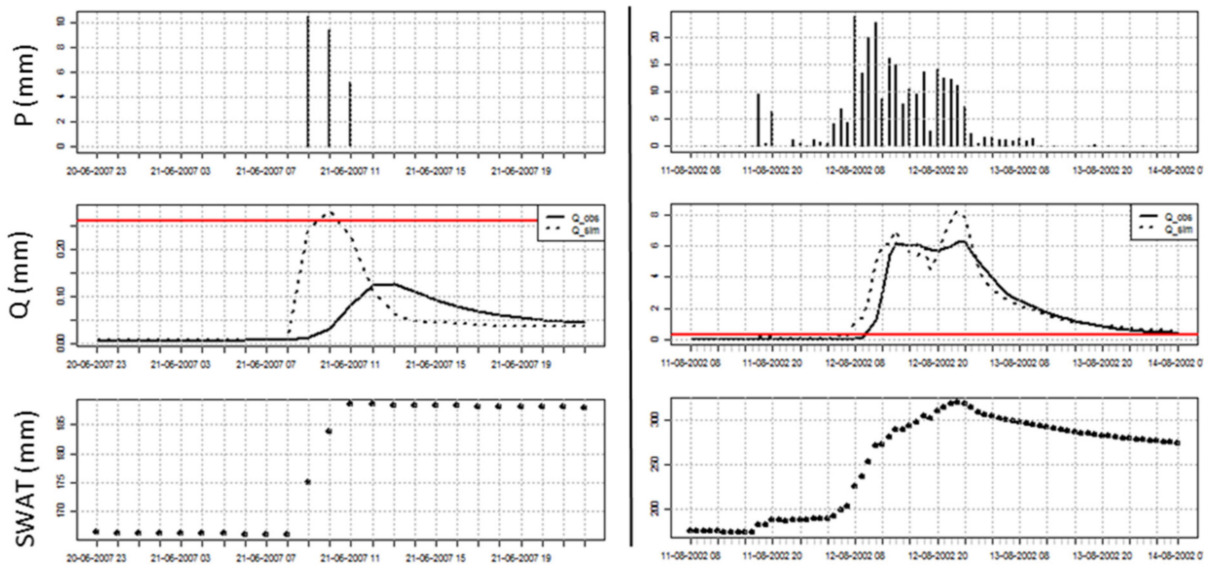

Figure 6. Examples of a false alarm (left side) and a correct alarm (right side). P = precipitation (mm), Qobs = observed discharge (mm), Qsim = simulated discharge (mm) and SWAT = estimated soil moisture (mm). The red line in the second row indicates the discharge threshold.

4. Conclusions and Outlook

This case study has tested the definition of a rainfall threshold methodology. The thresholds were estimated by running a physically based model with synthetic rainfall under various pre-event moisture conditions of the catchment. Thus, it resulted in a whole range of rainfall threshold curves categorized according to the hyetotype of rain input and antecedent soil moisture. Under dry conditions, critical discharge is caused by higher rainfall than under wet soil conditions. Thus, in addition to the high precipitation intensities, antecedent soil moisture also plays an important role in the estimation of rainfall thresholds for flash floods. This finding was consistent with that of Penna et al. (2011), who investigated the influence of soil moisture on threshold runoff generation processes in an alpine headwater catchment. Depending on soil type, soil depth, and pre-event soil moisture, soils in the catchment can store a large amount of rainwater before surface flow occurs.

Using rain gauge data, validation with 40 selected events in the study period led to a correct rate greater than 91% for identifying the critical wetness state in the considered catchment. The relatively high FAR can be explained by the limitation of the rainfall runoff model as well as the selection of critical discharge. The proposed adjusted FFG approach has the potential to provide reliable support in flash flood forecasting. It is a one-time action used to derive the thresholds and requires little information for operational use, being based solely based on rainfall forecasting and daily soil moisture information as well as available information on study site characteristics. The R-Br90 version is a good and handy tool for this application. This version allows to run the model in batch mode to investigate the catchment under various pre-event conditions and data inputs. However, a more detailed rainfall-runoff model is needed to improve warning accuracy.

Nevertheless, the actual framework was tested only for a 'perfect' prediction without uncertainties in meteorological variables, especially in rainfall. Determining the quality of different meteorological forecasts (predictability) of heavy precipitation events will be a task in future investigations.

Further investigations will focus on precipitation input derived from numerical weather prediction and radar data sets. Several improvements to the model and method should lead to improved prediction skill. For instance, the choice of critical discharge is crucial for model verification with observed events; thus, a sensitivity analysis is needed to define a critical value for method performance. Additionally, the computed runoff could be improved by a spatially distributed model and better temporal resolution. Then, a critical antecedent soil moisture level derived from the BROOK90 model could serve as the starting condition for running a more complex hydrological model that in turn checks for the alarm level. This combination would allow the monitoring of soil moisture status with very good coverage of critical head catchments with little computational effort, while more complex modelling could be performed only in selected situations. However, to implement the proposed method operationally, we recommend additional reductions in computational time via an integrated modelling framework.

Author Contributions: Conceptualization, all authors; methodology, T.T.L., C.B. and J.P.; BROOK90 model in R, R.K.; calibration and validation, T.T.L. and J.P.; inverse model structure, T.T.L. and R.K.; event detection, J.P.; writing—original draft preparation, T.T.L.; writing—review and editing, all authors. All authors made a significant contribution to the final version of the publication. All authors have read and agreed to the published version of the manuscript.

Funding: The research was supported in the framework of the EXTRUSO project funded by the European Social Fund (ESF) under the award number 100270097.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: MDPI Research Data Policies.

Acknowledgments: We thank all colleagues at the Chair of Meteorology, especially Uwe Eichelmann and Heiko Prasse, for their support of the Wernersbach measurements since more than 30 years. Open Access Funding by the Publication Fund of the TU Dresden.

Conflicts of Interest: The authors declare no conflict of interest.

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Erklärung

Hiermit erkläre ich, Luong Thanh Thi, die vorliegende Arbeit selbständig und ohne die Hilfe anderer Personen angefertigt zu haben. Weiterhin versichere ich, nur frei zugängliche oder lizenzierte Software verwendet zu haben, welche mir im Rahmen einer Anstellung als wissenschaftlicher Mitarbeiter an der Professur für Meteorologie des Instituts für Hydrologie und Meteorologie der TU Dresden zur Verfügung stand.

Ich bestätige, dass ich die Promotionsordnung der Fakultät Umweltwissenschaften der TU Dresden anerkenne.

Tharandt,