water

MDPI

Article

# Assessment of Near-Term Runoff Response at a River Basin Scale in Central Vietnam Using Direct CMIP5 High-Resolution Model Outputs

**Do Hoai Nam [1,*], Phan Cao Duong [2], Duong Hai Thuan [3], Dang Thanh Mai [4] and Nguyen Quoc Dung [5]**

1 Hydraulic Construction Institute, Vietnam Academy for Water Resources, Hanoi 116830, Vietnam
2 Graduate School of Life & Environmental Sciences, University of Tsukuba, Tsukuba 305-8577, Japan; pcduong8088@gmail.com
3 LEGOS Lab, Toulouse University, 31013 Toulouse, France; duonghaithuan@gmail.com
4 National Centre for Hydro-Meteorological Forecasting, Hanoi 117000, Vietnam; thanhmaidang1973@gmail.com
5 Hydraulic Construction Institute, Vietnam Academy for Water Resources, Hanoi 116830, Vietnam; nguyenquocdunghsc@gmail.com
* Correspondence: namdh@vawr.org.vn; Tel.: +84-947-026-025

Received: 10 March 2018; Accepted: 11 April 2018; Published: 13 April 2018

**Abstract:** Global warming is becoming more serious and causing changes in rainfall pattern and runoff regime in most river basins. Exploration of the changes will help develop appropriate management and adaptation strategies. This study presents an assessment of changes in rainfall and runoff in the upper Thu Bon River basin in central Vietnam in the near-term (2026–2035) climate using direct Coupled Model Intercomparison Project Phase 5 (CMIP5) high-resolution model outputs. A nearly calibration-free parameter rainfall–runoff model was employed to explore the runoff response in the study basin. Most model simulations have detected greater decreases in the near-term runoff in the dry season compared with those of any preceding decades in the baseline (1979–2008) climate, though the rainfall in this period is expected to increase slightly. Meanwhile, monsoonal season flooding has the potential to become more severe, and Japanese models project further increase in the intensity of such extreme weather events. The results also indicate that the treatment of the model physical parameterization schemes tends to contribute more sensitivity to the future projections.

**Keywords:** runoff response; near-term climate; high-resolution model; super-tank model

## 1. Introduction

Variability in runoff at a river basin greatly influences development and management practices. Such variability is either the consequence of change in climate variables or land cover across the river basin. However, it has been clearly documented in the recent literature that change in rainfall is the main driver of variability in runoff (e.g., [1–4]). In line with rising surface temperature, which is projected based on all greenhouse gas emission scenarios, rainfall is expected to increase in most places around the globe, but its distribution is varying in time so that more extreme rainfall events are projected during wet seasons; on the contrary, drought situations will be more critical during dry seasons [4]. This will increase the risk of flooding in the wet seasons and exacerbate water scarcity in the dry seasons [5,6]. Thus, assessing potential runoff response is critical to making informed decisions for future river basin planning and management under a changing climate.

Assessment of runoff response is primarily based on a coupling approach between general circulation models (GCMs) and hydrological models (e.g., [1,2,7]). Benefiting from increases in computational power, GCMs have improved quickly both in model structure and spatial resolution [8]. GCMs, therefore, can provide better simulations of small-scale (e.g., river basin scale) weather phenomena [8,9]. At the same time, the ensemble size of the models has also been significantly increased, taking into account new knowledge of future emission scenarios, so that the uncertainty of climate modeling is better evaluated compared with that of other assessments using a single model or downscaling methods [10,11].

This study, as an extension of a research series focusing on assessments of runoff response to climate change in the mid- and long-terms [11–13], further explores climate change impacts on hydrology and water resources on a decadal time scale (2026–2035) in the near-term climate of the upper Thu Bon River basin in central Vietnam. The near-term runoff response assessment is based on the outputs of the state-of-the-art high-resolution climate models by leading climate modeling centers around the world in contribution to the Coupled Model Intercomparison Project Phase 5 (CMIP5). This high-resolution multi-model-based assessment is assumed to not only provide better accuracies but to also help quantify the sensitivity of the projections, given the incompleteness of model formulations, as well as the inaccurate estimations of greenhouse gas emissions. As a result, this assessment shows advantages over assessments using a single model [11,12]. More importantly, it is also hoped that the boundary conditions setup for GCMs are less uncertain in the near-term compared with the setup for those in the longer-term; in addition, a near-term assessment of climate change impacts on runoff is apparently not a long time lag to verify the climate modeling capabilities.

## 2. Materials and Methods

### 2.1. High-Resolution Climate Models

Providing a standard set of climate simulations (for the past and future climates) for the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [4], the CMIP5 included approximately 40 climate models used by climate modeling centers around the world. As compared with those from the previous phase (CMIP3), the climate models of the CMIP5 showed significant improvements in horizontal resolution as a result of increased computational power; in particular, some of the models were categorized as high-resolution models with model horizontal resolutions of the order of 20–60 km with attempts for further understanding future climate change on local scales. Therefore, this study used the rainfall estimates by the high-resolution multi-model experiments developed by the two leading climate modeling institutions, the Meteorological Research Institute (MRI) of Japan and the Geophysical Fluid Dynamics Laboratory (GFDL) of the United States of America (USA). In addition, a preliminary screening procedure was also performed to remove models that exhibited significant underestimates of rainfall by comparing their estimates with actual observations. As a result, the selected CMIP5 high-resolution climate models and experiments are presented in Table 1. Experiments for two time periods, the baseline (1979–2008) climate and the near-term (2026–2035) climate, were selected. The baseline climate experiments were diagnosed with mean monthly sea surface temperatures (SST) observed in the same period. Meanwhile, future climate experiments were performed using SST data based on the projections by the multi-model ensembles according to the A1B emission scenario, prescribed SST (the multi-model mean over the four representative concentration pathway scenarios), and sea ice concentration anomalies by the MRI and the GFDL, respectively.

**Table 1.** Selected CMIP5 high-resolution climate models and experiments.

| Name of Modelling Group | CMIP5 Official Model-Name | Spatial Resolution | Experiment * |
|---|---|---|---|
| Meteorological Research Institute of Japan | MRI-AGCM3.2S | 20 km | r1i1p1 (Expt. 1) |
| | MRI-AGCM3.2H | 60 km | r1i1p1 (Expt. 2) r1i1p3 (Expt. 3) |
| Geophysical Fluid Dynamics Laboratory—USA | GFDL-HIRAM-C360 | 25 km | r1i1p1 (Expt. 4) r2i1p1 (Expt. 5) |

* r, i, and p denote experiment number, initialization, and parameterization scheme of a model experiment, respectively.

## *2.2. Hydrological Model*

With respect to impact assessment, it is preferable to use less complex hydrological models, which can accommodate the insufficient information of future watershed for rainfall–runoff analyses. There are available several hydrological models that are capable of performing a runoff simulation across various scales of time and space (e.g., [7,10,13–16]). However, a lack of long term rainfall and streamflow monitoring data for many catchments is a common problem and a key constraint for developing countries to formulate increasingly realistic catchment hydrological models that can simulate future changes in rainfall patterns. As an advantage over previous works in this research series, this study employed the super-tank model to perform the hydrological response of the catchment to climate change impacts. With physically based features, the super-tank model has demonstrated a great applicability in runoff simulations across a wide range of temporal and spatial scales [17–19]. The model has been recognized as a robust tool for assessing the runoff response of a catchment to climate change and has been considered particularly suitable for scattered/ungauged catchments. The details of the model description and model setup for river basins with various spatiotemporal scales can be found in the literature [11,12,19]. In short, the super-tank model is a semi-distributed rainfall–runoff model that includes a complete hydrologic process within the catchment scale. With respect to spatial representation, the whole basin is divided into sub-basins composed of grid cells that have similar spatial parameter characteristics and hydrologic responses and are represented by channel nodes. The vertical structure of the super-tank model consists of linear cascade tanks, as schematized in Figure 1. The super-tank model has nearly calibration-free parameters, as they have been internally calibrated using geo-topographical and land-surface information. Basically, three parameters (interception storage capacity, a dimensionless modification coefficient on the saturated hydraulic conductivity, and a coefficient used to determine the roughness coefficient in the river) of the model are required for calibration. However, it is notable that these parameters have been optimized through physical interpretation or similarity [17–19].

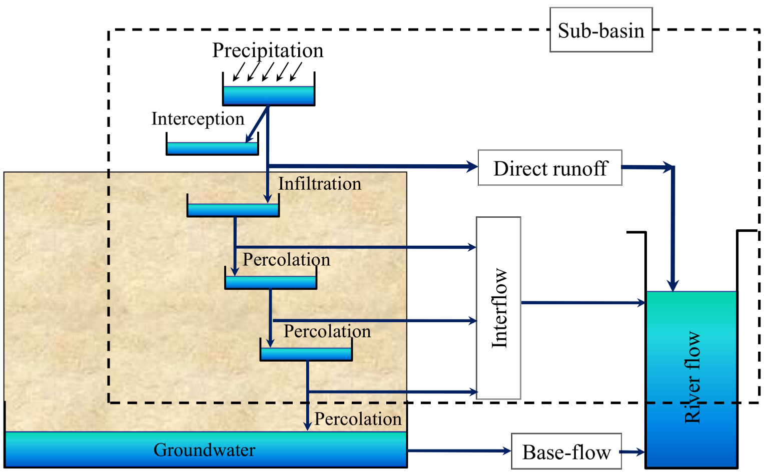


**Figure 1.** Schematic of the super-tank model, modified after [19].

The evaluation of model performance was based on three recommended statistics [7,20] including: (i) Nash–Sutcliffe efficiency (*NSE*), which measures the predictive power of a hydrological model [21]; (ii) observations standard deviation ratio (*RSR*), which standardizes root-mean-square error (*RMSE*) using the observations standard deviation [20]; and (iii) percent bias (*PBIAS*), which determines the average tendency of the simulated values to be larger or smaller than their observed ones [22]. The above recommended statistics are expressed in Equations (1), (2) and (3), respectively.

$$NSE = 1 - \frac{\sum_{i=1}^{n} (S_i - O_i)^2}{\sum_{i=1}^{n} (O_i - \overline{O}_i)^2} \tag{1}$$

$$RSR = \frac{RMSE}{SRDEV_o} = \frac{\sqrt{\sum_{i=1}^{n} (O_i - S_i)^2}}{\sqrt{\sum_{i=1}^{n} (O_i - \overline{O}_i)^2}} \tag{2}$$

$$PBIAS = \left[ \frac{\sum_{i=1}^{n} (O_i - S_i) * 100}{\sum_{i=1}^{n} O_i} \right] \tag{3}$$

where $O$ is the observed streamflow; $\overline{O}$ is the mean observed streamflow; and $S$ is the simulated streamflow.

Statistical interpretation of the model performance statistics is as follows: the *NSE* ranges from $-\infty$ to 1, and the maximum value indicates a perfect match of the simulated streamflow and the observed streamflow; the *RSR* is always greater than or equal to zero, and the lower the *RSR*, the lower the *RMSE*, which implies the better performance of the model; and the optimal value of the *PBIAS* is equal to zero, while positive and negative values of the *PBIAS* depict model under- and over-estimation bias, respectively.

### 2.3. Assessment of the Changes

The common feature of climate models, even very high-resolution models, is that intrinsic model errors will always exist. Presently, there are two main approaches applied to assess the climate change impacts on meteorological and hydrological variables in future climates. The first approach attempts to (i) implement dynamical downscaling [13] or statistically correct large-scale variables simulated by GCMs using past climate data and then (ii) apply transfer functions to adjust future simulations (e.g., [12,23–25]). The second approach adopts errors in model simulations and then evaluates relative changes amongst the model simulations in past and future climates (e.g., [2,26–28]). In this study, the latter method is adopted to estimate the climate change impacts on a catchment runoff by comparing the runoff simulated by a hydrological model using direct GCM outputs for the past climate with that of the future climate. By means of this method, the effects of both GCM and hydrological model errors caused by incomplete model structures and parameterization estimates on the direction of change in streamflow might become minimal [28].

### 2.4. Uncertainty Evaluation

Uncertainties are inherent in any climate change impact study. The uncertainties in runoff responses arise from such sources as hydrological model structure and estimations of rainfall and model parameters (e.g., [29–31]). Most studies have demonstrated that the major source of uncertainties in runoff responses is the precipitation estimations by GCMs (e.g., [29,32,33]). The uncertainties are due to limitations in defining the emissions scenario, climate model structure, downscaling method, and the internal variability of the climate system; however, the largest uncertainty can be attributed to the configuration of the GCMs and model experiments [7,33]. So, the inclusion of various GCMs and model experiments in the present study would be useful for quantifying the range of uncertainties in runoff responses. It was then assumed that changes in streamflow are normal distribution; the confidence intervals of the changes were computed as a function of the mean and standard deviation of changes in streamflow projected by multi-model simulations [34].

### *2.5. Test Case Study Area*

The upper Thu Bon River basin is selected as the test case study area, covering a drainage area of 3150 km$^2$, as delineated at the Nong Son stream gauge (Figure 2). The Thu Bon River belongs to the Vu Gia-Thu Bon River system, one of the biggest river basins in central Vietnam, originating from the Annam Range, then flowing through a narrow floodplain, and finally emptying into the East Sea. As characterized by tropical monsoon climate and topographical features, the upper Thu Bon River basin receives the highest rainfall (average 3300 mm/year) in the region, but rainfall distribution varies significantly over time and space. Approximately 80% of annual rainfall occurs in a short wet period, lasting from September to December; meanwhile, the remaining 20% of rainfall is distributed in a long dry period (January–August), and as influenced by an orographic terrain, more rainfall is observed in elevated areas than low-lying places. In addition, observation data has recently indicated that the wet season tends to get more average rainfall; on the other hand, the dry period is getting drier. These trends really influence the basin planning and management activities.

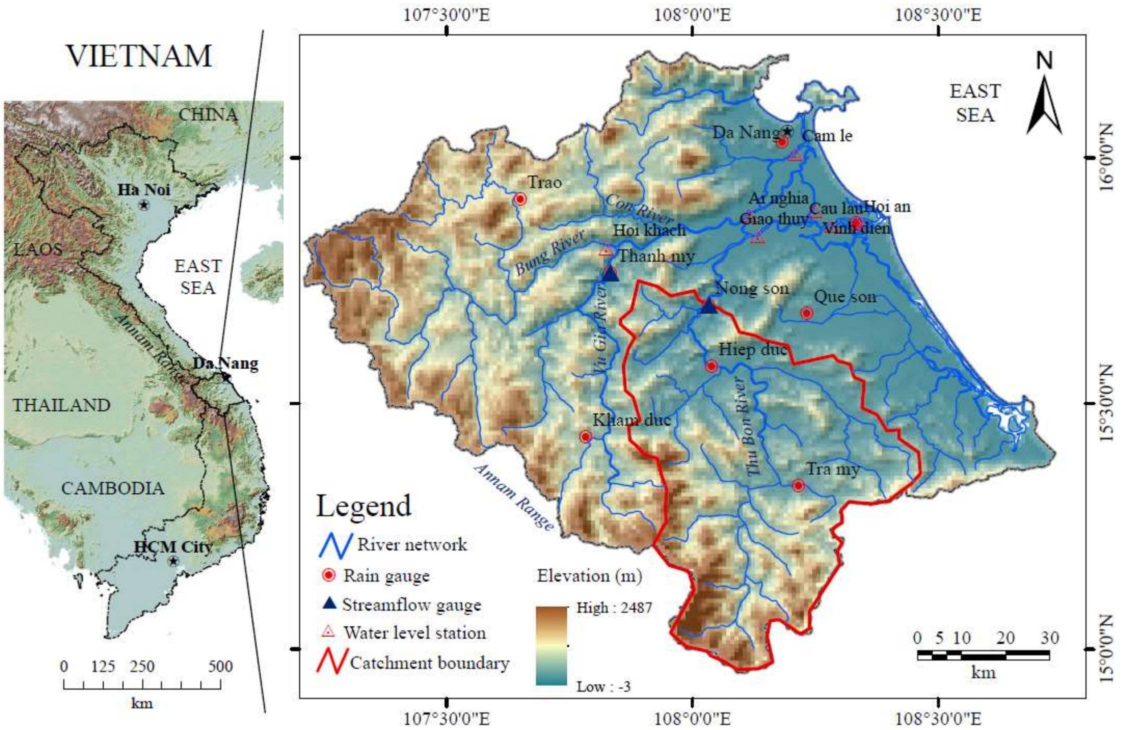


**Figure 2.** Map of the upper Thu Bon River basin as delineated at Nong Son stream gauge and locations of hydro-meteorological observation, modified after [11].

Hydro-meteorological data available for hydrological model setup, calibration, and validation is illustrated in Figure 2. Scattered rainfall observation points within or close by the study area were selected to compute the area-average rainfall using the inverse distance weighting interpolation method. A streamflow gauge located at the outlet of the basin provides discharge information for the whole catchment. This hydro-meteorological data is on daily basis and available since the late 1970s, in line with the time period of the climate model experiment, we selected to represent the baseline climate and also used for the hydrological model calibration and validation purposes.

## 3. Results and Discussion

### 3.1. Streamflow Simulation

The computational mesh of the super-tank model setup for the upper Thu Bon River basin was $1 \times 1$ km grid distance. Input datasets for the super-tank model included information on precipitation, evapotranspiration, land use, soil type, and topographic features of the catchment. These input datasets were defined for each model grid cell. The inverse distance weighting method was utilized to interpolate the daily rainfall information from nearby rain-gauges and grid point outputs of the GCMs into the computational mesh of the super-tank model. Evapotranspiration was merely set for forest and urban land use types (Figure 3). Similarly, hydraulic conductivities in the range of $10^{-4}$ to $10^{-7}$ m·s$^{-1}$ were defined for the three topsoil types: silt, loam, and clay loam, as illustrated in Figure 3. Other catchment features (e.g., slope, flow direction, river network, etc.) were derived from a digital elevation model, the Shuttle Radar Topography Mission with a spatial resolution of 90 m.

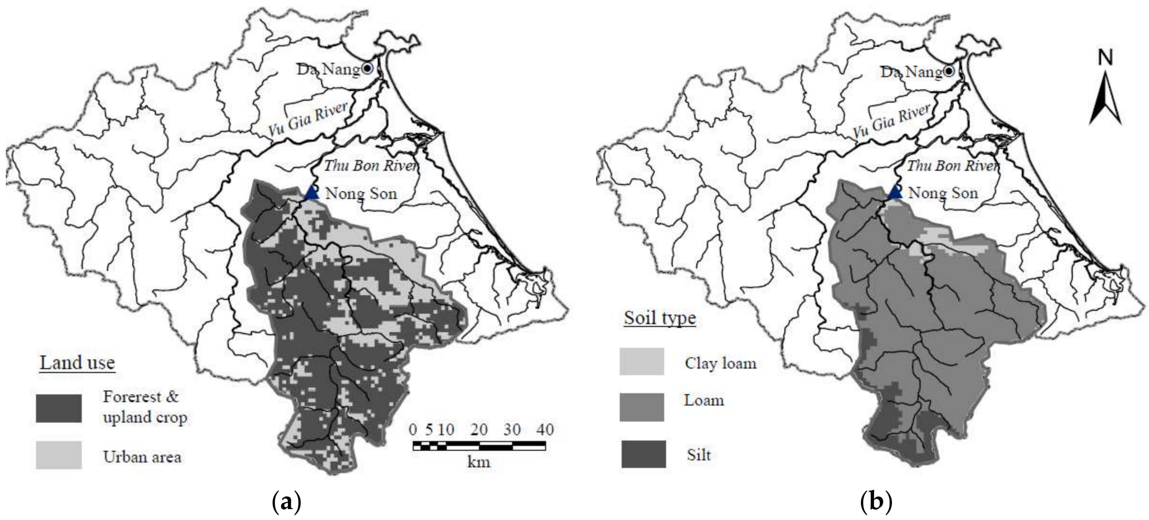


**Figure 3.** Distribution of (**a**) land use and (**b**) soil type in the upper Thu Bon River basin.

In previous works [11,12], the super-tank model calibration and verification were performed using the daily rainfall and streamflow information of twenty years (1981–2000). The present study further examined the model performance based on an extended dataset of thirty years (1979–2008); within this dataset, the period of 1989–2008, during which most of the extreme events occurred, was used for model calibration, and the remainder of the dataset was used for model validation.

The streamflow in this study was simulated on a daily interval and then aggregated into a monthly basis for different time scale evaluations. The results are shown in Figures 4–6. Figure 4 demonstrates the model calibration and validation based on the daily dataset in periods (1989–2008) and (1979–1988), respectively. Figure 5 shows a scattered plot of daily observed and reproduced streamflow for both the model calibration and validation. Meanwhile, the monthly reproduced streamflow is compared to that observed by the stream gauge in Figure 6.

It has been found that the streamflow was reasonably reproduced by the super-tank model in both the calibration and validation phases. As seen in those Figures, the reproduced hydrograph shows very good agreement with the observed streamflow at the stream gauge. The scatterplot also exhibits a quite close distribution of the streamflow reproduced by the model to the perfect line. Model performance statistics are presented in Table 2. As classified in the literature [20], if $0.75 < NSE < 1.0$, 0.0 < *RSR* < 0.5, and *PBIAS* < ±10% for streamflow, the model performance can be evaluated as "very good"; a "good" model performance is evaluated when 0.65 < *NSE* < 0.75, 0.5 < *RSR* < 0.6 and ±10% < *PBIAS* < ±15%. Based on these criteria, the super-tank model shows "very good" performance in the daily streamflow simulation for the calibration dataset and "good" performance in the case of model validation. In the meantime, the monthly aggregated streamflow indicates "very good" performance in both calibration and validation.

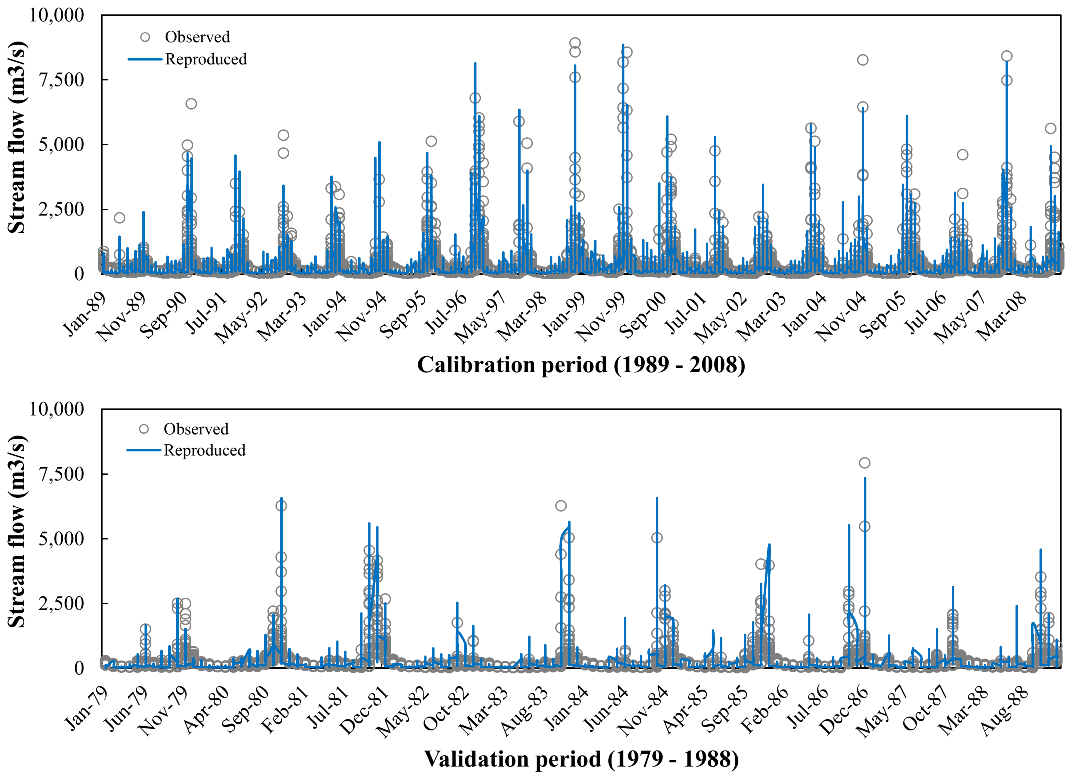


**Figure 4.** Time series of the daily observed and reproduced streamflow for the upper Thu Bon River basin at Nong Son: (**Upper**) calibration period (1989–2008) and (**Lower**) validation period (1979–1988).

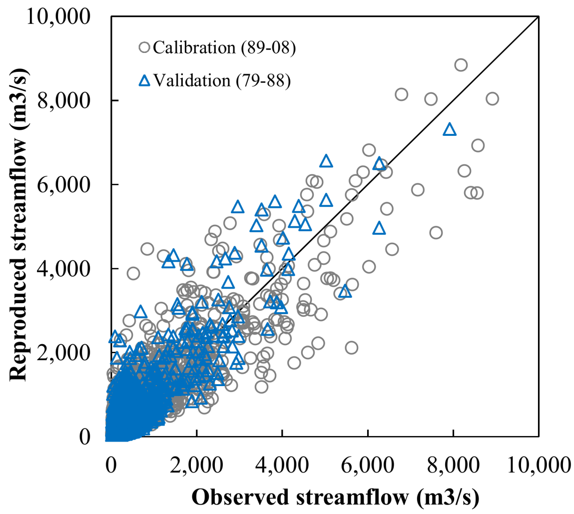


**Figure 5.** Scattered plot of daily observed and reproduced streamflow for the upper Thu Bon River basin at Nong Son in the calibration period (1989–2008) and validation period (1979–1988).

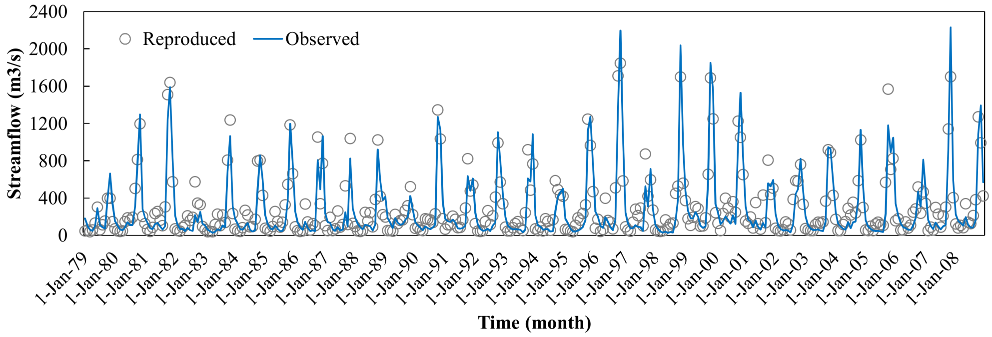


**Figure 6.** Time series of monthly observed and reproduced streamflow for the upper Thu Bon River basin at Nong Son in the period of 1979–2008.

**Table 2.** Super-tank model performance statistics.

| Criteria | Time Scale | Calibration (1989–2008) | Validation (1979–1988) |
|---|---|---|---|
| Nash–Sutcliffe efficiency (*NSE*) | Daily<br>Monthly | 0.77<br>0.86 | 0.71<br>0.83 |
| Observations standard deviation ratio (*RSR*) | Daily<br>Monthly | 0.48<br>0.38 | 0.54<br>0.40 |
| Percent bias (*PBIAS*) | Daily<br>Monthly | −2.87<br>−2.06 | −9.20<br>−9.13 |

However, it is also found that the reproduced streamflow depicts over- and under-estimation of low and high streamflow periods, respectively. These discrepancies are clearly seen in Figure 7, showing the average monthly streamflow in period (1979–2008). The discrepancies are mainly subject to inaccurate rainfall estimations. During the dry periods, the study area was dominant by highly inconsistent rainfall, Some localized rainfall events were probably captured by the rain gauges, but it did not represent for the entire basin; and on the contrary, rain might have fallen in other parts of the basin but was not captured by the rain gauges. Meanwhile, relatively widespread consistent rainfall only occurred as there was a combined influence by cold surges from the North and tropical depressions from the East in the wet seasons [35]; therefore, high streamflow periods are more reasonably reproduced by the super-tank model. With respect to the average annual streamflow comparison (not showed), it is notable that relative errors of average annual runoff reproduced by the model are insignificant. As a result, it is suggested that the calibrated and validated super-tank model is suitable for studies on climate change impacts on the catchment runoff, especially in places where ground observation is scattered.

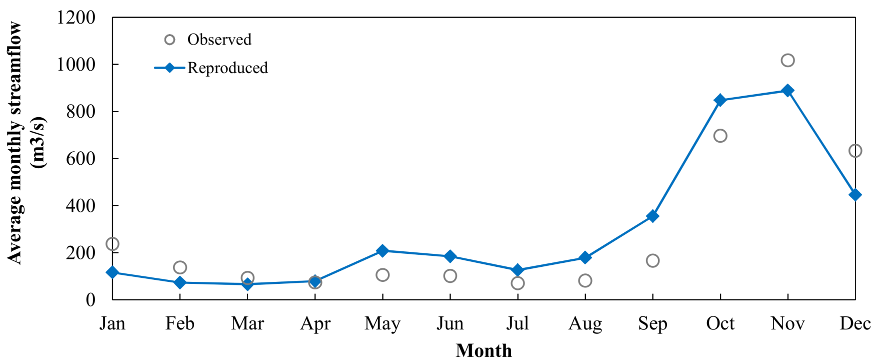


**Figure 7.** Average monthly observed and reproduced streamflow for the upper Thu Bon River basin at Nong Son in the period of 1979–2008.

## *3.2. Projection of Changes in Rainfall*

Increasing surface temperature would promote extra rainfall as a result of more water vapor in the atmosphere, and this was clearly addressed in the recent assessment reports by the Intergovernmental Panel on Climate Change [4], which state that most places around the world will expect changes in rainfall. In the context of this assessment as previously mentioned, the changes in rainfall over the upper Thu Bon River basin in this study were assessed based upon the differences between model experiments for the baseline and near-term climates. The results show that MRI experiments (Expt. 1 to Expt. 3) indicate a slight increase in rainfall in the near-term climate; on the other hand, GFDL experiments (Expt. 4 to Expt. 5) tend to project a reduction of rainfall in that same period, as seen in Figure 8, which illustrates changes in average monthly rainfall projected by the individual model experiments. Although there are variations between the different model experiments, there are some consistent patterns across all five experiments. The consistent pattern being that from December to April, rainfall is going to be less than in the past, but in the months of May to November rainfall is going to be more than in the past. The decrease and increase of rainfall in these two periods are approximately 10 percent, respectively. These result in a 1.2% decrease in the average annual rainfall (not showed) projected for the upper Thu Bon River basin in the near future.

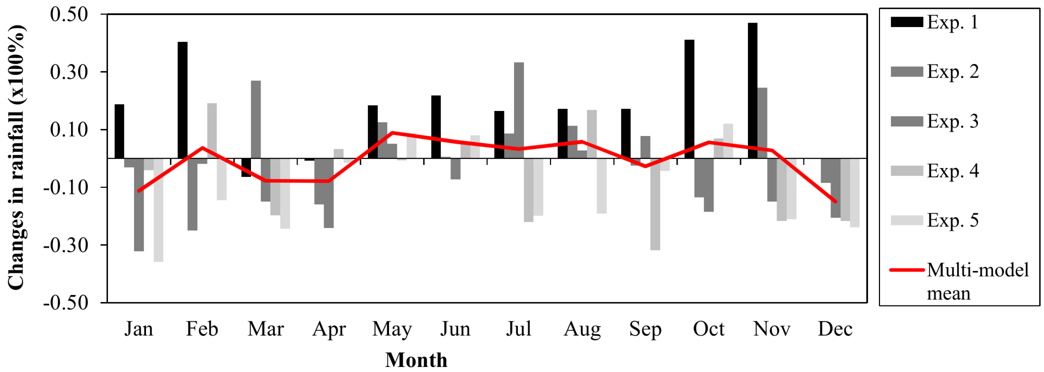


**Figure 8.** Changes in average monthly rainfall for the upper Thu Bon River basin in the near-term (2026–2035) climate projected by individual model experiments, relative to the baseline (1979–2008) climate.

## *3.3. Projection of Changes in Runoff Response Projection*

Changes in the catchment runoff are obviously influenced by climate and non-climate variability factors. In fact, most climate change impact assessment studies have neglected the influence of the non-climate variability factors, such as changes in land use and land cover (e.g., [5,11,31]). With respect to the climate variability factors, rainfall and evapotranspiration variation are the principal drivers of change in the catchment runoff. Increasing surface temperature is likely to enhance the evapotranspiration process, so that a higher evapotranspiration rate is expected in the future. However, in the near-term climate, it is found that the increasing surface temperature in the study area is likely to increase the potential evapotranspiration rate of 6% and as a result, reduce the total runoff of 1% (not showed) relative to the baseline period (1979–2008). Thus, this study merely performed the effect of the rainfall variability on the catchment runoff; while the effect of the evapotranspiration variability on the streamflow was omitted.

Similar to the assessment of changes in rainfall, changes in the catchment runoff were assessed by comparing the differences between runoff simulations for the baseline and near-term climates. Catchment runoff was simulated using daily rainfall diagnosed by GCMs and then aggregated to a monthly basis for the comparison. Figure 9 demonstrates the changes in the average monthly streamflow in the near-term climate for the upper Thu Bon River basin projected by all the runoff simulations, relative to the baseline period. It is apparent that most of the simulations show a reduction of the average monthly streamflow in the near future. Among the three simulations derived from the GCM experiments by MRI, Expt. 1 and Expt. 2, indicate a moderate decrease in streamflow; in particular, these simulations project a remarkable increase of the streamflow in November, which is known as the wettest period of the year. Meanwhile, Expt. 3 projects larger decreases in streamflow throughout the year. It can be understood that Expt. 1 and Expt. 2 were setup with the same model structure (except the difference of model resolution) and parameterization scheme [36], which considerably enhances the climatology of tropical convection [8], and, therefore, perform realistic estimates of tropical precipitation [37]. Meanwhile, Expt. 3 was examined with another parameterization scheme [38] that was developed for application to a meso-scale convection system. In the meantime, it is interesting to observe that the two model experiments (Expt. 4 and Expt. 5) with the same parameterization scheme (a scheme for moist convection and large-scale cloudiness based on the parameterization of shallow convection as described in the literature [39]), but different initializations used by GFDL illustrate relatively consistent decreases in streamflow. These findings indicate that the treatment of physical parameterization schemes of GCMs tend to contribute more sensitivity to the projection of runoff responses.

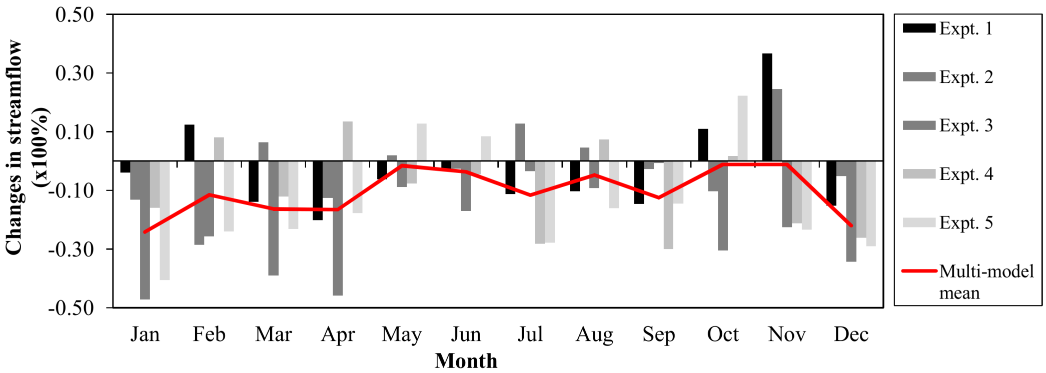


**Figure 9.** Changes in average monthly streamflow in the near-term (2026–2035) climate simulated using projected rainfall, relative to the baseline (1979–2008) climate.

Figure 9 also illustrates the multi-model mean of the runoff response in the near-term. It seems that the catchment will be facing a year-round reduction in streamflow, and in particular, it will suffer a greater reduction during the period of December–April as a result of the decreases in rainfall in this period, which is almost certainly going to increase the severity of the current problem of saltwater intrusion associated with low flow in the dry season months. This will have important economic and social impacts on this key economic zone. It is notable that slight decreases in streamflow are also projected for the period with increasing rainfall projection. The reduction of streamflow during May–August is understood as the effect of the decrease in rainfall in the previous dry months (December–April), which causes greater depletion of soil moisture and groundwater table and then requires larger recharge to the ground in the following months. On the other hand, the rainfall in this period is projected to increase, but it is apparently less than the initial loss; thus, it seems that there will be no contribution to the basin runoff. So, a message that can be inferred from the assessment for adaptation purposes is to invest in efforts that will strengthen retention and recharge at the landscape scale (to increase baseflow), in combination with the promotion of drought-tolerant measures suited to the local soils, climate, and market conditions.

### *3.4. Uncertainty*

As mentioned earlier, uncertainties are always inherent in almost all assessments of climate change impacts. The previous study presented an evaluation of the uncertainty caused by a downscaling method as showed in the literature [11]; however, it has been revealed that an artificial neural network-based model bias correction technique exhibited insignificant uncertainties in the projection of extreme events. The present study, employing five GCM experiments of different model formulations and physical treatments, is worth describing in terms of the variation of the runoff responses. Figure 10 shows the 95% confidence interval of the changes in the near-term runoff responses. It seems that monsoonal season flooding has the potential to become more severe, though the severity of these storms varies according to different simulations. The MRI experiments pay arguably the greatest attention to these types of climate processes and phenomena. These experiments, specifically used by MRI to explore extreme phenomena occurring at small scales [8], predict further increases in the intensity of such extreme weather events. Therefore, as per most other predictions to date, Vietnam's central coast region needs to further strengthen its capacity to manage the impacts of monsoonal storm events and associated flooding, erosion, landslides, and sedimentation of estuaries.

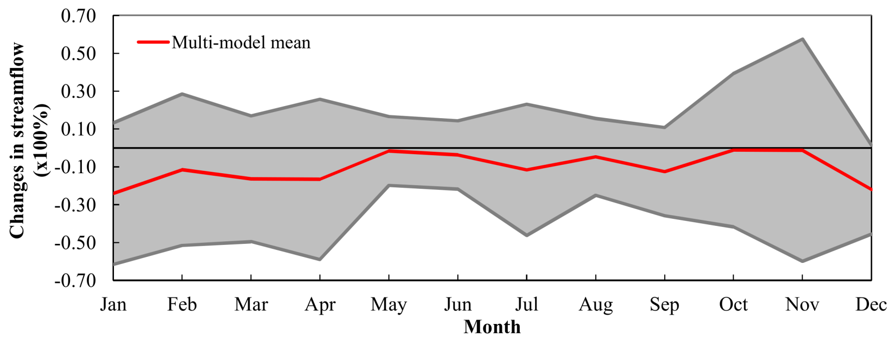


**Figure 10.** The 95 percent confidence interval of changes in the average monthly streamflow in the near-term (2026–2035) climate simulated using projected rainfall, relative to the baseline (1979–2003) climate.

With respect to the seasonal runoff variation, Figure 11 presents a box-and-whisker plot of dry season, wet season, and annual streamflow derived from all the runoff simulations for decadal-based time periods in the baseline and near-term climate. It is interesting to see that high-resolution climate models show reasonable estimates of the means of annual and wet season streamflow, with the average absolute relative error at less than 10%; meanwhile, the mean streamflow in dry periods was overestimated (by more than 50%) in the baseline climate. The near-term projections of the runoff responses indicate an obvious reduction in the means of annual, wet season, and dry season streamflow compared with any preceding decade in the baseline climate. All the simulations show the convergent projections of the runoff in dry periods; meanwhile, it is likely that more extreme events are projected for wet seasons, though the indication of the high streamflow in this decade is less than that of any preceding decade in the baseline.

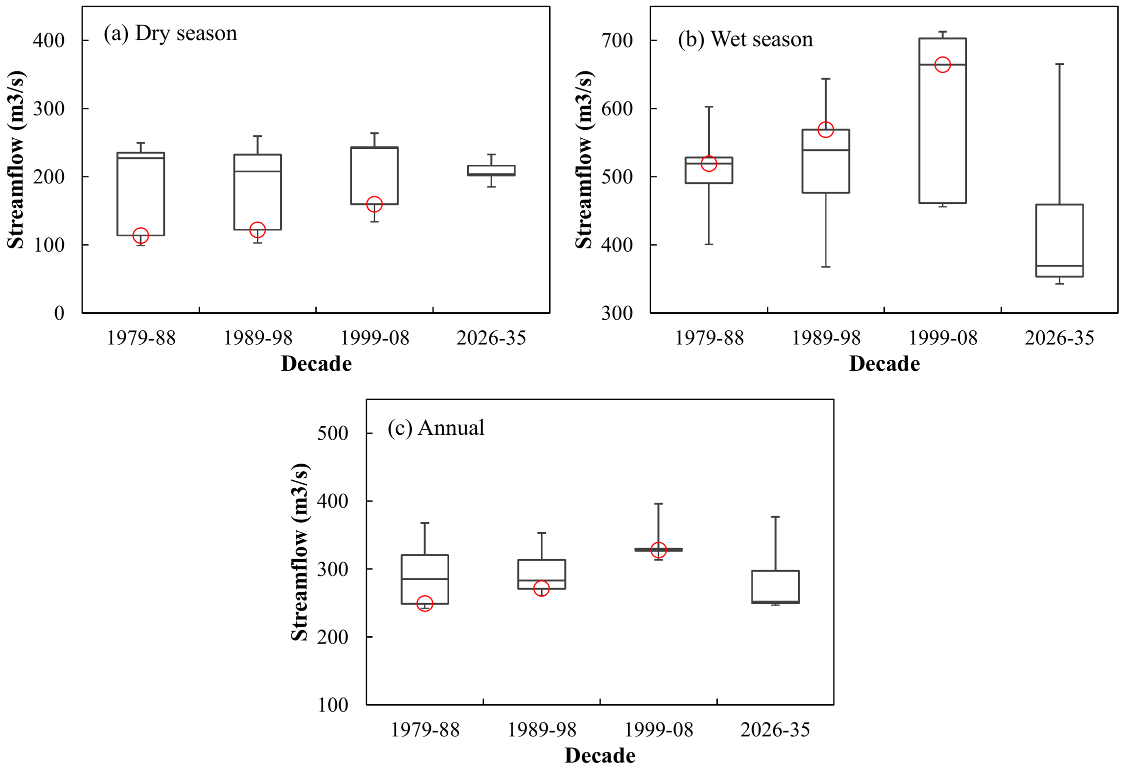


**Figure 11.** Box-and-whisker plot of (**a**) dry season, (**b**) wet season, and (**c**) annual streamflow simulated using high-resolution multi-model simulations for each decade in the baseline and near-term climates; the red circles represent mean streamflow simulated using observed rainfall.

## 4. Conclusions

The results of the CMIP5 high-resolution climate model experiments provide a potential source of input data for modeling rainfall–runoff responses of small-scale catchments under the influence of a changing climate. Using the Thu Bon River basin, located in the central coast region of Vietnam, this study has sought to quantify the variability of streamflow simulated using the rainfall derived from five different CMIP5 models. The Thu Bon River basin is a good choice for this study as it is one of the larger catchments in the vast central coast region of Vietnam, it is home to the economic center of Da Nang, it has a history of extreme weather events (both monsoonal flooding and low water flow induced estuary salinization), and there is an existing calibrated super-tank model for the upper Thu Bon River basin developed and applied by the authors [11,12,19] that has reasonable performance characteristics.

The results exhibit that, although rainfall is projected with a slight variation compared to that in the baseline climate, the runoff is very likely to decrease in the near-term decade. Decreases in runoff in the dry season are detected by most model simulations with a high level of confidence, though the rainfall in this period is expected to increase slightly compared with that of any preceding decades in the baseline climate. The results also show that the treatment of the model physical parameterization schemes tends to contribute more sensitivity to future projections. Experiments by MRI seem to project increases in streamflow, particularly during the high streamflow period; while models used by GFDL project consistent decreases of the basin runoff. As a result, this exploration is believed to be critical to making informed decisions for the implementation of proper adaptation strategies in this river basin and the downstream areas as well. In addition, this near-term assessment is also considered a good reference to verify the attempts of the climate modeling community in providing climatic knowledge to the public, because there is not a long wait to see what will be happening in the coming decades.

However, it is worth noting that the effects of increasing evapotranspiration and non-climate variability factors have not been included in this assessment, given the assumption of minor changes in surface temperature in the near-term climate and the fact that climate variability factors dominate the others in contributing to changes in runoff. More importantly, this work is merely the first attempt to explore the pattern of change based on simulation datasets in the past and future. Thus, we plan to apply model bias correction to the projected rainfall, the principal driver of runoff variability, to obtain a better simulated runoff. So, following publication of this research series, the performance of model bias concretion will be explored.

**Acknowledgments:** This work was financially supported by Vietnam's National Foundation for Science and Technology Development (NAFOSTED) for a basic research project (Code: 105.08-2014.23).

**Author Contributions:** Phan Cao Duong performed the data compiling and analysis; Dang Thanh Mai and Duong Hai Thuan performed the modeling; Nguyen Quoc Dung wrote the draft version of the paper; and Do Hoai Nam supervised the work and corrected and finalized the paper.

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

## References

1. Arnell, N.W. The effect of climate change on hydrological regimes in Europe: A continental perspective. *Glob. Environ. Chang.* **1999**, *9*, 5–23. [CrossRef]
2. Chiew, F.H.S.; McMahon, T.A. Modelling the impacts of climate change on Australian streamflow. *Hydrol. Process.* **2002**, *16*, 1235–1245. [CrossRef]
3. Milly, P.C.D.; Dunne, K.A; Vecchia, A.V. Global pattern of trends in streamflow and water availability in a changing climate. *Nature* **2005**, *438*, 347–350. [CrossRef] [PubMed]
4. IPCC. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2013; 1535p. [CrossRef]
5. Milly, P.C.D.; Dunne, K.A.; Delworth, T.L. Increasing risk of great floods in a changing climate. *Nature* **2002**, *415*, 514–517. [CrossRef] [PubMed]
6. Takara, K.; Kim, S.; Tachikawa, Y.; Nakakita, E. Assessing climate change impact on water resources in the Tone river basin, Japan, using super-high resolution atmospheric model output. *J. Disaster Res.* **2009**, *4*, 12–22. [CrossRef]
7. Chen, H.; Guo, S.L.; Xu, C.Y. Comparison and evaluation of multiple GCMs, statistical downscaling and hydrological models in the study of climate change impacts on runoff. *J. Hydrol.* **2012**, *434–435*, 36–45. [CrossRef]
8. Mizuta, R.; Yoshimura, H.; Murakami, H.; Matsueda, M.; Endo, H.; Ose, T.; Kamiguchi, K.; Hosaka, M.; Sugi, M.; Yukimoto, S.; et al. Climate simulations using MRI-AGCM3.2 with 20-km grid. *J. Meteorol. Soc. Jpn.* **2012**, *90*, 213–232. [CrossRef]
9. Kitoh, A.; Ose, T.; Kurihara, K.; Kusunoki, S.; Sugi, M. Projection of changes in future weather extremes using super-high resolution global and regional atmospheric models in the KAKUSHIN Program: Results of preliminary experiments. *Hydrol. Res. Lett.* **2009**, *3*, 49–53. [CrossRef]
10. Dibike, Y.B.; Coulibaly, P. Hydrologic impact of climate change in the Saguenay watershed: Comparison of downscaling methods and hydrologic models. *J. Hydrol.* **2005**, *307*, 145–163. [CrossRef]
11. Nam, D.H.; Udo, K.; Mano, A. Assessment of future flood intensification in Central Vietnam using a super-high resolution climate model output. *J. Water Clim. Chang.* **2013**, *4*, 373–389. [CrossRef]
12. Nam, D.H.; Udo, K.; Mano, A. Climate change impacts on runoff regimes at a river basin scale in Central Vietnam. *Terr. Atmos. Ocean. Sci.* **2012**, *23*, 541–551. [CrossRef]
13. Vo, N.D.; Gourbesville, P.; Vu, M.T.; Raghavan, S.V.; Liong, S.-Y. A deterministic hydrological approach to estimate climate change impact on river flow: Vu Gia–Thu Bon catchment, Vietnam. *J. Hydro-Environ. Res.* **2016**, *11*, 59–74. [CrossRef]
14. Wang, Z.; Batelaan, O.; De Smedt, F. A distributed model for water and energy transfer between soil, plants and atmosphere (WetSpa). *Phys. Chem. Earth* **1996**, *21*, 189–193. [CrossRef]

15. Ciarapica, L.; Todini, E. TOPKAPI: A model for the representation of the rainfall-runoff process at different scales. *Hydrol. Process.* **2002**, *16*, 207–229. [CrossRef]
16. Blazkova, S.; Beven, K. Flood frequency estimation by continuous simulation of subcatchment rainfalls and discharges with the aim of improving dam safety assessment in a large basin in the Czech Republic. *J. Hydrol.* **2004**, *292*, 153–172. [CrossRef]
17. Kato, H.; Mano, A. Flood runoff model on one kilometer mesh for the Upper Chang Jiang River. *Proc. GIS RS Hydrol. Water Resour. Environ.* **2003**, *1*, 1–8.
18. Kardhana, H.; Tatesawa, H.; Mano, A. Flood forecast based on numerical weather prediction and distributed runoff model. In *River Basin Management IV*; Brebbia, C.A., Katsifarakis, K.L., Eds.; WIT Press: Southampton, UK, 2007; pp. 201–211. [CrossRef]
19. Nam, D.H.; Mai, D.T; Udo, K.; Mano, A. Short-term flood inundation prediction using hydrologic-hydraulic models forced with downscaled rainfall from global NWP. *Hydrol. Process.* **2014**, *28*, 5844–5859. [CrossRef]
20. Moriasi, D.N.; Arnold, J.G.; Van Liew, M.W.; Bingner, R.L.; Harmel, R.D.; Veith, T.L. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans. ASABE* **2007**, *50*, 885–900. [CrossRef]
21. Nash, J.E.; Sutcliffe, J.V. River flow forecasting through conceptual models, Part I—A discussion of principles. *J. Hydrol.* **1970**, *10*, 282–290. [CrossRef]
22. Gupta, H.V.; Sorooshian, S.; Yapo, P.O. Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. *J. Hydrol. Eng.* **1999**, *4*, 135–143. [CrossRef]
23. Wilby, R.L.; Dawson, C.W.; Barrow, E.M. SDSM—A decision support tool for the assessment of regional climate change impacts. *Environ. Model. Softw.* **2002**, *17*, 145–157. [CrossRef]
24. Salathé, E.P. Comparison of various precipitation downscaling methods for the simulation of streamflow in a rainshadow river basin. *Int. J. Climatol.* **2003**, *23*, 887–901. [CrossRef]
25. Kiem, A.S.; Ishidaira, H.; Hapuarachchi, H.P.; Zhou, M.C.; Hirabayashi, Y.; Takeuchi, K. Future hydroclimatology of the Mekong River basin simulated using the high-resolution Japan Meteorological Agency (JMA) AGCM. *Hydrol. Process.* **2008**, *22*, 1382–1394. [CrossRef]
26. Lenderink, G.; Buishand, A.; Van Deursen, W. Estimates of future discharges of the river Rhine using two scenario methodologies: Direct versus delta approach. *Hydrol. Earth Syst. Sci.* **2007**, *11*, 1145–1159. [CrossRef]
27. Toan, D.D.; Tachikawa, Y.; Shiiba, M.; Yorozu, K. River discharge projection in Indochina Peninsula under a changing climate using the MRI-AGCM3.2S dataset. *Ann. J. Hydraul. Eng. (JSCE)* **2013**, *69*, I_37–I_42. [CrossRef]
28. Koirala, S.; Hirabayashi, Y.; Mahendran, R.; Kanae, S. Global assessment of agreement among streamflow projections using CMIP5 model outputs. *Environ. Res. Lett.* **2014**, *9*, 064017. [CrossRef]
29. Prudhomme, C.; Jakob, D.; Svensson, C. Uncertainty and climate change impact on the flood regime of small UK catchments. *J. Hydrol.* **2003**, *277*, 1–23. [CrossRef]
30. Fowler, H.J.; Blenkinsop, S.; Tebaldi, C. Linking climate change modelling to impacts studies: Recent advances in downscaling techniques for hydrological modelling. *Int. J. Climatol.* **2007**, *27*, 1547–1578. [CrossRef]
31. Wilby, R.L.; Beven, K.J.; Reynard, N.S. Climate change and fluvial flood risk in the UK: More or the same. *Hydrol. Process.* **2008**, *22*, 2511–2523. [CrossRef]
32. Prudhomme, C.; Davies, H.N. Assessing uncertainties in climate change impact analyses on river flow regimes in the UK. Part 2: Future climate. *Clim. Chang.* **2009**, *93*, 97–222. [CrossRef]
33. Kay, A.L.; Davies, H.N.; Bell, V.A.; Jones, R.G. Comparison of uncertainty sources for climate change impacts: Flood frequency in England. *Clim. Chang.* **2009**, *92*, 41–63. [CrossRef]
34. Giorgi, F.; Mearns, L.O. Calculation of average, uncertainty range, and reliability of regional climate changes from AOGCM simulations via the "reliability ensemble averaging" (REA) method. *J. Clim.* **2002**, *15*, 1141–1158. [CrossRef]
35. Yokoi, S.; Matsumoto, J. Collaborative effects of cold surge and tropical depression-type disturbance on heavy rainfall in Central Vietnam. *Mon. Weather Rev. Sep.* **2008**, 3275–3287. [CrossRef]
36. Yukimoto, S.; Yoshimura, H.; Hosaka, M.; Sakami, T.; Tsujino, H.; Hirabara, M.; Tanaka, T.Y.; Deushi, M.; Obata, A.; Nakano, H.; et al. *Meteorological Research Institute-Earth System Model Version 1 (Mri-Esm1), Model Description*; Meteorological Research Institute: Tsukuba, Japan, 2011; No. *64*; p. 88.

37. Endo, H.; Kitoh, A.; Ose, T.; Mizuta, R.; Kusunoki, S. Future changes and uncertainties in Asian precipitation simulated by multiphysics and multi-sea surface temperature ensemble experiments with high resolution Meteorological Research Institute atmospheric general circulation models (MRI-AGCMs). *J. Geophys. Res.* **2012**, *117*, D16118. [CrossRef]
38. Kain, J.S.; Fritsch, J.M. Convective parameterization for mesoscale models: The Kain-Fritsch scheme, in The Representation of Cumulus Convection in Numerical Models. *Meteorol. Monogr.* **1993**, *24*, 165–170.
39. Bretherton, C.S.; McCaa, J.R.; Grenier, H. A new parameterization for shallow cumulus convection and its application to marine sub-tropical cloud-topped boundary layers. Part I: Description and 1D results. *Mon. Weather Rev.* **2004**, *132*, 864–882. [CrossRef]