Changes in environmental flow regimes caused by tropical cyclones in the Western North Pacific

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Abstract. Changes in environmental flow regime due to hydraulic construction projects and variability in precipitation patterns due to climate change over the past several years have increased the stress on ecohydrology, and the indiscriminate use of water has had a negative impact on the water environment in natural rivers and hydro structures. Previous studies on typhoon precipitation have simply estimated the intensity, duration, frequency, and magnitude of typhoon precipitations, but the study of the effects on water resource and ecosystem operations by separating typhoon precipitations from warm season precipitations was relatively inadequate. Therefore, this study investigated the characteristics of quantitative hydrological changes related to daily flow data of dam inflows considering the effects of the typhoon. According to the peak flow rate and frequency analysis, there is a distinct increase trend in the southern part of the Korean peninsula. Also, during non-typhoon periods, low flow rates are frequent, but low-flow changes due to typhoons are not significant. The results of this study could be used as a useful resource for establishing scientific measures for the preparation and coordination of responses to the changes in water and ecological environment systems in a changing climate.

1. Introduction

Atmospheric conditions, such as rising sea level due to global warming, sufficient water vapor, and the difference in the wind strength of the atmosphere, have created favorable conditions for developing typhoons [1, 2, 3]. Also, the latitude at which typhoons are generated is higher than in the past, and typhoons tend to increase rapidly in a shorter time than near the land [4, 5]. Therefore, it is necessary to prepare for the possibility of an invasion of the relatively large typhoon on the Korean peninsula [4, 5, 6].

So far, many studies have limited estimates of the intensity and frequency of storms caused by typhoons. These studies have limitations in understanding the impact of typhoons on water resources management and ecosystems. Therefore, this study analyzes monthly and seasonal data of the Korean peninsula multi-purpose dam based on the daily inflow data and typhoon data. Typhoon data were applied to typhoon domain of the Korean Peninsula, and the trend analysis was conducted by separating the total dam inflow, typhoon flow, and non-typhoon flow. Furthermore, to understand the effects of typhoons on the Korean Peninsula water environment, typhoons that were generated in the...
northwest Pacific Ocean and affected the Korean peninsula were extracted and analyzed for the magnitude, timing, duration, and frequency of typhoon-induced flows. The results of this study are expected to provide useful information for more efficient distribution of limited water resources through a more accurate diagnosis of flooding and non-flooding season with the emphasis on securing sustainable water resources and ecosystem conservation in a changing climate.

2. Data and methods
In the Nakdong River basin, there are three multi-purpose dams including Andong Dam, Imha Dam, and Juam Dam. The Andong dam, which is located in the inland area of the Korean peninsula, is included in the path of typhoons, so it is affected by the typhoon during the boreal summer. The Andong Dam was the first multi-purpose dam in the Nakdong River basin, this dam was built in April 1971 and was completed in October 1976 to reduce annual flood damage in downstream areas and secure agricultural, industrial and household water supplies. The specifications of Andong dam are rockfill dam (RFD) with a dam height of 83m and a length of 612m. The basin area is 1,584km², and the total storage capacity is 1,284 x10⁶m³.

In this study, dam inflow data from the National Water Resources Management Information System (www.wamis.go.kr) was used to analyze the runoff characteristics of the multipurpose dam. The typhoon data were obtained from the Typhoon Research Center (http://www.typhoon.or.kr) and the Japan Meteorological Agency (www.jma.go.jp). Typhoon-related runoff data have been extracted by examining areas of the Korean Peninsula affected by typhoons that have passed the targeted typhoon domain (120°E-138°E, 32°N-40°N). Trend analysis of dam inflow data was performed for hydrological alteration indices relevant the annual maximum flows (AMF) and 7-day low flows using the Mann-Kendall test [7, 8] and the Poisson regression technique [9].

3. Analysis results

3.1. Typhoons in the western North Pacific
The effects of typhoons were quantified by tracking the path of typhoons affecting the Korean peninsula, and the variation of the flow characteristics caused by the typhoon was analyzed. Figure 1 shows the path of the typhoon that occurred in the western North Pacific (WNP) region from 1977 to 2015 and the typhoons that affected the Korean Peninsula.

![Figure 1](image-url) Typhoon tracks (May-October) in the western North Pacific. The square dashed line around the Korean peninsula indicates the typhoon domain of the Korean peninsula used by the Korea Meteorological Administration.
During the period 1979-2015, 213 typhoons landed on the Korean Peninsula and affected directly or indirectly. In addition, more than 98% of the typhoons affecting the Korean Peninsula between 1977 and 2015 occurred between May and October. During May, six typhoons were analyzed to have affected Korean peninsula, and it was found that 69 typhoons passed the typhoon domain of the Korean peninsula the most in August.

3.2. Variability in typhoon-induced flows

Figure 2 shows the runoff analysis results for the period from May to October considering the influence of typhoon in the Andong dam basin. From the analysis of the typhoon flow from 1975 to 2015, an annual average of 15.18% of the seasonal flood inflow was caused by rainfall into the typhoon, and the variation was very large due to the influence of the typhoon intensity (average: 15.18, standard deviation: 42, coefficient of variation: 2.77). The highest flood season was during 2003, and the impact of "Super Typhoon Maemi," which hit the southern part of the Korean peninsula, was huge.
The trend analysis was conducted based on the observed inflow data of the Andong dam from 1977 to 2015 (Figure 3). As a result of the maximum daily flow analysis, there was a statistically significant increase in three flow metrics including magnitude, occurrence frequency, and duration of the total inflow. The 7-day low-flow analysis showed a decreasing trend in the magnitude and occurrence frequency. Day maximum flow and 7-day low flow tend to decrease in early summer and winter.

Approximately 70% of the inflows of the Andong dam are operated for flood control during the typhoon season, and 30% of inflows are mainly for non-flood seasons and are operated for hydropower generation. Therefore, this study is expected to cope with hydrological variability for optimal dam operations by identifying the dam inflows due to typhoon activities in the Northwest Pacific region and constructing a water resource management system in a changing climate.

4. Conclusions

Typhoon occurrences in the North Pacific are changing due to the rise in sea surface temperature due to global warming, the occurrence of El Niño and La Niña, and changes in evolution patterns of sea surface temperature. Notably, the typhoon genesis, typhoon tracks, and the intensity of the typhoon are changing. It was confirmed that there was a positive correlation between KP-affecting typhoons and typhoon-induced runoff in a Korean multipurpose dam. Therefore, it is necessary to establish mid- and long-term countermeasures against the typhoon by analyzing various hydrological variables and the relationship between large-scale atmospheric circulation patterns and changes in sea surface temperature to investigate the ecological system change of the watershed by the influence of typhoon. The results of this study are expected to provide useful information for the expansion of infrastructures considering typhoons, the establishment of watershed countermeasures, and securing of the water resources.

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