論文の内容の要旨
Thesis Summary

論文題目　**Study on hydrodynamic river model with reservoirs for improved simulation of floods in a low-lying floodplain**

（低平氾濫原の洪水シミュレーション改善に向けた貯水池を含む水文動的河川モデルに関する研究）

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本文

Floods are complex processes that are affected by human-natural system interactions. The accelerating human interventions to the hydrological cycle necessitates the representation of coupled human-natural systems in analysing and understanding water management options. The operation of artificial reservoirs is among the human interventions with the largest impact to the hydrological cycle. While multiple benefits can be gained from reservoir operation, the multi-functional nature of reservoirs makes their operation difficult – trade-offs may exist between each competing functions. Integrated models are necessary for addressing such issues. While the impacts of the operation of large reservoirs on augmenting limited water supply (e.g. through irrigation, water scarcity, water withdrawal related studies) have already been assessed through integrated models, their impacts on large scale flooding and flood inundation are rarely assessed. The increasing flood risks necessitates the development of better tools which takes into account the impacts of artificial reservoirs to flood inundation.

This dissertation aims to improve the representation of human impacts, particularly of reservoirs and their operation, in a hydrodynamic river model. This goal is attained by representing reservoirs in elevation maps and integrating their operation as a subroutine in a state-of-the-art global hydrodynamic model, CaMa-Flood Model. The reservoir operation subroutine is based from the reservoir operation algorithm and module in one of the pioneering integrated water resources model, H08. By doing so, a new tool which allows more seamless large-scale assessments of human impacts to hydrodynamic flows is developed.

To ensure the local applicability of the model, it is applied and tested in the Chao Phraya River Basin, the largest and most important geographical unit in Thailand. The lowermost region is a delta which empties into the Gulf of Thailand. These geographic features make the region highly prone to flood inundation. In 2011, successive and excessive rainfall resulted to an immense flood catastrophe in the Chao Phraya River Basin. To date, the Thailand flood of 2011 is said to be the most economically damaging flood in history, both in overall losses and insured losses.

Several studies have already been conducted to analyze the Thai floods but most of them have focused on the natural factors that impacted the flood event. This dissertation contains one of the pioneering research which assessed the impacts of large-scale reservoir operation on the Thai flood inundation. H08, an integrated water resources model with a reservoir operation module, was combined with CaMa-Flood, a river routing model for the representation of flood dynamics. The combined H08-CaMa model was applied to simulate and assess the historical and alternative reservoir operation rules in the two largest reservoirs in the basin, Bhumibol and Sirikit Reservoirs. The combined H08-CaMa model effectively simulated the 2011 flood: regulated flows at a major gauging station have high daily NSE-coefficient of 92% as compared with observed discharge; spatiotemporal extent of simulated flood inundation match well with those of satellite observations. Simulation results show that through the operation of reservoirs in 2011, flood volume was reduced by 8.6 billion m^3 and both flood depth and flood area were reduced by 40% on the average. Nonetheless, simple modifications in reservoir operation proved to further reduce the flood volume by 2.4 million m^3 and the flood depth and flood area by 20% on the average. A more realistic simulation of the 2011 Thai flood was made possible by modeling reservoir operation with a hydrodynamic model; the possibility of reducing flood inundation through improved reservoir management was quantified.

The utility of the combined H08-CaMa model in simulating the impacts of climate change and reservoir operation to the water balance and flood inundation in Chao Phraya River Basin was also demonstrated. The ensemble means of the simulation results using eight bias-corrected CMIP5 general circulation models (GCMs) under two representative concentration path scenarios (RCP), RCP4.5 and RCP8.5, for the near future from 2041 to 2059 and far future from 2081-2099 were compared with the base period simulation from 1981 to 1999. While the percent change in evapotranspiration within the catchment area of the two reservoirs in both RCP scenarios will not significantly increase, precipitation may significantly increase. This results to an increase in runoff of 40-50% in RCP8.5. While the change in dry season ranges from -10mm to 10mm, the wet season runoff could increase by as much as 160mm in RCP8.5. Hence, the frequency of reservoir emptying will decrease while spilling will increase by as much as 5 times of that of the base period in RCP8.5. Consequently, flooding in the basin will be more frequent and more severe. It was found that the mean inundated area downstream of the two reservoirs will increase by about 130% in RCP8.5. These results clearly indicate that under a changing climate, in the future, a shift of reservoir operation towards prioritizing flood mitigation over drought mitigation will be beneficial in the Chao Phraya River Basin. The study is thus relevant for preparing necessary adaptation measures to minimize the damages in the future.

These studies demonstrate the relevance of including anthropogenic effects in advanced global hydrological and river routing models for improving water resources management and flood mitigation in the present as well as in the future. However, several challenges still remain for the model to be useful for operation or practical purposes: (1) relatively coarse resolution, (2) low predictive skill of flooding in delta, and (3) several physical inconsistencies in forcing CaMa-Flood with the reservoir operation flows.

While numerous studies have shown that finer resolutions result to better predictions of catchment-scale floods using catchment-scale hydrodynamic models, the impact of finer spatial resolution on flood predictions using global-scale river models is rarely examined. Hence, the suitability of CaMa-Flood river model with a new complex flow scheme which represents multi-directional downstream connectivity (MDC), in hyperresolution modelling of large-scale floods was assessed. The impacts of (1) spatial resolution, and (2) representation of sub-grid processes on simulating the inundated area and discharge during the immense flood in 2011 in Chao Phraya River Basin, Thailand was examined. Using several statistical metrics, it was found that when MDC is considered, simulation results slightly improved with finer spatial resolution. However, when MDC is ignored, the predictive capability of the model significantly declined with finer spatial resolution; Nash-Sutcliffe Efficiency coefficient decreased by more than 35% in simulation results at 1km resolution as compared with those at 10km resolution. In coarser spatial resolutions, floodplains flow along the same direction as the main channels. When simulating in finer spatial resolutions, areas that were expressed as floodplains in coarser spatial resolutions are discretized into small river channels. This results to disconnected floodplains which may only flow towards the main channels. Hence, the flow capacity of such floodplains is greatly reduced. In the event of heavy flooding, the reduced flow connectivity and flow capacity result to unrealistic "build-ups" and backflows. MDC pathways reduce such impacts by allowing water to flow in between floodplains, thereby maintaining the similar flow capacity as in coarser resolutions. The representation of MDC thereby results to more realistic flows between floodplains and deltas in hyperresolution modelling. These results indicate that large-scale flood predictions may not necessarily improve with hyperresolution modelling – improved physical process representation will have to be implemented.

Several models have already succeeded in representing artificial reservoir operation in hydrological and river routing models. These representations usually rely on virtual representations of reservoirs and manipulations of volumetric flows from storage relationships. Physically representing reservoirs in models will be beneficial for biogeochemical assessments, calculation of nutrient cycling and flows, and ecological assessments, among others.

Due to the limitation in satellite observations, dams and their corresponding reservoirs are typically physically represented in existing topography maps as shallow, elevated lakes that suddenly fall to its downstream. The volume of water impounded in dams are thereby underrepresented and underestimated. To improve the representation of reservoir operation, Bhumibol and Sirikit Reservoirs were explicitly represented by using interpolation techniques to modify the elevation of the areas identified as "flat" in the original elevation maps. A new algorithm was developed to detect the dams and their corresponding reservoirs using existing DEMs and river flow maps derived from SRTM and HydroSHEDS; the topography underlying the water surface was inferred and interpolated using the following information: the elevation of the inflow and outflow grids, river lengths, and river sequence map. To integrate the reservoir operation algorithm previously used in H08, a similar computer code was then written as a subroutine in CaMa-Flood. The new code uses empirically-derived dam storage-water level relationships to convert the simulated water level to reservoir storage. The dam outflows were calculated using the reservoir storage and release rules. The outflows, water level, and dam storage in the downstream grid is then updated.

It was found that the natural flows would significantly change when the bathymetry is changed. The flat elevation in the original DEMs significantly reduces the flow gradient within the reservoirs. Such topography causes water to create a pool of water upstream of the reservoir in order to create a sufficient gradient for water to flow downstream. The pooling of water results to delayed and lower peaks in discharge, particularly during the dry season. It also results to lower flow fluctuations, suggesting slower response to rainfall and runoff. Such effects may be significant during droughts and when intense rainfall suddenly occurs after a dry spell.

Such changes in the natural flows were taken into account in the reservoir operation algorithm. By using the new elevation and the new modelling framework, it was found that the reservoir storage and water levels can be more realistically simulated. The flat elevation in the original DEMs cause extensive backflows when the reservoir operation algorithm is used. By representing the bathymetry of the reservoirs, such unrealistic backflows can be avoided, resulting to a significant improvement in the simulated flood inundation within the areas surrounding the reservoir. Hence, the efficiency of the model in simulating flows in the reservoirs and the surrounding areas have significantly improved.

In summary, this research demonstrated that global hydrological and river models can be used to provide locally-relevant information such as those needed for better water management, disaster mitigation, and climate change adaptation. New techniques for representing human impacts, particularly, reservoir operation, were developed and have been implemented in global models, H08, integrated water resources model and CaMa-Flood, hydrodynamic model. The relative impacts of finer spatial scales and subgrid processes representation on flood prediction have also been assessed. It was found that CaMa-Flood can be suitably used for hyperresolution modelling provided that floodplain flow processes are adequately represented.

To conclude, the results of this research are deemed to be important in directing efforts in modelling anthropogenic impacts with hydrodynamics in regional to global scales. The discussions provided are essential for improving our understanding of the underlying issues of scale and the necessary representation of physical processes. Overall, this dissertation contributes to progress in physically-based modelling and their application for better prediction of large-scale floods.