UNIVERSITY OF TWENTE.

MASTER THESIS

ENHANCING EARLY WARNING SYSTEM IN THE UPPER BEKASI WATERSHED THROUGH THE EMPLOYMENT OF HYDROMETEOROLOGICAL MODEL

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ABSTRACT

Hydrometeorological disasters often occur around the world, including floods due to overflowing rivers. One of them is the flood in urban areas in the Upper Bekasi watershed, West Java Province, Indonesia. The selected flood-prone area is located between two tributaries, namely the Cileungsi river and the Cikeas river. Early warning systems were established to reduce the risk of flooding. However, the flood incident due to heavy rain that lasted for a long time on 1 January 2020 was classified as very severe and caused significant damages. To improve preparedness, this study uses a new hydrometeorological model, WRF-Hydro. This study aims to provide insight into the existing early warning in the study area, analyze the response to actions taken by the community and local disaster management agencies, and test WRF-Hydro's ability to simulate torrential rain. This study uses an exploratory approach to describe the early warning system that existed and an experimental approach to test the model's capabilities. This study shows how WRF-Hydro can be optimized for use by competent authorities to improve the flood early warning system.

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LIST OF ABBREVIATIONS

BMKG	Indonesian Agency for Meteorology, Climatology, and Geophysics
BNPB	Indonesian National Agency for Disaster Management
BPBD	Regional Agency for Disaster Management
BBWSCC	Centre for Ciliwung-Cisadane River Basin
GFS	Global Forecasting System
GSMaP	Global Satellite Mapping of Precipitation
GWP	Global Water Partnership
IMC	Indonesian Maritime Continent
KP2C	Cileungsi-Cikeas River Care Community
NMHSs	National Meteorological and Hydrological Services
NOAA	National Oceanic and Atmospheric Administration
NWM	National Water Model
NWS	National Weather Service
PCC	Pearson's Correlation Coefficient
RMSE	Root Mean Square Error
TRMM	Tropical Rainfall Measuring Measure
WMO	World Meteorological Organization
WRF	Weather Research and Forecasting

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CHAPTER I INTROUDCTION

1.1. Background

Every year floods have severely damage infrastructure across the planet (Jonkman, 2005). According to the disaster event database (EM-DAT), 3,751 natural disasters occurred during the last ten years (2008-2017), of which 84 percent were weather-related disasters (Fisher et al. 2018). The number of victims of these natural disasters reached around 2 billion people, and 95 percent of them were victims of extreme weather events. Besides, the economic losses suffered by 141 countries due to natural disasters during that period were expected at USD 1,658 billion, and 73 percent of these were disasters related to extreme weather. Extreme weather events in Indonesia harm society and the environment, and they can even lead to disasters. Hydro-meteorological events such as tornadoes, floods, landslides, and drought are the major natural disasters that frequently occur in Indonesia. Based on the 2020 Indonesian National Agency for Disaster Management (BNPB) report, the number of disasters due to hydro-meteorological events was 847 out of the 958 natural disasters that occurred from January to March 26, 2020. As shown in Figure 1, of the 25,652 natural disasters that occurred from 2000 to the beginning of 2020 in Indonesia, the incidence of hydrometeorological disasters reached more than 90 percent.

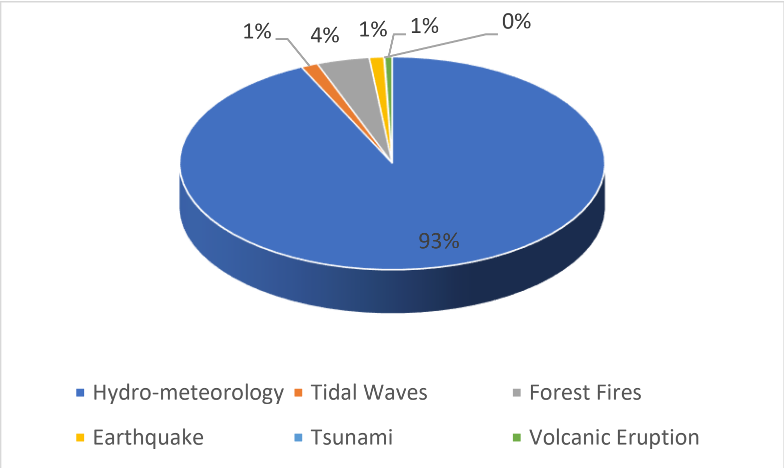


Figure 1 Percentage of Natural Disaster Events in Indonesia between 2000 and 2020

Source: BNPB (2020)

One of the hydrometeorological disasters that frequently occurs in Indonesia is flooding. Based on data from BNPB, there have been 9,442 flood events from 2000 to early 2020. Because of the floods, thousands of residences have been inundated, thousands of fatalities, tens of thousands of people were injured, and nearly thirty million people suffered and were displaced. Not to mention the damage to tens of thousands of various public facilities such as health, religious and educational facilities.

Hirabayashi et al. (2013) stated that due to global warming an increase is projected in the frequency of floods that can cause loss of both lives and properties.

One of the efforts that can reduce losses caused by flooding is to disseminate early warning. The early warning systems have the main objective to empower individuals and communities to respond quickly and appropriately to hazards in order to mitigate the risk of damage or loss of property and injuries and even fatalities (UNISDR, 2006). The World Meteorological Organization / WMO (2008) highlighted the vital role of the National Meteorological and Hydrological Services (NMHSs) and the WMO itself is to contribute to efforts to protect human assets and lives by providing early guidance related to hydrometeorological hazards and other information to reduce risks. To support an effective early warning system, WMO (2015) promulgated impact-based forecasts program which aims to support economic growth and sustainability. Therefore impact-based forecasts must be presented from the perspective of the end-users such as local policy makers, disaster managers, and communities.

Conventional instruments such as rain gauges and river water level gauges can be used as input for hydrological modeling in predicting floods. However, they are less effective in achieving early warning objectives due to the relatively short time lag in reducing the flood risks. Contrarily, numerical weather prediction is an essential model for forecasting long-term floods in a watershed (Rogelis & Werner, 2018). It is possible to produce long-term flood forecasts because the numerical weather prediction can generate weather forecasts for the next few days so that disaster management agencies can respond adequately to early warnings provided by National Meteorological and Hydrological Services. Quantitative precipitation forecasting is one of the numerical weather prediction methods that has been used in recent years as input for hydrological modeling (Seo et al., 2018). Therefore, the use of quantitative precipitation forecasting for this purpose indicates the need for a qualitative shift in the rain forecast paradigm (light or moderate or heavy rains) to quantitative weather predictions which explains the numerical range of possible rainfall (WMO, 2016).

Weather Research and Forecasting (WRF) (Skamarock et al., 2008) is one of the numerical weather predictions that are widely used around the globe, with dispersed applications for research and operational weather forecasting (Powers et al., 2017). Based on the study by Li et al. (2017), the quantitative prediction forecast produced by WRF can be used as a reliable reference for flood warnings in a watershed. Reliable flood early warning requires accurate forecasts of when the flood occur and how much it will occur to know the resulting runoff (Wehbe et al., 2018). Vivoni et al. (2008) claimed that soil conditions at the regional scale can influence rainfall formation, river flow and evapotranspiration. One of the newly developed features in the WRF application is WRF-Hydro, which utilizes terrestrial and high-resolution hydrological data that can be run fully coupled with the WRF itself as well as stand-alone capabilities (Gochis et al., 2013). According to Senatore et al. (2015), WRF's ability to predict soil moisture and rainfall is not sufficient compared to WRF-Hydro modeling (Gochis et al., 2015), because WRF-Hydro has a smaller bias. The same thing was stated by Wehbe et al. (2018), where WRF-Hydro has less bias and error when compared to conventional WRF. As a hydrometeorological model, WRF-Hydro has the potential to be employed operationally as a tool to predict floods (Sun et al., 2020).

WRF-Hydro has been employed widely by researchers to predict and analyze flood events in various parts of the world (Zarekarizi, 2018; Ryu et al., 2017; Yucel et al., 2015; Avolio et al., 2019). However, there has been no study on how to use WRF-Hydro in Indonesian maritime continent which has complex geo-chemical-physical processes due to the strong land-sea-air interaction. Therefore, it is necessary to compare the conventional WRF and coupled WRF-Hydro models which have important value to determine which model is more reliable for predicting flooding at Indonesian maritime continent.

This research focused on the early warning system by utilizing numerical weather prediction models WRF and WRF-Hydro, which were used to analyze extreme rainfall events that occurred from 31 December 2019 to 1 January 2020. This extreme weather has resulted in the breakdown of one of the embankments in the Cikeas River, which caused flooding in the surrounding area and resulted in the loss of property and life. Based on data from BNPB, it was recorded that 9 people were killed and 366,274 residents had to be evacuated from their homes. The research focused on the downstream area of the Upper Bekasi watershed because there are 2 sub-watershed confluences, namely the Cileungsi sub-watershed and Cikeas sub-watershed. Figure 2 depicts the confluence of two rivers. Apart from these reasons, the research location was chosen because the area is a densely populated residential area and many economic sector activities are disadvantaged when there is a flood. Besides, the downstream area of the Upper Bekasi watershed is also frequently flooded due to high rainfall. (Prihartanto & Ganesha, 2019). Based on the research of Kadri & Kurniyaningrum (2019), this happened because the area in the Upper Bekasi watershed experienced a land use change of 43 percent into built-up areas.

Figure 2 The Confluence of Cileungsi River and CIkeas River

Source: Personal Documentation

1.2. Problem Statement

The confluence of Cikeas sub-watershed and Cileungsi sub-watershed that are situated in Bekasi city is considered as a densely populated urban area. This location is facing frequently natural hazards during rainy season, causing floods induced by torrential rain. Floods in this area often bring not only infrastructure damages and economy losses but they also threat human lives. As the landscape of this area has been changing over time and the erratic weather extremes are increasing due to climate change, the situation is also worsening. To minimize calamities because of urban flooding, an effective early warning system crucial for the community at risk and the disaster management board to take appropriate actions and make decisions. Therefore, the current situation of the urban flooding in Bekasi, including early warning systems in place, and the capability of WRF-Hydro should be analyzed. These situations need to be evaluated, diagnosed and improved in order to tackle and prevent flood problems.

Early warnings that are disseminated several days before the occurrence of extreme weather events have a vital role. Disaster management agencies and the community must respond to such information. The question is whether such early warning systems and the warnings are in place, used to their fullest potential and could be improved. There are three reasons to investigate the employment of WRF-Hydro to reduce flood risk. Firstly, the ability of WRF-Hydro to predict torrential rain at the Indonesian maritime continent is not yet known until now. Secondly, it is yet to be elaborated whether in areas embryonal early warning systems are in place in local communities. Lastly, the potential for improvement WRF-Hydro might offer is of interest, as is the receptivity of authorities and community to embrace and make the best use of WRF-Hydro. Furthermore, it is of interest to address how that best could be arranged, and to elaborate what the gains might be.

1.3. Research Objective

This study aims to provide recommendations to the community at risk and disaster management agencies for improvements on early warning system and flood forecasting in Bekasi. To achieve this primary aim, three specific objectives will be pursued: 1) providing insights regarding embryonal early warning system and flood forecast in Bekasi urban area; 2) analyzing response actions taken by community at risk when early warnings were disseminated, 3) experimenting the capability of WRF-Hydro to simulate and visualize the severe extreme weather event occurred in 1st January 2020.

1.4. Research Questions

Based on the state-of-the-art described above, the main research question is formulated as follows:

> To what extent and how could the hydrometeorological model WRF-Hydro improve society's motivation to take flood preparedness and response action?

Sub research questions as follows:

1. What are the main characteristics in the selected flood-prone areas related to flood risks, flood preparedness and response action?
2. Is the meteorological and hydrological simulation-based WRF-Hydro model capable of providing better flood risk warnings and guidance to response action than systems in place? (cf. flood occurred on 1st January 2020).
3. How could WRF-Hydro best be embraced and implemented by authorities and communities in the selected flood prone areas?

1.5. Thesis Outline

The thesis is organized as follows: Chapter 1 describes the components of introduction the including background of the research, problem statement, research questions, and research objectives. Chapter 2 elaborates literature reviews related to relevant theoretical background and information within the scope of the research. Chapter 3 explains the research design, which comprises the research framework, research strategy, research demarcation, and methods of collecting data. Chapter 4 provides findings in answering research questions using descriptive analysis of the existing early warning systems and evaluative analysis of hydrometeorological modelling performance. Chapter 5 gives concluding remarks of this research project and recommendations for future research.

CHAPTER II LITERATURE REVIEW

This chapter elaborates on the theories and concepts related with the research question. It consists of three sections: The first section explains urban conditions associated with hydrometeorological extreme events. The second section describes early warning systems as decision-maker tools. The last section presents the weather models and the employment of WRF-Hydro in earlier research.

2.1. Extreme Rainfall

In the weather science, Indonesia is prominent as the Indonesian Maritime Continent because of the strong interaction between air and sea, which resembles small-scale earth (Yamanaka, 2016). The archipelagic country of Indonesia with its vast waters is located between two continents, namely the Asian continent and the Australian continent. Indonesia is also located between the Pacific Ocean and Indian Ocean and has approximately 17,000 islands. As a result of archipelagic topography and the induction of sea surface temperatures, the influence of geographic features that become a large-scale climate phenomenon varies throughout Indonesia (Aldrian & Susanto, 2003). The variation of climatic and weather phenomena has become the concern of researchers and has produced a lot of literature on Indonesian maritime continent including research, such as conducted by Ramage (1968) about monsoon, McBride (1998) about inter-annual climate variability, Zhang (2013) regarding Indonesian Throughflow that is related with intra seasonal variability or Madden-Julian Oscillation, and Pribadi et al. (2012) that studied about diurnal weather variation. The variations in the climate and weather phenomena mentioned above are closely related to extreme rain events. For instance, the phenomenon of the active phase of the Madden-Julian Oscillation which occurred in conjunction with the incidence of very heavy rain resulted in flooding in mid-January 2013 in Jakarta (Wu et al, 2013).

Severe rain events that caused flooding so that hundreds of thousands of people were evacuated and claimed lives have also occurred in the Jakarta and surrounding areas in February 2007 (Voorst, 2014). Subsequently, according to Wu et al. (2007), physical factors that induced this extreme rain events in January and February 2007 are as follows:

1) Asian monsoons flowing from the north. In these months, the surface wind flows from the northern hemisphere across the equator towards the southern hemisphere while the wind in the upper layer blows inversely, from southern hemisphere to northern hemisphere.
2) A strong vertical shear.
3) Low relative humidity in the middle layer
4) The convection process that supports cloud development often appears during the day in mountainous areas located south of Jakarta, while at night the convection process occurs in the northern region.

Moreover, based on Roca & Fiolleau, (2020) research, the amount of extreme rainfall that occurs in the tropics is often an accumulation of rain due to a long duration mesoscale convection system. The convective precipitation system on Earth is a mesoscale convection system with an area ranging from tens to hundreds of kilometres (Dong et al, 2020). Extreme amounts of rainfall, long duration of events, and slow movement of a mesoscale convection system are the main factors causing flooding (Houze, 2004).

2.2. Urban Hydrometeorology

The hydrometeorological physics process in urban areas is strongly influenced by the urban heat island where the term urban heat island was first introduced by Balchin & Pye (1947). The term urban heat island, which has appeared in the 1940s, indicates that the atmosphere in urban areas is warmer than in rural areas. According to Stewart and Oke (2012), the warmer temperature of urban areas has two effects, it can be positive or negative depending on the macro climate of the city. The positive impact of urban heat island can be felt by cities that have a cold macro climate, where urban heat island has benefits for human activities because urban heat island can reduce home heating costs, lessen the amount of road icing that can cause slippery and become road threats to motorists, and make outdoor activities more comfortable. Not only benefits humans, urban heat island in a city with a cold macro climate also indulges plant growth and is also good for several animal habitats. Meanwhile, in a city with a hot macro climate, urban heat island triggers negative impacts because urban life becomes increasingly uncomfortable due to hotter weather, increases demand for energy due to increased use of air conditioning, and can potentially increase heat stress and even death.

From a meteorological point of view, a densely populated urban area can affect the climate in the area as explained by Oke (1982) as outlined below:

1) The density of buildings in urban areas where the sun's reflection and radiation is trapped causes the absorption of solar radiation to increase.
2) Industry, transportation and housing emit combustion waste thereby increasing the release of latent heat and sensible heat.
3) The surface of urban areas causes solar radiation to be converted to sensible heat rather than latent heat.
4) The surface of urban areas consisting of buildings and asphalt also causes greater heat absorption and longer heat dissipation.

Apart from that, urban areas also influence how the precipitation system is formed. Lin et al. (2011) compared how the development of rain cloud systems in urban and rural areas using WRF modeling.

Lin et al. revealed that the rain cloud system in urban areas is growing slower but the system is stronger than if it is grown in rural areas.

Meanwhile, hydrologically, urban areas that are the destination areas for urbanization have experienced changes in the landscape so that they tend to be separated, fragmented, and complex due to there are many buildings. Based on Zhang et al. (2019) study regarding the effect of landscape change in cities located in a watershed, it is stated that changes in the urban landscape exacerbated by climate change cause an increase in the total amount of runoff. The influence of urban areas on water distribution was also investigated by Liu & Shi (2017), where the results of these studies indicate that there is a very strong correlation between river flow and the proportion of buildings in residential areas. The denser the residential area, the higher the vulnerability of the area to flooding.

The area of study, which is an urban area located at the junction of 2 sub-watersheds, continues to grow, both in terms of economy, population growth, and also experiencing land changes. How the characteristics of the research area are important to be understood because urban areas are known to have an influence on the hydrometeorological characteristics that occur in the area.

2.3. The Elements of Early Warning and Flood Forecast

In Indonesia, Law of the Republic of Indonesia Number 24 of 2007 concerning Disaster Management states that the government is responsible for carrying out disaster relief management. One of the efforts to manage disasters is to reduce disaster risk. To achieve this goal, one of the possible ways is to disseminate early warning. In Government Regulation of the Republic of Indonesia number 21 of 2008 concerning the Implementation of Disaster Management (2008, p2), it is stated that early warning is defined as "a series of activities to provide immediate warning to the public about the possibility of a disaster occurring in a place by the competent institution." To cope with certain types of disasters, this government regulation also stipulates that there are certain government agencies authorized to observe disaster precautions. Heavy rain that can cause flooding can be classified as a form of extreme weather event. Therefore, based on the Law of the Republic of Indonesia number 31 of 2009 concerning Meteorology, Climatology and Geophysics, an extreme rain warning is issued by the Indonesian Agency for Meteorology, Climatology, and Geophysics (hereinafter referred to as BMKG).

Particularly in urban areas, the risk of flooding has increased over time as a result of pressure of population, property values and infrastructure. Therefore, to reduce the risk of disasters, especially high rainfall that can cause flooding, building an effective early warning system is very important to achieve community resilience. In 2006, UNISDR released a directive on the effective early warning system which consists of four elements, among which are the following:

1) **Risk knowledge**: Emerged risks is a combination of hazards and vulnerabilities in a particular area. Therefore, collecting data and analyzing it is a prerequisite for motivating people to take appropriate action against natural disasters. Learning and risk mapping are the main activities in this element.
2) **Monitoring and warning services**: These services are the essence of the system. Science-based knowledge must be strengthened to predict the occurrence of natural hazards. In addition, continuous 24-hour monitoring of natural hazard precedents should be undertaken. In addition, the impact of these hazards must be communicated and coordinated through existing networks.
3) **Dissemination and communication**: The effective early warning system emphasizes that warnings must reach communities at risk. Therefore, it is necessary to develop an identification level of communication and the establishment of an authority to respond to these risks. This system is expected to ensure that as many people at risk as possible receive a warning.
4) **Response capacity**: The appropriate actions that need to be taken when a natural disaster occurs can be implemented through response education by disaster management agencies. In addition, changing the behavior of vulnerable people is essential to build strong preparedness. Besides, rescue routes must also be available before natural disasters occur.

These principles can be applied to various types of disasters, including the incidence of heavy rains that cause flooding. In 2013, The Associated Program on Flood Management (APFM) as an initiative of the WMO and the Global Water Partnership (GWP) published guidelines for making flood forecasts. In this guide, we should pay attention to several things related to flood prediction, such as hydro-morphological characteristics, physical processes that occur during a hydrometeorological event, and ensure that technically and economically services can be carried out as a mitigation effort. The Associated Program on Flood Management (2013) stated the importance of the flood forecast lead time before flood events occuring. Here, the flood forecast lead time is the minimum period required by the affected community to take effective action against the risk of flooding some time after the warning. In generating flood forecasts, several types of data are needed, such as hydrological data, meteorological data, topographic data, and social data.

With current technological developments, the numerical weather prediction product in the form of quantitative precipitation forecast is widely used for flood forecasting. However, to increase the level of flood warning system confidence, one of the challenges that needs to be answered by the warning system is increasing the capability of the numerical weather prediction (Cloke & Pappenberger 2009). In this study, I will compare the skill of WRF/WRF-Hydro with conventional WRF to identify which numerical weather prediction resulting the better atmospheric simulations in the study area.

2.4. Early Warning Systems as Decision-making Tools

Hydrometeorological forecasts that can provide useful information about flood events support decision-makers to formulate flood impact reduction strategies (Morss, 2010). Recently, numerical weather predictions have been producing hydrometeorological forecasts with a forecast lead time of up to several days before flood events. With prolonged forecast lead time, information about the hazards that will occur will provide input to the disaster management agency to determine mitigation measures for reducing the impact of the disaster. Also, the longer forecast lead time opens up opportunities for greater dissemination of early warning information to local communities to take proper action to save their lives and their property.

However, various sophisticated weather forecasting models that exist today are under-valued if the forecast results are misunderstood, used inappropriately, or even ignored by the recipients of the information (Demeritt et al., 2010). Besides, the majority of the hydrometeorological community also lacks understandings of how communities and disaster management agencies interpret forecast information and use it to make decisions (Morss, Lazo, & Demuth, 2010). Both of these indicate ineffective warning communication. Furthermore, Parker et al. (2009) also explained that a lack of understanding of warning information and how to take protective measures when receiving warning information was one of the reasons for the ineffectiveness of early warnings. Therefore, how numerical weather prediction outputs be best implemented to empower people at risk and disaster managers is highly important.

2.5. WRF and WRF-Hydro

To generate flood forecasts for up to ten days, one of the varieties of tools that capable to produce precipitation estimation is WRF. WRF is one of the open source-based numerical weather predictions which is developed and employed by diverse communities such as universities, government laboratories, and operational weather prediction (Skamarock et al., 2019). Not only WRF has been used for weather research and forecasting but WRF also has been used to scrutinize other systems that occur on earth such as air chemistry, hydrology, forest fires, tropical storms, and regional climates (Powers et al., 2017). In simulating atmospheric conditions, WRF has flexibility and efficiency since it can be employed using diverse computer systems ranging from laptops to clusters / super-sophisticated computers. To get a more comprehensive weather simulations, WRF can be combined with several other WRF features that represent real conditions on earth, such as WRF-Chem (atmospheric chemistry), WRF-Fire (forest fire modeling), and WRF-Hydro (hydrological modeling). Generally, the ARW framework can be seen in Figure 3. One of the advantages of WRF is that, compared to global weather modeling, it has higher resolutions to simulate regional weather conditions that cause floods (Asghar et al. 2019). This can be done by downscaling the global modeling.

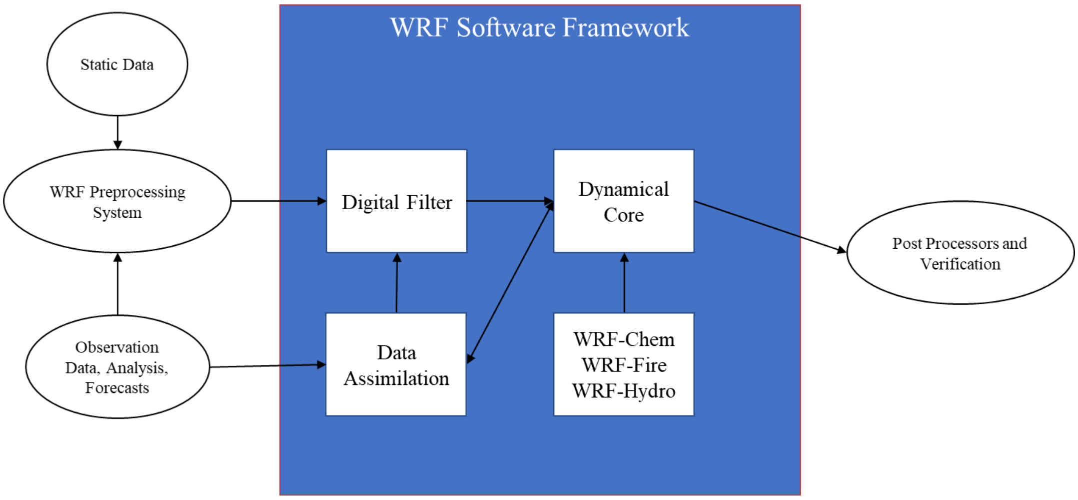


Figure 3 WRF Components

Source: adapted from Skamarock et al. (2019)

WRF-Hydro is a model developed by the National Oceanic and Atmospheric Administration (NOAA) and the National Weather Service (NWS) with several other agencies to predict flooding and streamflow which is used nationally in the United States as the National Water Model (NWM) (Krajewski et al., 2017). Furthermore, WRF-Hydro can generate streamflow prediction in certain areas (White et al., 2019) because WRF-Hydro harnesses Noah surface terrain modeling, which is capable of calculating the increasing complexity of the ground state, providing a physically consistent ground flux, and providing channel flow information for use in hydrometeorological research (Gochis et al., 2015). For the latest version of the WRF-Hydro, a new land surface model has been added, namely Noah-MP. Improving capability has also been made in the latest WRF-Hydro to allow for more general mapping, and on the use of irregularly shaped objects such as water catchments or hydrological response units (Gochis et al., 2020). As land surface modeling, both Noah and Noah-MP require a meteorological variable as forcing which can be seen in Table 1.

Table 1 Meteorological forcing variables for Noah and Noah-MP

Meteorological Variable	*Units*
Incoming Longwave Radiation	W/m^2
Incoming Shortwave Radiation	W/m^2
Specific Humidity	kg/kg
Air Temperature	K
Zonal and Meridional Surface Wind	m/s
Surface Pressure	Pa
Liquid Water Precipitation Rate	mm/s

Both WRF and WRF-Hydro can be used as research tools because those tools provide many options for physical configuration by parameterization. The parameterization of a numerical weather prediction aims to depict a state of physical processes in nature that is too small, too short, too complex, too difficult to understand, or too expensive to compute (Knievel, 2008). WRF and WRF-Hydro provide various parameterizations including microphysics parameterization, cumulus parameterization, shallow cumulus parameterization, surface layer, planetary boundary layer, atmospheric radiation. The combination of parameterizations in the WRF will produce different rainfall simulations due to the complexity of the physical process in the rain event (Mu, Zhou, Peng, & He, 2019). Therefore, the selection of parameterization becomes important to simulate rainfall events accurately, both spatially and temporally.

2.6. The Employment of WRF/WRF-Hydro

Several studies have been carried out employing WRF-Hydro in different fields of science, as summarized below.

A study by Kerandi et al. (2017) on the employment of a fully coupled conventional WRF with WRF-Hydro (hereafter “WRF/WRF-Hydro”) is used to study hydrometeorological conditions in the Tana river basin in Kenya. Kerandi et al. (2017) stated that WRF/WRF-Hydro modeling results showed a slight reduction in rainfall, evapotranspiration, groundwater storage but increased runoff compared to conventional WRF. Although WRF/WRF-Hydro modeling produces precipitation far below satellite observations, it is able to make an annual water discharge that is close to the observed result, which is 323 mm per year and 333 mm per year, respectively.

Naabil et al. (2017) employed WRF/WRF-Hydro for planning, decision-making, and management of water resources at the Tono dam in Ghana. WRF/WRF-Hydro modeling output is compared with precipitation observations from the Tropical Rainfall Measuring Measure (TRMM) satellite and available hydrological data. WRF/WRF-Hydro described the estimated streamflow attribute with a Nash-Sutcliff efficiency (NSE) value of 0.78 and a Pearson correlation of 0.89. Naabil et al. (2017) explained that improvements in model parameter calibration of WRF-Hydro have the potential to be used in water resource planning, particularly estimating streamflow and dam levels.

In 2017, Verri et al. used WRF/WRF-Hydro to reconstruct the local water cycle in a small catchment in Southern Italy. The research was conducted in the Ofanto River, a small catchment area, a porous aquifer in the downstream area, and the Ofanto watershed is also an area that is often affected by flash floods. In the study of Verri et al. (2017), several tests were carried out with various settings so that the best results could result in a reduction in error / RMSE of 84 percent and an increase in correlation of 41 percent for the estimation of precipitation. Meanwhile, the runoff estimation results in a 20 percent RMSE reduction and a 24 percent increase in correlation.

Research by Arnault et al. (2018) compared fully coupled WRF/WRF-Hydro with conventional WRF in the Central European region. Arnault et al. (2018) consider that conventional WRF modeling does not calculate soil moisture transport in a three-dimensional process, in contrast to WRF/WRF-Hydro, which considers this. By activating lateral terrestrial water flow in WRF-Hydro, generally, there is an increase in soil moisture, surface evaporation, and rainfall in the study area. Usually, in conventional WRF, these variables are reduced by reducing the runoff partition – infiltration parameter. However, this good can only occur under certain conditions such as moderate topography, high surface flux spatial variability, and local weather formation processes dominating the weather regime. Arnault et al. (2018) explained that WRF-Hydro is suitable for use in ensemble weather predictions.

Wehbe et al. (2019) employed WRF/WRF-Hydro to analyze extreme rain events that induced floods in the United Arab Emirates. Then, for comparison, the results of surface observations and satellite observations are used in the form of rainfall data, soil moisture, and satellite fractions to validate the conventional WRF and WRF/WRF-Hydro outputs. This study indicated that the use of WRF/WRF-Hydro in rainfall forecasts results in a reduction of 24 percent for RMSE, 13 percent for bias, and an increase in Pearson's correlation by 7 percent compared to the conventional WRF.

CHAPTER III RESEARCH DESIGN

This chapter elaborates on how the objectives of the study were achieved through a conducted research project. The following sections elucidate the research framework, research strategy, data collection, and research matrix.

3.1. Research Framework

According to Verschuren and Doorewaard (2010), a research framework is a schematic way of answering research questions comprises of several steps taken to achieve it. Applying a stepwise approach, therefore, activities carried out are as follows:

1) Characterize briefly the objective of the research project

The aim of this study is to identify flood risk and flood preparedness, analyze response actions taken by communities and authorities, and compare the capability of WRF-Hydro and conventional WRF in producing extreme rainfall forecasts in a case study. Having these aims achieved, I formulated recommendations how the improved weather forecast can induce for a better decision-making and response in the tropical urban catchment area.

2) Determine the objects of the research project

The objects of this research are the characteristics of the flood-prone area in Bekasi, the skill of WRF-Hydro in the Bekasi catchment area compared to conventional WRF, and response action to flooding by the governance and society after producing flood forecast with a long lead time.

3) Establish the nature of the research perspective

This research scrutinizes on flood risks and flood preparedness in the Bekasi floodplain. Thus, it is practice-oriented research based on data gathered from governments, an NGO, and vulnerable communities. Moreover, this study also employed a state-of-the-art hydrometeorological model to examine its skill to generate extreme weather forecasts on the Bekasi flood prone area, therefore, it is also an experimental study. Finally, this research performed a diagnostic gap review to make the best use of prolonged flood forecast.

4) Determine the sources of the research perspective

In this study, reviewing scientific literature as well as studying existing documentation help to develop theoretical framework. Table 2 below outlined the theories and concepts to be used in this study.

Table 2 Key concepts of the study

Key Concepts	Literature and Documentation
Extreme rainfall	WRF-Hydro employment
Urban hydrometeorology	Literature on urban characteristic
Early warning system	Literature and document on early warning
Decision-making and response during flood	Literature and document on flood early warning

5) Make a schematic presentation of the research framework

The research framework is depicted in the flowchart below:

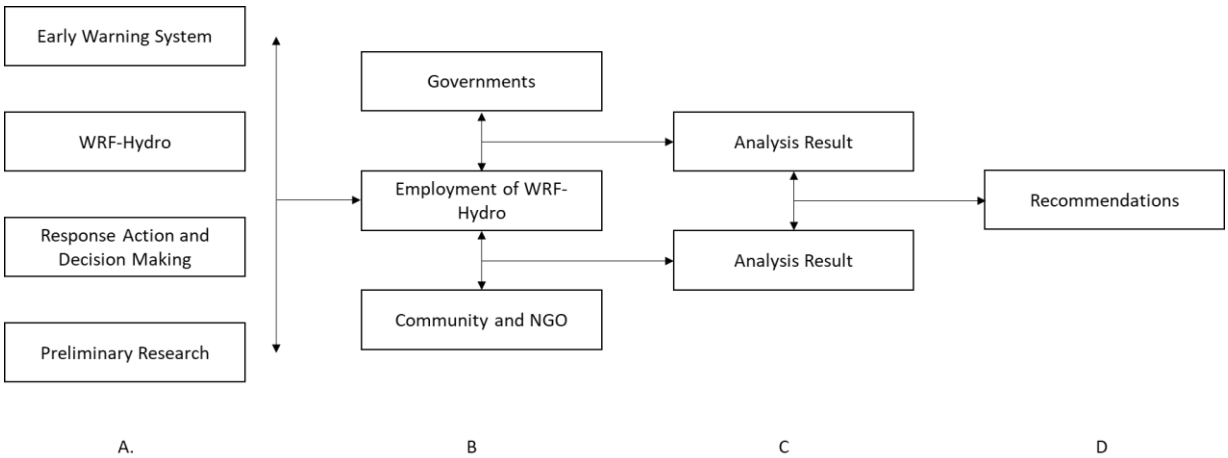


Figure 4 Research Framework

6) Steps that were followed during the research project are as follows:

a. Conducting analysis on theories regarding early warning system, WRF-Hydro, response action, and decision making. Also, preliminary research on flood plain area characteristics and the employment of WRF-Hydro are established.

b. Running both the conventional WRF and WRF/WRF-Hydro to simulate torrential rain events and carrying out assessments of flood risks, existing early warning system established by governments, and response actions were taken through interviews and document reviews.

c. Comparing the output between conventional WRF and WRF/WRF-Hydro and confronting the analysis results of the interviews to propose recommendation.

d. Recommendations for improving early warning systems so they can reduce losses caused by floods.

7) Check whether the model developed necessitates any changes to the research objective

As study is an iterative process, there is no indication of any changes required yet.

3.2. Research Strategy

A case study approach is used in this research project. It used qualitative-quantitative mixed method and evaluative analysis to study each research unit. Subsequently, this research underpins a desk research that was combined with a literature review, interviews, and experimental running program. The study analyzed explanatorily all gathered data to describe the implementation of early warning system. Next to it, the successful prolonged flood forecast lead time is proposed to be employed in generating flood forecast.

3.2.1. Running the Conventional WRF and WRF/WRF-Hydro

Above the research strategy is described in a condensed manner. There is one element that requires more explanation in detail to foster clarity. That is the element of 'experimental running program' as referred to in §3.2: In this research an experimental approach was applied in which to compare the torrential rain simulation as based upon conventional WRF that is already employed in Indonesia and the newly developed WRF-Hydro feature that is not yet to be employed in Indonesia. By comparing conventional WRF and WRF/WRF-Hydro, it will be known which model that have a higher capability to predict extreme rain events (cf. §2.4 and §2.5). This study employed WRF version 4.2 and WRF-Hydro version 5.1.2.

Usually, the experimental approach used in running WRF is sensitivity tests by setting different WRF configurations that aim to improve the prediction of catastrophic events (Avolio & Federico, 2018). In this study, both conventional WRF and WRF/WRF-Hydro parameterization configuration used is following settings suggested by Sun & Bi (2019) relating the validation of sensitivity test to the operation of WRF in the tropical belt. Due to the study area that located in the urban area, this study also used urban canopy model parameterization. The parameterization configuration can be seen in Table 3.

Table 3 Parameterization Configuration of Conventional WRF and WRF/WRF-Hydro

Parameterization Type	Parameterization Used
Physics suite	*"tropical"*
Microphysics	*WRF Single–moment 6–class Scheme* (Hong & Lim, 2006)
Cumulus parameterization	*New Simplified Arakawa–Schubert Scheme* (Han & Pan 2011)
Long wave atmospheric radiation	*RRTMG Shortwave and Longwave Schemes* (Iacono et al., 2008)
Short wave atmospheric radiation	*RRTMG Shortwave and Longwave Schemes* (Iacono et al., 2008)
Planetary boundary layer	*Yonsei University Scheme / YSU* (Hong, Noh, & Dudhia, 2006)
Surface layer	*Revised MM5 Scheme* (Jiménez et al., 2012)
Land surface	*Unified Noah Land Surface Model* (Tewari et al., 2004)
Urban Surface Options	*Urban Canopy Model* (Chen et al., 2011)

To produce weather predictions for up to several days, WRF uses Global Forecasting System (GFS) data as input. In this study, the WRF forecast is a 72-hour forecast using GFS data. The GFS data that is available every three hours is forecast data which has a resolution of 0.5^0 x 0.5^0 or approximately 56 km with the GRIB2 data format. The GFS data used in this study is forecast data starting on December 30, 2019 at 00 UTC until January 2, 2020 at 00 UTC which is freely downloaded at https://rda.ucar.edu/datasets/ds084.1/ (NCAR, 2020). This data is used as input to make predictions and early warnings three days before heavy rains and floods. Hopefully, disaster managers and communities at risk will have sufficient time to prepare for hazards. The outputs of conventional WRF and WRF/WRF-Hydro were verified by ground observation data.

3.2.2. Output Data Analysis and Verification

After the two models above are run, both produced output in meteorological data for WRF only and meteorological data accompanied by river flow data for WRF-Hydro. The meteorological output of both models has a time series of an hourly dataset so that there are 72 meteorological variable datasets at the output. There are various meteorological variables from 1 output dataset, including air temperature, humidity, air pressure, wind direction and speed, precipitation, and other variables. From the meteorological variables generated from the model, the simulation of meteorological phenomena can be analyzed. This study analyzed the meteorological data generated by the two models to determine the cause of heavy rains on January 1, 2020.

The spatial distribution of precipitation results from the two models was compared with observation. Two types of observation data were used: ground station observation and weather satellite observation. Due to limited timeframe, the researcher used visual /eyeball verification when comparing the spatial rainfall distribution. Also, a statistical test was conducted to know the reliability of models. The statistical test used the forecast results and the observed data from the BMKG automatic observation station in the modelling domain. The meteorological variables tested were rainfall parameters at seven points, namely Jatiasih, Cibongas, Citeko, Jagorawi, Halim Perdana Kusuma, and TMII. Forecasts from WRF and WRF-Hydro are deterministic forecasts. Then, this study compares the hourly rainfall between the model output (denoted by the letter F) with the available observations (denoted by the letter O). Therefore, the type of verification used in this study is continuous verification, namely bias and association (F. Fundel, n.d.). This study carried out two statistical tests as follows:

1) Pearson's correlation coefficient (PCC) to see the relationship between the observed value and the forecast value. The PCC value ranges from -1 to 1, where a value of -1 means that the relationship between observations and predictions is inversely proportional. A value of 0 means that there is no relationship. A value of 1 means that the relationship between observations and predictions is

comparable. The PCC value is used to see the relationship between the observed values and the output values of the model (Benesty, Chen, & Huang, 2008).

$$PCC = \frac{\sum_{i=1}^{n}(\mathrm{O}_i - \bar{\mathrm{O}})(\mathrm{F}_i - \bar{\mathrm{F}})}{\sqrt{\sum_{i=1}^{n}(\mathrm{O}_i - \bar{\mathrm{O}})^2 \text{ x } \sum_{i=1}^{n}(\mathrm{F}_i - \bar{\mathrm{F}})^2}}$$

2) Root mean square error (RMSE) is used to see the average error of the modelling output compared to the observation results. This study uses RMSE because RMSE is sensitive to the probability of outlier data occurrence (Chai & Draxler, 2014).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(\mathrm{O}_i - \mathrm{F}_i)^2}{n}}$$

3.2.3. Research Boundaries

To ensure the objectives of the study are achieved within the limited timeframe, the research boundaries are delicately determined. Research boundaries are outlined as follows:

1) The research analyzed one torrential rain event on 1st January 2020 that caused damages to embankments in Cikeas sub-watershed.
2) The study did not conduct intensive sensitivity tests that investigate multiple combinations of configurations to find out which combination has the best forecast skills.

3.2.4. Research Unit

The research units of this research were governmental authorities involved in early warning systems in Indonesia, such as Regional Disaster Management Agency (in the future referred to as BPBD), BMKG, Centre for Ciliwung-Cisadane River Basin (referred as BBWSCC), non-governmental organizations and numerical model experts. Due to the limited time of finalizing this study, the selection of the research unit was considered adequate to provide analysis regarding the early warning system in place, response actions taken and implementing newly developed hydrometeorological model WRF-Hydro. Additionally, the number of research units also depended on the availability of interviewees.

3.2.5. Selection of Research Unit

A combination of purposive and snowballing sampling was employed. On the one hand, purposive sampling was adopted, as this technique is appropriate to explore specific informative cases (Neuman, 2014). On the other hand, snowball sampling (or respondent-driven sampling) was applied, because the first respondent has interrelations with other respondents in achieving the same goal. Initially, the researcher identified the first person related to early warning dissemination and numerical prediction model expert. Subsequently, the first respondents connected to new respondents in their network.

The first participant is a flood warning provider, who then directed the researcher to the regional disaster management agency in charge of flood-prone areas. Likewise with numerical weather experts, first responders referred to other experts. This study identifies interviewees using a coding plan. Each code represents each interviewee (e.g., IN-1 refers to the first respondent). The professional profiles and codes of the interviewees are shown in Table 4.

Table 4 Interview codes and interviewees positions

Interviewee	Interviewee Code	Position Held	Interview Method
Puarman	IN-1	Founder and chairman of the KP2C community	Personal Interview
Dede Armansyah, ST	IN-2	Head of Prevention and Preparedness for BPBD Bogor Regency	Personal Interview
Suhendra, S.Sos	IN-3	Head of the Rehabilitation and Reconstruction Section of the BPBD Bekasi Municipality	Personal Interview
Agie Wandala Putra, S.Si, M.Sc	IN-4	Head of BMKG Weather Early Warning Subdivision	Online Interview
Siswanto, M.Sc	IN-5	Weather and Climate Model Expertise. He was involved in arranging the Jakarta Flood Early Warning System that employed hydrological and meteorological modelling	Personal Interview
Dr. Amsari M. Setiawan, M.Si	IN-6	Multi Model Ensemble Expertise	Online Interview
Supari, M.Sc, Ph.D	IN-7	Multi Model Expertise	Online Interview

The selection of research units is based on the following criteria: 1) Personnel that actively involved in generating and disseminating early warnings; 2) Local disaster managers; 3) Numerical modelling experts.

3.3. Data Collection

The qualitative data that was collected comprise primary and secondary data. To obtain the primary data, in-depth interviews with semi-structured formats were conducted (see Appendix B. Questionnaire). The secondary data chosen in this study was obtained by the desk research method. This research examined various documentation and literature that includes scientific journals, academic reports in the form of theses, reports from agencies or organizations, including various regulations and policies related to research problems. Documentation studies and literature studies produced information about the early warning system and how to optimize the use of this information to reduce losses. There are several sources of data and knowledge methods of accessing them to answer the sub-questions. Interviewees also provided several documents that are not available on the internet. Table 5 shows the sources and collection methods for each type of data and information.

Table 5 Sources of data and accessing method

Research questions	Data/Information required to answer the question	Sources of data	Accessing data
1. What are the main characteristics in the selected flood-prone areas related to flood risks, flood preparedness and response action?	- Damages caused by floods on inundated areas - Existing flood early warning in flood-prone areas - Response action being taken for 1st January 2020 flood	Primary data, secondary data, documents	Interview and literature search
2. Is the meteorological and hydrological simulation-based WRF-Hydro model capable of providing better flood risk warnings and guidance to response action than systems in place? (cf. flood occurred on 1st January 2020).	- The output of the WRF-Hydro model - Atmospheric condition based on hydrometeorological model simulation	Secondary data, documents	Experimental approach and download data
3. How could WRF Hydro best be embraced and implemented by authorities and communities in the selected flood prone areas?	- General information regarding optimization and operationalization of hydrometeorological model	Primary data, secondary data, documents	Interview and literature search

3.4. Data Analysis

In answering research questions, according to Creswell & Creswell (2018), data analysis in qualitative research can be done simultaneously between data collection and writing findings. Table 6 illustrates the analysis methods used in this research.

Table 6 Data and method of analysis

Research Sub-questions	Method of accessing data	Method of Analysis
What are the main characteristics in the selected flood-prone areas related to flood risks, flood preparedness and response action?	Interview and literature search	Qualitative: analyzing the governments and society efforts to reduce flood risk
Is the meteorological and hydrological simulation-based WRF-Hydro model capable of providing better flood risk warnings and guidance to response action than systems in place? (cf. flood occurred on 1st January 2020).	Experimental approach and download data	Quantitative: analyzing model output results, then comparing which model is closer to observation data
How could WRF Hydro best be embraced and implemented by authorities and communities in the selected flood prone areas?	Interview and literature search	Qualitative: analyzing the potential use of the hydrometeorological model to reduce flood risk

3.5. Ethics Statement

To answer research questions, the researcher conducted interviews with different actors. Thus, this study followed the University of Twente Ethics Policy. This study was reviewed by the ethics committee and approved. This research gives respect to the rights of interviewees by fulfilling ethical considerations. Also, the recorded personal information of the interviewees are kept confidential and disclosed if they allowed to do so. Interviewees filled out standard University of Twente consent forms. However, the consent form was also translated into Indonesian as the local language because some interviewees were not fluent in English. Examples of two versions of the consent form are in the Appendix C. Two Versions of Consent Form.

CHAPTER IV RESULTS AND DISCUSSION

This chapter starts with background information regarding administrative and geographic situations of flood-prone areas. Then it presents the results on flood risks and costs; flood preparedness and response actions; meteorological analysis; comparisons between model outputs; and how the newly developed hydrometeorological model can be embraced and implemented. Lastly, a discussion is provided regarding the results.

4.1. Background Information about the Flood-Plain

4.1.1. The Profiles of Cileungsi and Cikeas Watersheds

The Cileungsi river and the Cikeas river are located in the West Java Province of Indonesia. The selected research area is the downstream part of the Upper Bekasi river basin, where the confluence of two sub-watersheds is located. The two sub-watersheds are the Cileungsi sub-watersheds and Cikeas sub-watersheds. The coordinates of the confluence of the two rivers are 6°18'15.2"S and 106°58'19.1"E. After the confluence of the Cileungsi and Cikeas rivers, the river that flows downstream is called the Bekasi river. Figure 5 shows the position of the three rivers. According to Kadri (2011), the Bekasi Weir is the separator between the Upper Bekasi and Lower Bekasi watersheds. After passing through the dam, the Bekasi river, which flows until it disembogues into the sea around the coast of the Bekasi Regency, is in the Lower Bekasi Watershed. This study focused on the occurrence of floods that inundated several areas in the Upper Bekasi watershed. The total area of the Upper Bekasi watershed is approximately 39,045 ha. The Bekasi Hulu watershed is divided into three sub-watersheds: the Cileungsi sub-watershed, the Cikeas sub-watershed, and the Upper Bekasi sub-watershed. The Cileungi sub-watershed is the largest in the Upper Bekasi watershed, where the sub-watershed has approximately 26,525.9 ha or has a percentage of 67.9 percent of the Upper Bekasi watershed. Meanwhile, the Cikeas sub-watershed has about 11,352.9 ha or has a proportion of 29.1 percent of the Upper Bekasi watershed, and the area of the Upper Bekasi sub-watershed is approximately 1,166.2 ha (Bekasi Municipality, 2016). With the difference in the proportions of the two sub-watersheds, the Cileungsi sub-watershed has a dominant influence on flood events in the downstream part of the Upper Bekasi watershed because the catchment area is 2.3 times that of the Cikeas sub-watershed catchment area (Kadri, 2011). However, when viewed from the length of the river, the Cikeas river is longer than the Cileungsi river, with a river length of 49,924 m and 41,829 m, respectively. Figure 5 also depicts the catchment area of the Upper Bekasi watershed and Table 7 described the profile of the sub-watersheds in the Bekasi Hulu watershed.

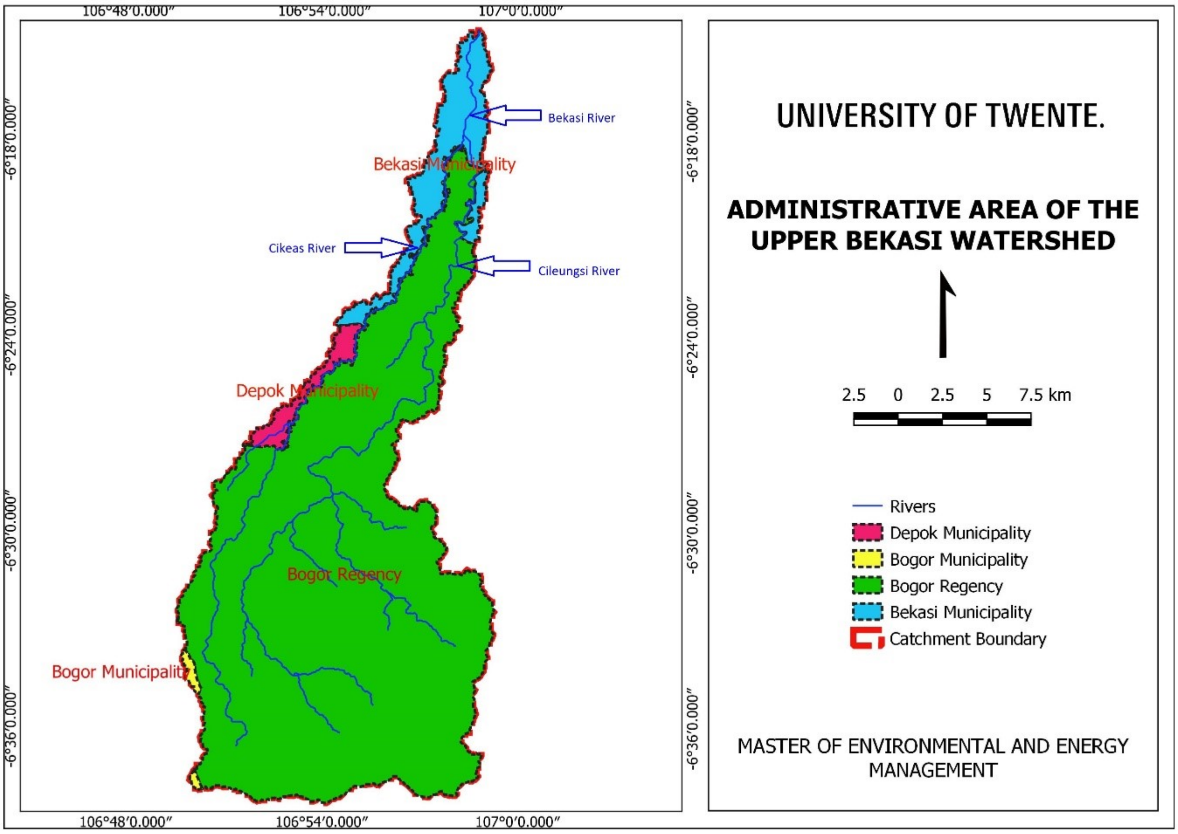


Figure 5 Catchment Area of the Upper Bekasi Watershed

Table 7 Upper Bekasi Watershed Profile

No	The Name of the River	Width (m)		Depth (m)	Discharge (m^3/s)	
		Surface	Riverbed		Max	Min
1	Cikeas River	10	24	30	250	5.9
2	Cileungsi River	10	40	30	350	8.5
3	Upper Bekasi River	10	50	30	375	14,4

Source: (BPBD Kota Bekasi, 2018)

The Cileungsi and Cikeas sub-watersheds originate from the Bogor Regency area. However, these two sub-watersheds have different characteristics. According to the Cileungsi-Cikeas River Care Community (hereinafter referred as KP2C) (2021), on the one hand, the upstream area of the Cileungsi sub-watershed is located between two sub-districts in Bogor Regency, namely the Babakan Madang sub-district and Sukamakmur sub-district. Viewed from the topography, the upstream area of the Cileungsi sub-watershed are elongated hills, elongated ridges, and steep valleys. Cileungsi River is a river with an open stretch, and the width of the river can reach 40 meters. The Cileungsi River is highly polluted from household and factory waste. The Ministry of Environment and Forestry stated that more than 50 factories are operating along the Cileungsi river. The IN-1 highlighted that river water is often foamy and emits an unpleasant odor, is black, and much dead fish flounder.

On the other hand, the Cikeas River has a different topography from the Cileungsi River. Cikeas River has a characteristic in the form of a narrow and meandering area. Cikeas river is frequently covered by a thicket of trees along the riverbank. The majority of trees that grow along the Cikeas river are bamboo trees. Even though the Cikeas river is free from domestic and factory activities, it is unfortunate that the too-shady bamboo trees cause natural waste problems in the Cikeas river. The bamboo logging, the strong current of the river so that the roots of the bamboo trees on the river banks were uprooted, and the cliffs collapsed into three factors that caused many bamboo trees to enter the Cikeas river. Although the Cikeas River and Cileungsi River have different characteristics, the two sub-watersheds carry the same threat of flooding in the downstream area of the Bekasi Hulu watershed, especially during the rainy season. If there is heavy rain upstream of the two sub-watersheds, the downstream areas will be inundated.

4.1.2. Administrative Areas between Watersheds

As shown in Figure 5, the catchment area of the Bekasi Hulu watershed includes four administrative regions, namely Bekasi Municipality, Depok Municipality, Bogor Regency, and Bogor Municipality. However, 7 per cent of this catchment area is in the Bekasi City area, and a hefty 89 per cent is in Bogor Regency. Sites that are often affected by floods are also in these two administrative areas. Therefore, this study concentrates on discussing Bekasi City and Bogor Regency exclusively.

The Cileungsi and Cikeas river also form the border of Bekasi Municipality and Bogor Regency. The area flanked by these two rivers is the Bogor Regency area, while to the west of the Cikeas river and the east of the Cileungsi river is the Bekasi Municipality. Figure 6 depicts the administrative area of Bekasi Municipality. The scope of the city of Bekasi is approximately 210.49 km^2 (Bekasi Municipality 2017). Bekasi Municipality is divided into 12 sub-districts. Table 8 shows the division of sub-districts in Bekasi and the recorded population in 2020. Topographically, Bekasi Municipality is included in a flat area, with slope from 0 percent to 2 percent, and the altitude of Bekasi Municipality is between 11 and 81 meters above sea level. The administrative boundaries of Bekasi Municipality are as follows:

1. North: Bekasi Regency, Jakarta Capital Region
2. East: Bekasi Regency
3. South: Bogor Regency
4. West: Jakarta Capital Region

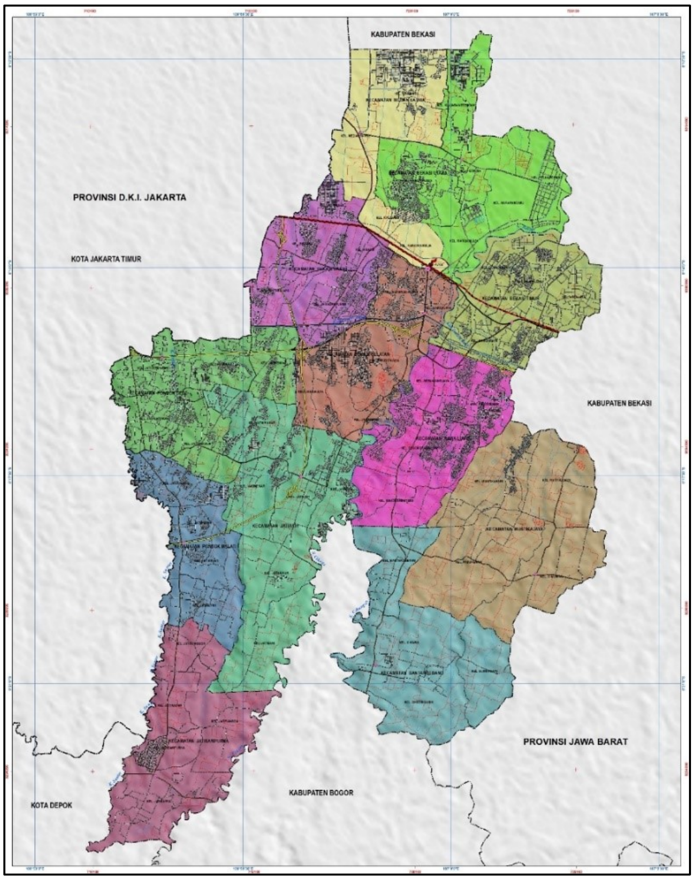


Figure 6 Map of Bekasi Municipality

(Source: Peta Tematik Indonesia 2013)

Table 8 Total Area and Demographics of Bekasi Municipality

No.	Sub-districts	Total Area (km^2)	Population (thousands)
1	Pondokgede	15.92	251.20
2	Jatisampurna	19.54	123.92
3	Pondokmelati	11.8	131.12
4	Jatiasih	24.27	247.36
5	Bantargebang	18.44	107.22
6	Mustikajaya	26.42	213.52
7	Bekasi Timur	14.63	257.03
8	Rawalumbu	16.85	220.70
9	Bekasi Selatan	16.06	210.81
10	Bekasi Barat	14.93	281.68
11	Medan Satria	11.88	162
12	Bekasi Utara	19.75	337.01

Source : (BPS Kota Bekasi, 2021)

Bogor Regency is larger than Bekasi Municipality. It has an area of 2,664 km^2 consisting of 40 sub-districts, with each sub-district ranging from 21 to 208 km^2. The list of sub-districts in Bogor Regency is presented in the appendix B below. Due to its vast area, the Bogor Regency area has a very varied topographic range. This can be seen from the height range of sub-districts in Bogor Regency, between 51 m to 661 m measured from the mean sea level. Therefore, the Bogor Regency has diverse topography, such as slopes, valleys, and peaks. In the middle of the Bogor Regency area, there is another administrative area, namely the Bogor Municipality. To get a clearer picture of the Bogor Regency area, see Figure 7. Moreover, the following are the other administrative boundaries of Bogor Regency:

1. North: Tangerang Regency, Depok Municipality, Bekasi Municipality, and Bekasi Regency.
2. East: Purwakarta Regency, Karawang Regency, Bekasi Regency, and Cianjur Regency.
3. South: Sukabumi Regency
4. West: Lebak Regency

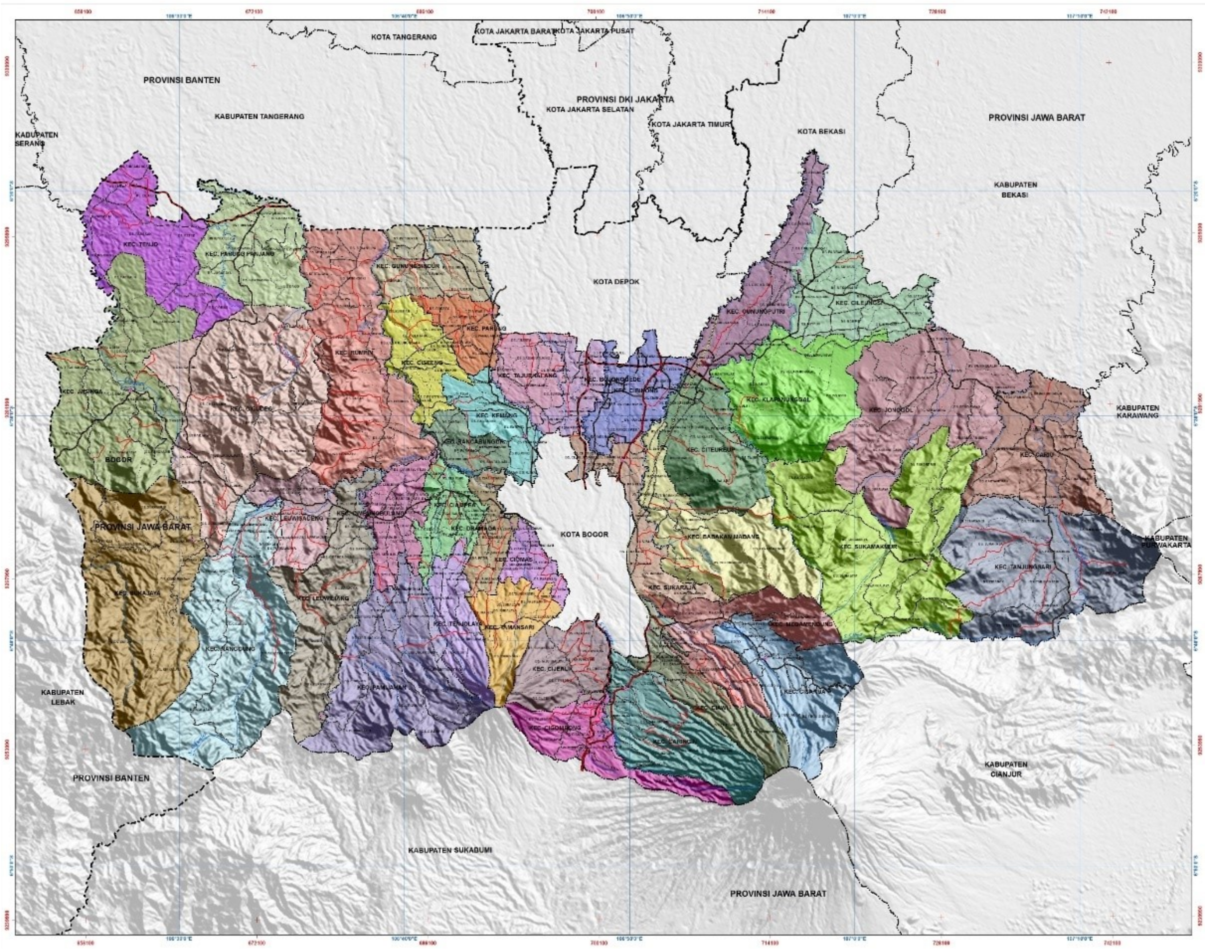


Figure 7 Map of Bogor Regency

(Source: Peta Tematik Indonesia 2013a)

Bekasi Municipality is inhabited by more than 2.5 million people in terms of population, while Bogor Regency has more than 5.4 million people. However, from a population density perspective, Bekasi

Municipality has a higher population density than Bogor Regency, with population densities in the two areas being 12,085 and 1,817.

4.1.3. Flood Prone Areas

Heavy rains that flushed the upstream areas of the Cikeas and Cileungsi rivers for several hours caused the water discharge in the two rivers to increase dramatically. Along with the increase in water discharge, the river water level also rises. This can cause flooding in the sub-districts traversed by the Cikeas and Cileungsi rivers. Not only floods that occur, but sometimes flash floods can also occur around the two rivers. However, floods frequently inundate densely populated areas downstream, causing infrastructure damages, stop economic activities, and hinder developments.

Areas that often flood due to overflowing from the river after heavy rains upstream in the Bekasi Municipality are densely populated residential areas in the sub-districts of Jatiasih, Rawalumbu, South Bekasi, and East Bekasi. In particular, the Pondok Gede Permai housing area, located at the confluence of the Cileungsi and Cikeas rivers in the Jatiasih sub-district, is the most frequently hit area by floods. As for the administrative area of Bogor Regency, floods often hit the Gunung Putri sub-district, particularly the Bojong Kulur village. The Bojong Kulur village area is flanked by two rivers making it very vulnerable to flooding. Furthermore, in the Bogor Regency area, the threat from the Cikeas river can also be in the form of flash floods that occur due to overflowing river water. In the Citeureup sub-district in 2019, flash floods occurred due to torrential rains in the upstream area and river flow blocked by bamboo waste (KP2C, 2019). Table 9 presents the residences that are often flooded in Bekasi City and Bogor Regency due to the overflowing of the Cileungsi, Cikeas and Bekasi rivers during the rainy season. However, the IN-1 stated that an exceptional event occurred on January 1, 2020, when the excessively high rainfall caused flooding in flood-prone areas and areas that had never been flooded.

Table 9 Frequently Inundated Areas When Flooding

No	District	Sub-district	Name of the Residence
1	Bogor Regency	Gunung Putri	Vila Nusa Indah 1, Vila Nusa Indah 2, Vila Nusa Indah 3, Vila Nusa Indah 5, Bumi Mutiara, Vila Mahkota Pesona, Cibubur City
2	Bekasi Municipality	Bantargebang	Pangkalan 1A
		Jatiasih	Puri Nusaphala, Mandosi Permai, Pondok Gede Permai, Vila Jatirasa, Kemang Ifi Graha, Komplek AL, Pondok Benda, Jatiasih Indah (PPA)
		Bekasi Selatan	Pondok Mitra Lestari, Jaka Kencana, Depnaker, Pekayon Jaya
		Rawalumbu	Kemang Pratama
		Bekasi Timur	Taman Kartini

Source: (KP2C, 2021)

4.2. Flood Risks and Costs

The flood that threatens the most flood-prone areas is usually induced by high rainfall upstream of the Cileungsi and Cikeas rivers. The IN-1 claimed that locally downpouring heavy rain in the flood plain has never triggered floods. Overflowing rivers that inundate residential areas downstream of the rivers frequently occur in the rainy season even though there is no rainfall in flood-prone areas. Therefore, communities at flood risks frequently suffer economic loss. Economic losses due to floods, for example, are replacing properties, repairing household furniture, renovating buildings, and doing the medical treatment. Not to mention the lack of income due to skipping work to clean the house or the cessation of economic activities.

The IN-1 asserted that, albeit the floods frequently have been hitting the flood plain, there are no official data regarding flood losses suffered by society. However, Ahaliati (2013) has carried out a study to estimate the economic loss due to three flood events in January and February 2013. The study area was Pondok Gede Permai Housing in Jatiasih sub-district. This housing was built in 1988. To have a house in Pondok Gede Permai, people could pay micro installments, so many people were attracted. Nowadays, this area is densely inhabited. According to Ahaliati's (2013) research, the primary reason that forces people to live in Pondok Gede Permai Housing despite flooding was their financial condition. The floods that inundated Pondok Gede Permai Housing in 2013 occurred on 18 January, 4 February, and 12 February. The depth of these floods ranged from 1 – 3 m. Ahaliati calculated flood losses based on two types of losses, namely direct losses and indirect losses. Direct losses consist of replacement costs for lost household furniture and repair costs for damaged home appliances. Meanwhile, indirect losses consist of medical expenses, lost income, and additional costs. Ahaliati surveyed the value of the loss, both direct and indirect losses, from several respondents who were considered to represent the entire population. Ahaliati (2013) estimated the economic loss from the three flood events in 2013 at 2.7 billion IDR or approximately 192,132 USD.

There is no official data released regarding flood losses aftermath; however, local disaster managers conducted risk studies, including estimating physical losses and economic losses due to floods. Bekasi Municipality Regional Disaster Management Agency (starting now referred to as BPBD Bekasi Municipality), for instance, calculated the potential physical loss and economic loss in the event of a flood throughout the Bekasi Municipality. Calculation of potential loss based on the maximum value of compensation for physical damage provided by the government and the economic value lost during the flood based on productive land and gross regional domestic product. Based on BPBD Bekasi Municipality's (2018) calculation, the total loss due to floods in Bekasi Municipality can reach up to 29 trillion IDR or more than 2 trillion USD. Another example is Bogor Regency Regional Disaster Management Agency (from now on referred to as BPBD Bogor Regency) that conducted multi-risk studies. BPBD Bogor Regency (2019) estimated that the total loss in the Bogor Regency due to flooding is more than 1.5 trillion IDR or about 104 million USD. Table 10 details flood potential losses in flood-prone areas mentioned above. The potential loss due to flooding in flood-prone areas based on the calculation of the Bekasi City BPBD and Bogor Regency BPBD is IDR 1.24 trillion or around 85 million USD. However, the enormous loss is based on a flood depth of more than 1 m, whereas in reality, a flood depth of 1 meter in other places can mean that other places have entirely drowned. This means that losses due to flooding in flood-prone areas can be even more significant because they can be inundated by more than 3 m.

Table 10 Flood Potential Losses in Flood-prone Areas

No	Sub-district	Physical losses (Million Rupiah)	Economic losses (Million Rupiah)	Total Losses (Million Rupiah)
1	Bantargebang	3,893	19	3,912
2	Jatiasih	194,140	4,589	198,729
3	Bekasi Selatan	340,776	4,770	345,546
4	Rawalumbu	257,463	651	258,114
5	Bekasi Timur	378,670	1,127	379,797
6	Gunung Putri	46,330	4,546	50,876
Total Loss (Million Rupiah)		1,221,272	15,702	1.236.974

Source: (BPBD Kabupaten Bogor, 2019; BPBD Kota Bekasi, 2018)

In particular, the IN-1 stated that the enormous flood on 1 January 2020 is called the most significant flood in history that was induced from the highest rainfall in centuries. During regular floods, items that have been secured on the table or hung on the wall will not be flooded. However, with the catastrophic flood on 1 January 2020, people at risk could not save any of their valuables. The IN-1 exclaimed that this happened because many people did not expect how terrible the flood was on 1 January 2020. Most houses in flood-prone areas are submerged as high as approximately three meters. Figure 8 provides a better image of the depth of the flood that inundated the roof of one-story houses and reached the calves of adults on two-story houses.

Moreover, vehicles such as motorbikes and cars that had been evacuated to higher ground were swept away by the flood currents. The loss for repairing the vehicle is undoubtedly not slight, considering the damage to the vehicle is very severe due to hitting other complex objects while being washed away. On top of that, residents at risk have lost their livelihoods for more than two weeks because economic activities have stopped. Compared to frequent floods, flood alert category two often stops economic activity for approximately four hours.

Fortunately, there was no loss of lives during the enormous flood that occurred. This because the community at risk received extreme weather early warnings and flood early warnings in a timely manner. Besides that, people at risk responded well and quickly to flood warnings given. There was sufficient time to evacuate vulnerable groups to safe shelters. The recorded fatalities occurred on the second day after the flood due to cold in the refugee camps or too tired from cleaning up the mud leftover from the flood.


Figure 8 Flood Depth on 1 January 2020

(Source: KP2C Documentation)

4.3. Flood Preparedness and Response Actions

4.3.1. Extreme Weather Early Warnings

Based on Law No. 31 of 2009, the task of BMKG in the public sphere as the recipient of a mandate from the government is to provide services in the fields of meteorology, climatology, and geophysics in the form of public information. In meteorology, the BMKG provides two main kinds of public information, firstly, the routine weather forecasts issued regularly, both time and place scale based on each regional or local BMKG office task. Secondly, BMKG has to produce and disseminate extreme weather early warning for incidental events with high impacts. Particularly, extreme weather early warnings are regulated in the Regulation of the Head of the BMKG. According to BMKG (2010), extreme weather early warning includes several weather parameters that have to be issued by BMKG are as follows: funnel cloud (tornadoes), gale, torrential rain, hail, extreme visibility, extreme temperature, tropical cyclone, waterspout, extreme sea wave, extreme tidal wave.

Interview with IN-4 explained the process and equipment involved in monitoring and composing early weather warnings that BMKG has carried out. In terms of elements of an effective early warning system, BMKG has an essential role in the second element, namely monitoring and warning services. Therefore, the BMKG offices observe and monitor atmospheric conditions, synoptic surface observations, and upper-air observations 24-hours a day. In doing so, BMKG conducts basic in situ monitoring with calibrated tools. After observing, BMKG exchanges the recorded weather parameters worldwide using the WMO platform such as Global Telecommunication System and WMO Integrated Global Observing System. Then, the Global Data-processing and Forecasting System harnessed this basic weather monitoring to generate global modelling as boundary conditions of higher resolution weather models. Apart from basic monitoring, BMKG also conducts monitoring using advanced equipment such as weather radar, weather satellites, and wind profilers. These two types of monitoring are used as the basis for analysis and simulation to produce routine weather forecasts and early warnings.

BMKG harnesses global weather modellings from various sources such as the European Centre for Medium-Range Weather Forecast from the European Union's Copernicus Earth Observation Programme, WRF from the United States of America's National Center for Atmospheric Research, Aladin by Météo-France, and Australian Community Climate and Earth-System Simulator (ACCESS). The general public can also access the modelled weather forecast by selecting one of the desired sources. These numerical weather prediction models can produce forecasts with various lead times from nowcasts (up to 3 hours before expected weather events) and up to several days. However, the resolution of global modelling is not sufficient to produce accurate forecasts on the mesoscale or micro scale. Therefore, global modellings should be downscaled to mesoscale or micro scale to generate precise early warnings quickly and adequately. Despite numerical weather prediction models providing a better rainfall prediction both spatially and temporally, their accuracy remains uncertain compared to weather radar rainfall estimation (Shahrban et al., 2011). Compared to other near-real-time observation like weather satellite, the capability of the numerical weather prediction model is far left behind because satellite products can estimate tremendous rainfall pattern, scale, distribution, timing, and even extreme values (Wang, Wang, & Hong, 2016). All measuring ways have weaknesses; hence, according to IN-4, BMKG employs all weather monitoring means starting from basic weather observation, numerical weather prediction, weather radar, and weather satellite to generate reliable extreme weather early warning.

After analyzing the atmospheric conditions, BMKG disseminates early warnings to the public through several platforms such as the website, the infoBMKG application on smartphones, social media (Twitter, Instagram, Facebook), mass media and print media. Based on Standard Operational Procedures issued by BMKG (2017), any indication of a potential extreme weather event must be reported 1 to 3 hours before the event occurs. Not only BMKG disseminates early warnings to the public through the various media mentioned, but BMKG also disseminates them to several stakeholders, particularly BNPB as the emergency manager. BMKG and BNPB already have integrated platforms in responding to extreme weather threats. Figure 9 shows disseminated extreme weather events through infoBMKG application on Android or iOS and Twitter.

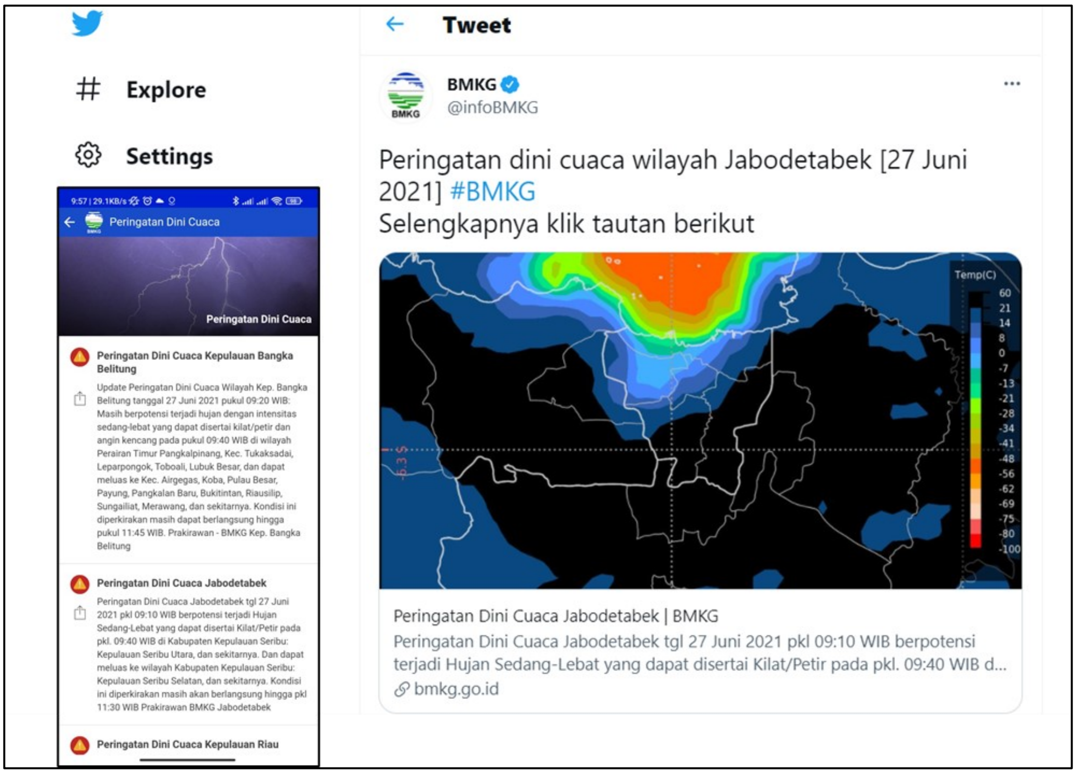


Figure 9 Extreme Early Warnings Disseminated Example in Indonesian

Source: infoBMKG app and @infoBMKG Twitter

In the catastrophic flood on 1 January, the BMKG issued an early warning for extreme weather, which is predicted to start at 17.00 WIB and is expected to end at 20.00. The BMKG warned of the potential for moderate to heavy rain accompanied by thunder and strong winds around Jabodetabek. After releasing the first warning, BMKG updated the information according to the dynamic conditions of the atmosphere.

4.3.2. Flood Early Warnings

In 2013, there was a flood early warning system built for Jakarta Capital Region employing hydraulic and hydrologic modelling SOBEK from Deltares the Netherlands (Ginting & Putuhena, 2014). This system was built for determining flood flow on thirteen watersheds in Jakarta using real-time data from several stakeholders and forecasting data as inputs for the models. These stakeholders are Agency for the Assessment and Application of Technology in which provided weather radar data, BMKG in which supplied weather data from automatic weather station, the Ministry of Public Works in which presented rain and water level gauge data. As for forecasting data, this flood early warning system used global weather modelling such as the European Centre for Medium-Range Weather Forecast, Conformal Cubic Atmospheric Model (CCAM), Global Forecast Model (GFS) and Australian Community Climate and Earth-System Simulator (ACCESS) as inputs. To run seamlessly this system, the Research Centre for Water Resources and BMKG used their super computer as online server. This system had been on trial periods for 2 years and had been installed on various stakeholders such as BNPB, Jakarta Public Work Agency, BPBD Jakarta, Centre for Ciliwung-Cisadane River Basin, Agency for Assessment and Application of Technology, and etc.

The Jakarta flood early warning system had generated the variety of products. Firstly, the basic product of this system was rain forecasts which used global numerical weather predictions as the main input for hydrological models to flood forecasting. Secondly, the main derivative product of this system was discharge and water level forecasts which based on rain forecasts. Thirdly, this system produced sea level forecasts by employing South China Sea Model which is developed from Delft3D software from the Netherlands. Fourthly, this system also displayed the rain monitoring system obtained from weather radar and ground observation. The last but not the least, inundation maps were generated by this system. To produce inundation maps, this early warning system integrated with SOBEK model. This system ran really well during trial periods and provided valuable various kinds of information. The purpose of this system was to give long flood forecast lead time so disaster managers and communities could act appropriately to the warnings. This was possible because numerical weather prediction can provide inputs for hydrological forecasts for up to 10 days even though the longer forecast period mean the bigger uncertainty.

However, from a spatial and implementation perspective, this flood early warning was very limited. First, from a spatial perspective, this system only functioned for watersheds in the Jakarta Capital Region, supporting cities in the Jakarta Metropolitan Area, such as Bogor, Depok, Tangerang, and Bekasi, did not receive this hydrometeorological service. In fact, many rivers flow across borders that originate in Bogor, then some rivers pass through Depok, Tangerang, Bekasi and some are downstream in the bay of Jakarta. Second, from the implementation point of view, the IN-5 that involved in the establishment of this early warning system stated that this flood early warning system only functioned well during the testing period, after which the system was no longer operational due to a lack of maintenance. This means communities at risk in the study flood-prone areas are not covered by this system.

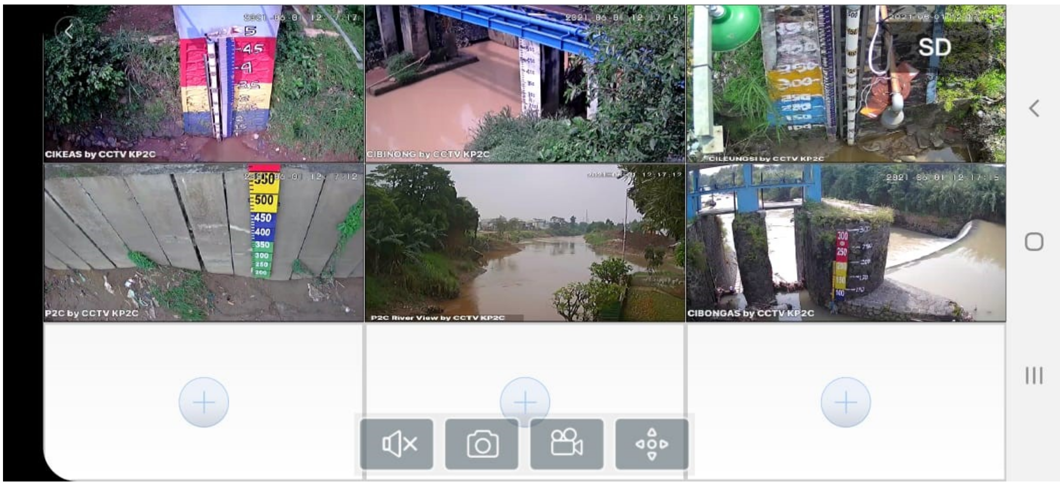


Figure 10 CCTV Monitored River Level

(Source: KP2C Documentation)

Communities in the study area can benefit from flood early warnings from 2 institutions, namely BBWSCC, a government agency, and KP2C, a non-governmental organization. This study discusses the flood early warning system operated by the two institutions. First, the flood early warning from BBWSCC was made based on water level measurements installed at several observation stations. The tool is a telemetry measuring device so that it is possible to take data from a long distance. In addition to telemetry equipment, BBWSCC has also installed closed-circuit television (CCTV) to complement water level observations. In addition to the water level measurement post, BBWSCC also installed a rainfall measuring station. However, measurements of rainfall and water level were installed in different places.

On the Cileungsi river, the BBWSCC's rain gauge post is at Sumur Batu station, and the water level monitoring post is at Gunung Putri Cileungsi station. Meanwhile, on the Cikeas river, a rainfall gauge post is installed at the Cibinong station, and a water level monitoring post is installed at the Cikeas Nagrak station. Both rain gauges are located at higher altitudes than the water level measurements.

On the Cikeas river, close to the confluence of the two rivers, there is also another measuring post, namely the Vila Nusa Indah Bekasi station. The post installed on the Cikeas river close to the confluence measures the presence of backwater due to the large discharge of water from the Cileungsi river, which should flow into the Bekasi river flows backwards into the Cikeas river during heavy rains upstream. On the Cikeas river, the length of the water journey from Cikeas Nagrak station to Vila Nusa Indah Bekasi station based on BBWSCC empirical calculations is about two to three hours. While on the Cileungsi river, the travel time from Gunung Putri Cileungsi station to the confluence point is not stated, but the lag time from Gunung Putri Cileungsi station to Bekasi Dam is known to be between three and four hours. The results of real-time water level measurements in both rivers can be accessed through the BBWSCC website.

Next is an elaboration of the warning system initiated and operated by the non-governmental organization KP2C. KP2C is a community organization founded by IN-1 and his colleagues in 2016. The IN-1 was one of the numerous victims of flood in 2006. He suffered great losses of his properties and should reapply important documents which took up a lot of time. These because he did not receive any information regarding the rise of water level due to rain in the upstream. After that, he traced Cileungsi and Cikeas rivers upstream and found river monitoring posts. Then, he built good communication with officers at the river monitoring posts so the officers let the IN-1 know when there is an increase in the river's water level. After receiving messages from officers, he resent the messages to all his groups in social media. He worked alone to disseminate flood early warnings until KP2C was established. Begin from with only 16 members, currently KP2C has more than 22,000 members in hope they receive the flood warnings immediately. Since 2020, KP2C officially has been being recognized by the governments as registered NGO (KP2C, 2021).

To produce flood warnings, KP2C utilizes river water levels monitored by CCTV and assigns monitoring officers in several spots, including the river's upper reaches and the two rivers' confluence. The monitoring water level in the Cileungsi river and Cikeas river through CCTV can be seen in Figure 10. Based on empirical river level monitoring, KP2C set several indicators to estimate flood events. There are three spots set to provide flood alerts, namely Cileungsi river level, Cikeas river level, and the river level at the confluence of two rivers. River level thresholds at the Cileungsi river, Cikeas river, and the confluence of the two rivers are 100 cm, 200 cm, and 350 cm, respectively. Also, KP2C established alert levels if the river level trespassing thresholds set for each spot. The alert levels ranging from level 4 to level 1. Alert level 1 is the level that should be well prepared for due to its the most severe. Besides, KP2C determined flood lead time based on empirical observation. In the Cileungsi river, if the river water level is observed to be rising at the nearest monitoring post, residents at risk will have about 4 hours to take action to respond. Meanwhile, in the Cikeas River, the travel time for river water from the nearest monitoring post to flood-prone areas is about 3 hours. Empirical characteristics of Ciluengsi and Cikeas River are summarized in Table 11. In the procurement of all equipment needed and operationalization of the existing flood early warning system, KP2C did not receive financial aid from the government. KP2C uses voluntary contributions from its members and donations from several parties, including corporate CSR, to operate their flood early warning system.

Table 11 Summary of Empirical Characteristics based on KP2C Estimation

No	Empirical Characteristics	Cileungsi River	Cikeas River
1	Normal Threshold	< 100 cm	< 200 cm
2	Arriving Time Interval	- Nearest Post: 4 hours - Furthest Post: 6 hours	- Nearest Post: 3 hours - Furthest Post: 8 hours
3	Alert Level 4	101 – 150 cm	-
4	Alert Level 3	151 – 200 cm	201 – 300 cm
5	Alert Level 2	201 – 300 cm	310 – 400 cm
6	Alert Level 1	> 300 cm	> 400 cm

KP2C expands its network from government agencies to community leaders. After receiving extreme weather early warnings from BMKG three hours before extreme weather events occur, the information is re-disseminated to the public. Then, KP2C updates information about the river level if severe rain occurs in the watersheds. This information is received by BPBD Bogor Regency, BPBD Bekasi Municipality, volunteers, heads of the sub-districts and villages, neighborhood chiefs, community leaders, religious leaders, and KP2C members. Currently, The IN-1 asserted that KP2C uses 18 Whatsapp Groups, 1 Telegram Group, Twitter, Facebook, and Instagram as media to disseminate flood early warnings. Furthermore, community leaders also delivered announcements of early flood warnings through loudspeakers from the mosques.

In the catastrophic flood event on 1 January 2020, BMKG disseminated flood warnings as mentioned in section 4.3.1. Because rain was predicted to fall in the catchment areas of the Cileungsi and Cikeas rivers, KP2C took action to monitor the rise in river levels both through CCTV and officers at the monitoring post. The rain continued to pour, causing a rise in the height of the Cileungsi river at midnight, then less-deep floods inundated flood-prone areas on 1 January 2020 at dawn. After that, the water temporarily receded. However, as torrential rains continued in the catchment areas of the two rivers, the river water level rose again. KP2C disseminated flood early warning information that it was predicted that flooding would occur in flood-prone areas along the banks of the Cileungsi river at around 10.30 am on 1 January 2020. Many residents have experienced a severe flood on 21 April 2016 with an alert level 1. Therefore, KP2C added information that there is a possibility that the flood will be more devastating than the flood incident on 21 April 2016 as a benchmark. However, the enormity and long duration of the rain on 1 January 2020 caused flooding that society could not imagine. Areas whose houses are usually not flooded become flooded so properties are damaged because they are people who are more unprepared than people who are often flooded.

Based on experience, KP2C concluded that every time there is an increase Cileungsi river level, it will be followed by a rise in water level in the Cikeas river about 5-7 hours later. This also applied during the flood on 1 January 2020. The peak of the flood caused by the overflow of the Cileungsi river occurred at around 13.00. Then, KP2C and Puarman firmly decreed residents living on the banks of the Cikeas river evacuate because flooding is predicted to occur at around 18.30. In the end, the flood arose, and people evacuated.

4.3.3. Flood Response Actions

Nationally, based on Presidential Decree No.8 of 2008, BNPB functions to carry out disaster management. However, the vast territory of Indonesia requires the decentralization of this task. Therefore, based on Presidential Decree No. 8/2008, BNPB and the local government established a BPBD regulated in local government regulation. In terms of administrative and responsibility areas, BPBDs have two levels, namely provincial-level BPBDs and city/district-level BPBDs. There are two BPBDs at the city/district level in charge of disaster management in the research area, namely the BPBD Bekasi Municipality and BPBD Bogor Regency.

In general, BPBD has three stages in carrying out disaster management, namely, pre-disaster activities, emergency response, and post-disaster actions. Firstly, pre-disaster activities include disaster management planning, disaster risk analysis, and education and training. Subsequently, the early warning system is included in emergency response activities if a potential disaster is detected. In addition, other emergency response activities carried out by BPBD are in the form of disaster preparedness and disaster mitigation. Lastly, BPBD also plays a role in post-disaster activities, which include rehabilitation and reconstruction.

Efforts to reduce flood risk are effectuated during the emergency response and the pre-disaster period. Several actors executed efforts to reduce the risk of flooding in the pre-disaster period. For example, the Bogor Regency Government has installed 19 pumps in the village of Bojongkulur to prevent the increase in flood inundation and accelerate flood receding. In addition, the Bekasi city government also provided pumps that are operated in the Jatiasih sub-district. The procurement of these pumps is very beneficial to reduce the risk of flooding except when the overflow of river water has exceeded the embankment near the pump. Another example is providing assistance such as rubber boats, generators, portable pumps, and cleaning equipment by BPBD Bogor Regency to Bojongkulur village officials. Figure 11 shows one of the pump stations that are operated to reduce the risk of flooding.

Figure 11 One of pump stations installed

Source: Personal Documentation

According to Law No. 24 of 2007, the early warning is one of three measures taken during emergency response. Early warnings should have clear objectives to quickly and appropriately reduce risk and prepare for emergency responses. From the many series of activities carried out by BPBDs, this study explored the duties and functions of BPBDs related to the four elements of an effective early warning system based on the literature review. In addition, interviews with BPBD Bogor Regency and BPBD Bekasi Municipality were used to elaborate on this finding.

The first pillar is risk knowledge. Both BPBD Bogor Regency and BPBD Bekasi Municipality have printed books on the results of flood risk analysis. Then, based on the risk analysis results, the two BPBDs carried out activities in the form of preparing disaster management plans, coordinating with various stakeholders, and disseminating disaster-prone maps.

The second pillar is monitoring and warning services. In the study area, the figures who carry out this task are BMKG as a weather service and BBWSCC and KP2C as a river water level service. BPBD Bekasi Municipality also has monitoring of water levels in the administrative area, which is its responsibility. BPBD Bekasi Municipality uses Automatic Water Level Recorder in three spots, namely Ciangsana, Jembatan Gantung, and Babakan Madang. Inadequate maintenance has encouraged BPBD Bekasi Municipality to keep assigning river water level supervisors. Soon, BPBD Bekasi plans to implement an OnliMo or online monitoring system to monitor that river water levels in real-time. Meanwhile, the

Bogor Regency BPBD intends to build a monitoring system similar to that developed by KP2C in other sites that are still their areas of responsibility.

The third pillar is dissemination and communication. To implement this element, the BPBD has a server that operates to redistribute early warnings to the BPBD's operations control center and several stakeholders. In addition, the two BPBDs also gave the dissemination of early warning information to several stakeholders who are members of the WhatsApp group. These stakeholders consist of military district commanders, volunteers, NGOs, youth organizations, community forums, and religious leaders.

The fourth pillar is response capacity. Based on Presidential Decree No. 1 of 2019, the disaster management agency has three functions for accomplishing disaster management: the coordination function, the command function, and the implementing role. By having these functions, the BPBD has the flexibility to apply its duties. For example, BPBD can conduct coordinate and command functions to clean up flooded mud by deploying the environmental service or public works department. This is because these services have the responsibility for cleaning the city and providing complete equipment. In addition, the mayor can implement an emergency alert command so that the BPBD can involve all local government agencies in disaster management. Then, the implementing functions of the BPBD are explained in the following manuscripts.

To perform the implementation function, the two BPBDs mobilized their personnel and equipment to respond appropriately and quickly to extreme weather early warnings from BMKG and flood early warnings from KP2C. Below are breakdowns of BPBD's response after receiving early warning information:

1. Sending personnel to the flood location.
2. Delivering various equipment such as inflatable boats, portable water pumps, and ready-to-eat food.
3. Checking and turning on the water pump that has been installed so that it can operate properly.
4. Building shelters for evacuation.
5. Assisting the evacuation of residents to the shelter with the help of various actors who have also received early warning information.
6. Coordinating with the Indonesian Red Cross and the Health Office to deal with the health problems of residents affected by the flood.
7. After the flood recedes, together with stakeholders, cleaning up the remaining waste of the flood.

In the 1 January 2020 incident, early warnings worked as they should, but extreme rain occurred in an extensive area, so that floods also appeared in various places. At that time, the IN-2 claimed that BPBD Bogor Regency personnel and equipment were lacking because hydrometeorological disasters in 126 villages such as floods and landslides coincided. During the flood in Bojongkulur village in the morning, BPBD Bogor Regency officers were taking response actions in the central Bogor area. BPBD Bekasi Municipality also experienced difficulties because there were more than 600 evacuation requests in flood-affected locations. The IN-3 asserted that the terrible flood inundated eleven of the twelve sub-districts in the Bekasi Municipality area. Also, the IN-3 stated that apart from the tremendous natural hazards during the 1 January 2020 flood, the significant impact of the flood was due to technical and non-technical factors from the BPBD Bekasi Municipality. These factors include institutional unpreparedness, lack of coordination between agencies, the minimal number of officers compared to the number of flood points, equipment lacking, and technology not being sophisticated.

Existing early warnings can genuinely empower people at risk in flood-prone areas to take response actions, even during the devastating flood on 1 January 2020. On that day, KP2C disseminated flood early warnings at 07.25 local times that the river water level was already very high and even predicted will be higher than the flood incident on 21 April 2016, which some people already perceive. Alert level 1 has also been disseminated. The IN-1 explained that, if alert level 1 is issued, the community should perform self-evacuate, secure valuable properties and documents in higher places, move vehicles to higher ground, and evacuate vulnerable people to safe shelters. In regular flood events, people secure precious objects at different heights depending on the location and size of the house. Usually, it is enough to put valuables on the table, and it turned out that on 1 January 2020, the flood touched the roof of the house. Thus, the losses suffered by the community are still very high-priced. Gratefully, the current early warning plays primary roles in realizing the first target of the Sendai Framework for Disaster Risk Reduction 2015-2030 (UNISDR, n.d.) to lessen the number of mortality emanating from the disaster.

4.4. Meteorological Analysis

BMKG issued the extreme weather early warning on 31 December 2019 based on atmospheric conditions using various instruments, including weather satellites. Figure 12 displays cloud-top brightness temperature measured by the infrared channel of the Himawari satellite at 9.30 UTC or 16.30 Local Times. One indirect measurement of precipitation is cloud-top temperature because it usually can differentiate convective form or stratiform of clouds (Rosenfeld, 2007). The satellite image depicted a vast area of the convective form (shown by the lowest temperature) in the southeast of Jakarta. Convective clouds covered all Jakarta Metropolitan Area. However, the reddest area was over the mountainous areas in central and eastern part of Bogor Regency, upstream of Cileungsi and Cikeas rivers. Initially, this indicated extremely high rainfall that might pour in that area. Then, based on observations at the Halim meteorological station, it started to rain at 16.30 local time. Light to moderate rain continued for about 10 hours. After that, the peak of heavy rain at Halim station was recorded from 3.00 local time until 6.00 local time on 1 January 2020, with the highest rainfall intensity reaching 72.6 mm/hour. This torrential rain is most likely due to convective part of the storm. The rain continued to fall until it finally stopped at 13.00 local time. The rain lasted for more than 20 hours.

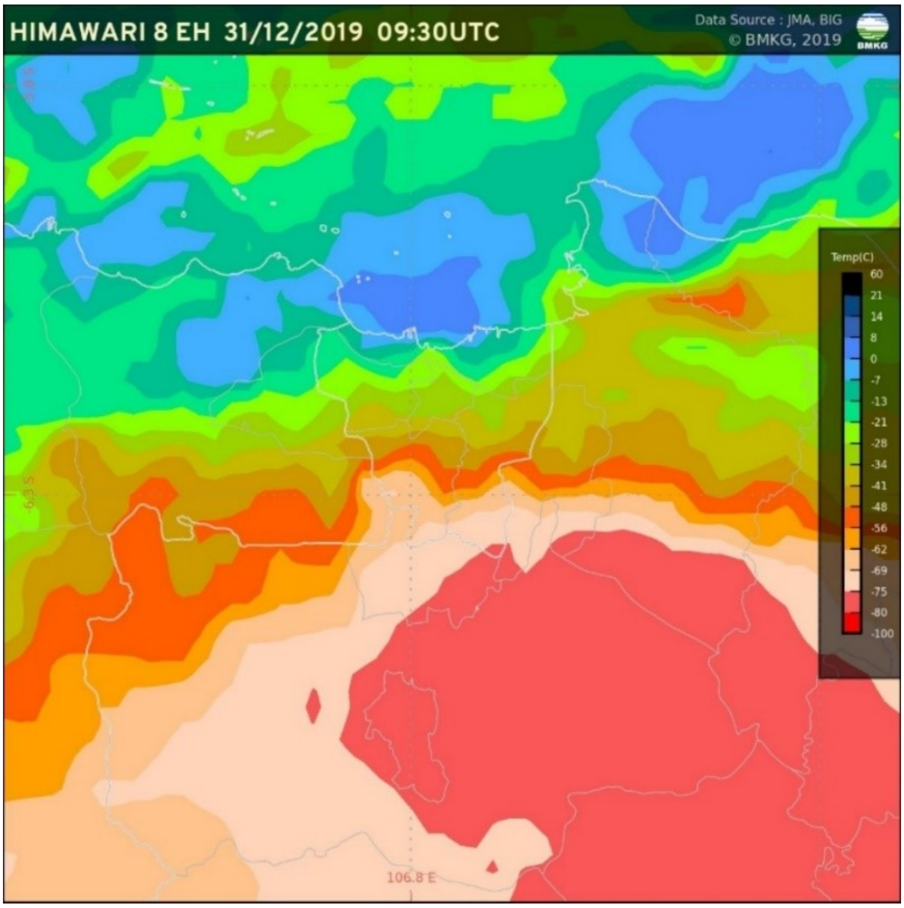


Figure 12 Enhanced infrared image of the Himawari satellite

Source: BMKG

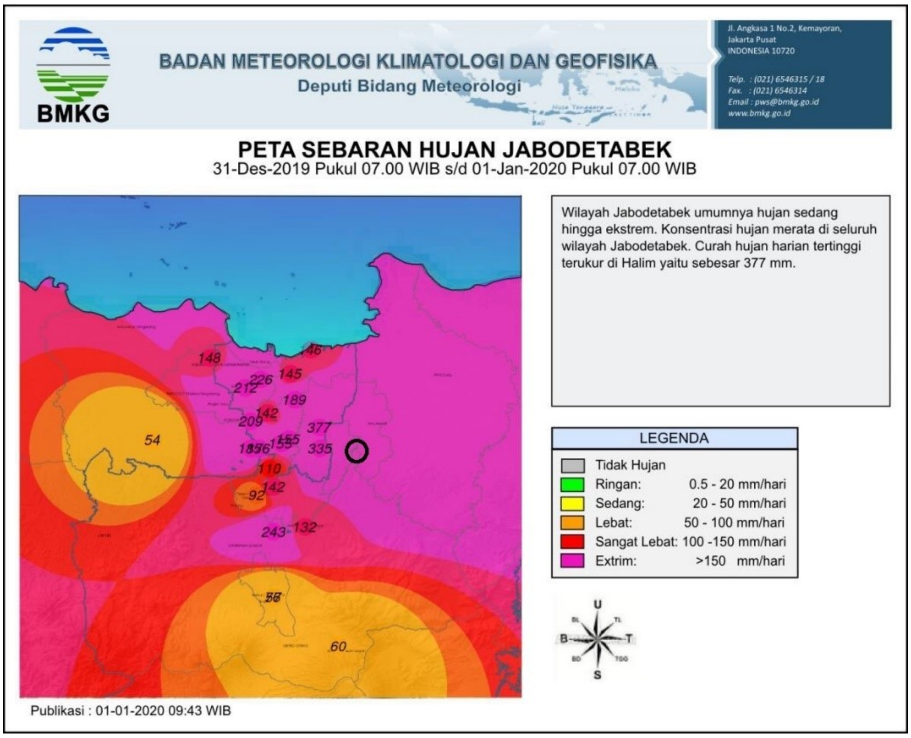


Figure 13 24-hr Observed Precipitation from 31 December 2019 00 UTC until 01 January 2020 00 UTC (The black circle shows the location of the studied flood-prone area)

Source: edited from BMKG

BMKG released information on rainfall based on rain gauge networks on 1 January 2020, at 02:43 UTC (09:43 local time). The intensity of extreme rainfall was observed in an extensive area, including the Jakarta Metropolitan Area, where the intensity of rainfall is considered extreme by the BMKG if the value exceeds 150 mm/day. Halim Meteorological Station recorded the highest 24-hour rainfall for decades with 377 mm. Figure 13 interpolation delineation of rainfall based on observations of rain gauges. The closest automatic weather station to flood plain Jatiasih recorded rainfall intensity of 260.8 mm/day. Torrential rain with a very long duration over a colossal area indicated a mesoscale convection system.

Computer-driven numerical weather predictions can be used to run atmospheric simulations and understand atmospheric conditions. Parker (2014) described in general terms three uses of computers in performing numerical weather predictions:

1. The atmospheric simulation of the weather model provides replacement observation data to cover the shortcomings of the observation network.
2. Computer-run weather models help prove hypotheses about interesting weather phenomena' causal factors (such as extreme events).

3. Experiments on the model itself using a computer so that the behaviour of the atmospheric and system models can be well recognized.

Therefore, this study discusses the analysis of atmospheric conditions for torrential rain events that last for teens of hours.

Starting from 30 December 2019, low-velocity northwesterly winds dominated the surface flow, while relatively high-velocity northeasterly winds blow in the upper layers. When it rains heavily on 1 January 2020 in the early morning, the surface wind blows from the north, while the middle layer upwards (level 500 millibar - 300 millibar) winds blow from the south. The remarkable difference in the wind direction between the upper and lower layers is also an indicator of the formation of heavy rains that caused flooding in 2007 and 2015 (Siswanto et al., 2017; Wu et al., 2007). In addition, there is a strong indication of vertical low wind shear due to the very striking difference in wind direction between the 900 and 700 millibar levels. However, based on calculations from the WRF output, the low-level vertical wind shear value is relatively small (below 10 m/s) compared to the heavy rains in Jakarta, which also caused flooding in 2007. Wu et al. (2007) remarked that heavy rains in 2007 were associated with a significant low-level vertical wind shear of 15 m/s. Figure 14 displays the vertical wind profile in a flood-prone area.

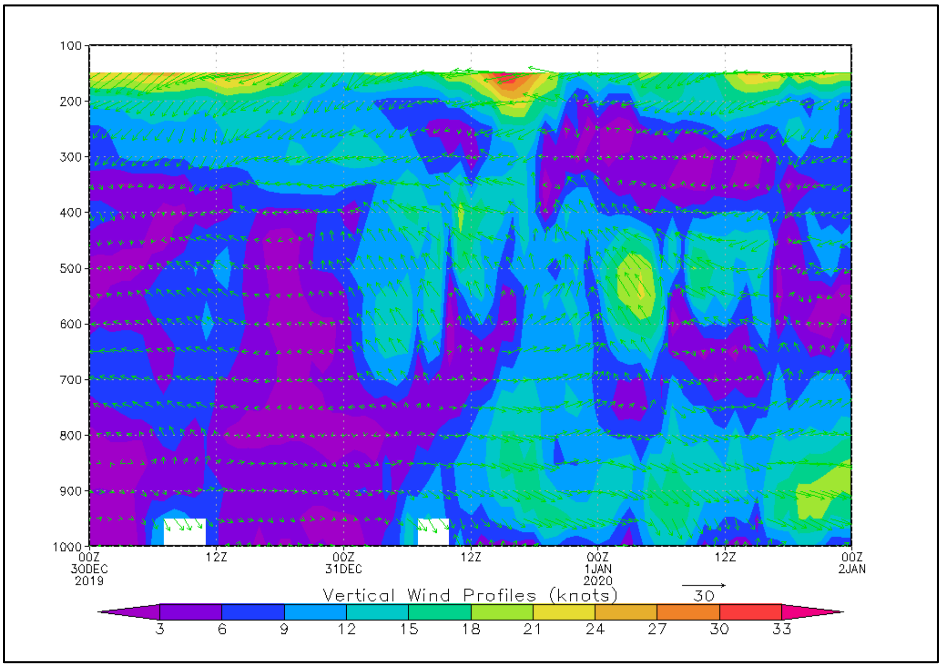


Figure 14 Vertical Wind Profile start from 30 December 2019 00 UTC until 2 January 2020 00 UTC

Furthermore, the relative humidity in the lower level was high since 30 December 2019, and even the value is close to 100 percent (see Figure 15). However, the air layer in the middle tends to be dry, indicating the presence of convective instability. The high supply of water vapour at the surface and this convective instability can potentially form convective cloud systems. Then, when it started raining on 31 December 2019 in the afternoon, the humidity was very high from the surface to the top layer. This is probably because the middle level is already saturated with water droplets from the rain cloud system.

Based on the analysis of atmospheric conditions, heavy rains that caused flooding on 1 January 2020 have similarities with heavy rains in 2007 and 2015, namely the difference in wind direction on the surface and the high level. Then, a similarity is also seen in the development and propagation of storm clouds. The rain cloud system began to grow in mountainous areas in the south during the day and moved northward, with the peak of rain occurring in the early hours of the morning. However, the low-level vertical wind shear is not very significant because its value is negligible. This heavy rain incident is more similar to the research conducted by Olaniyan et al. (2021) that heavy rain comes from the high moisture that supplies the storm system.

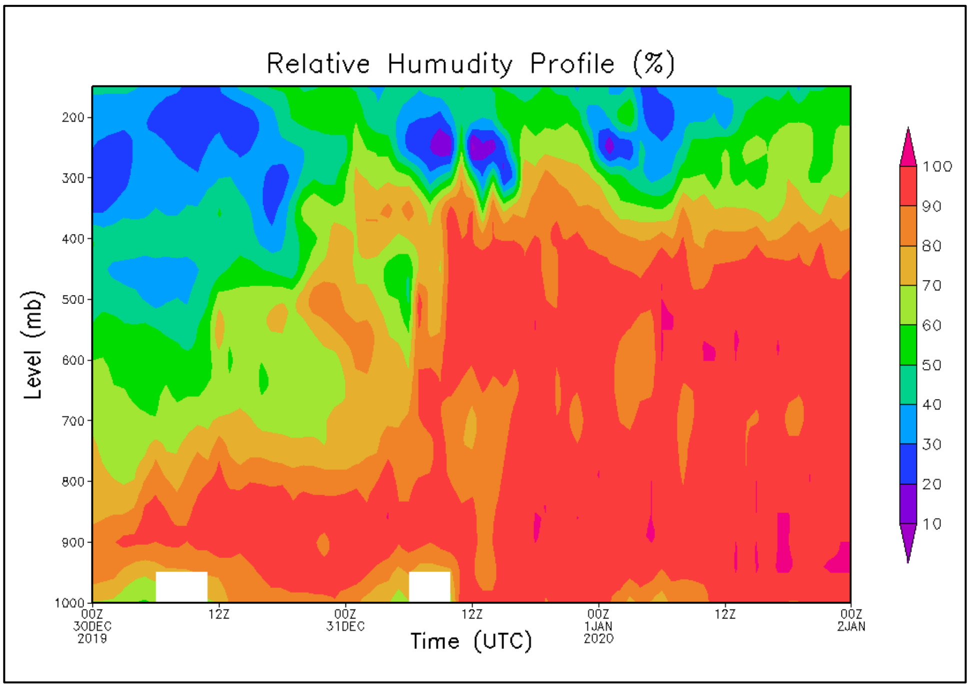


Figure 15 Vertical Relative Humidity Profile

4.5. Model Output Comparison

Briefly, both conventional WRF and WRF/WRF-Hydro are able to predict extreme rainfall. Both models have proven successful in predicting rainfall accumulation for 24 hours of approximately 300 mm with the chosen parameterization setup. This can be seen in Figure 16. Spatially, the distribution of rainfall produced by WRF-Hydro and conventional WRF looks similar. Both models predict that the highest concentration of rain occurred in Jakarta's southern and southeastern areas, covering Bogor Regency. The noticeable difference between the two models is that the rainfall from the conventional WRF forecast is more intense than the WRF-Hydro output. When compared with the interpolation pattern based on observations from ground stations, there is a striking difference. The concentration of rainfall distribution was in Jakarta, while the two models only predict light rain.

Furthermore, to examine the capabilities of the two models, the researchers also compared the accumulated rainfall output of WRF-hydro and conventional WRF with satellite observations. The daily satellite rainfall accumulation data is obtained from the global satellite mapping of precipitation (GSMaP). Using microwave and infrared radiometers from geostationary satellites, GSMap estimates surface precipitation with a rain-gauges-adjusted algorithm (Mega et al., 2019). Generally, GSMaP measured the presence of extreme rainfall throughout the Jakarta Metropolitan Area, with rainfall ranging from 100 to more than 250 mm (see Figure 17). The rainfall measured by GSMaP in the selected flood-prone areas is about 200 mm to 250 mm. Spatially, both models agree with satellite observations that the heaviest rain is in Jakarta's south and southeast areas, including upstream of the Cileungsi and Cikeas rivers.

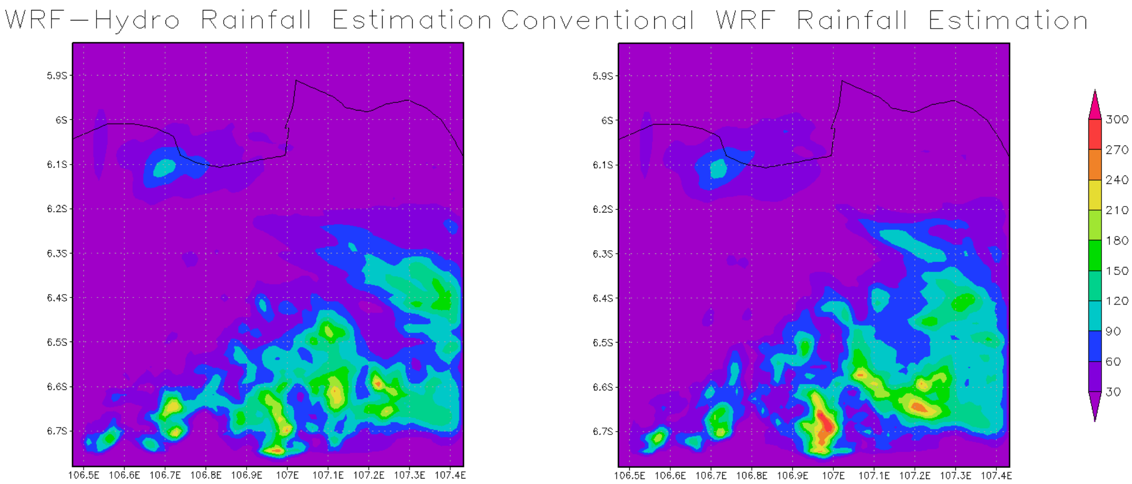


Figure 16 24-hr Rainfall Accumulation Forecasts of WRF/WRF-Hydro and Conventional WRF

Comparison of rainfall peaks shows a difference between the outputs of the two models and the satellite with ground observation interpolation. However, this comparison is less relevant because interpolation is also a model. In addition, the accuracy of the interpolation also depends on the density of the network of observations. It can be seen from Figure 13 that the ground observation network in Jakarta is denser than in other areas.

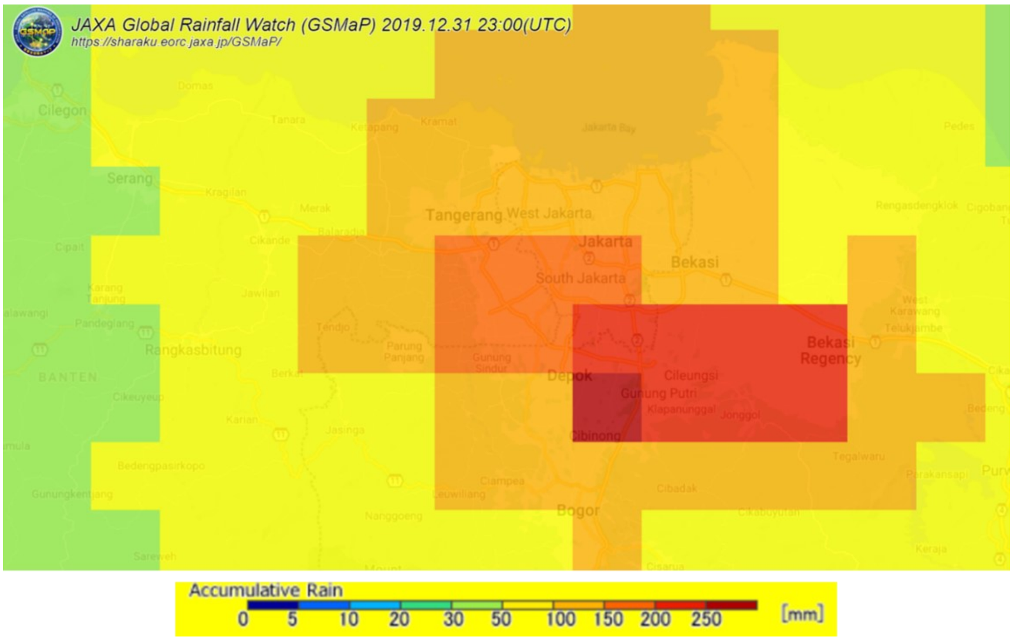
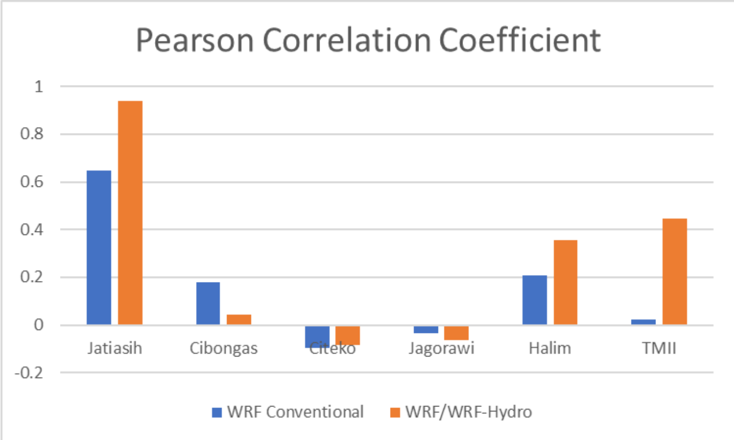


Figure 17 GSMaP Rainfall Accumulation
Source: GSMaP (2021)

In calculating PCC and RMSE, several steps must be taken. First, the output of both the model and the data from automatic weather station obtained is an accumulation of rainfall. Therefore, to compare the hourly data, converting it from accumulated rainfall to hourly rainfall is necessary. Then, the forecast data is compared with the actual data in the same time series. Finally, the researcher calculated PCC and RMSE of conventional WRF and WRF/WRF-Hydro. The RMSE unit is mm/hour, while the PCC value has no rules.

In general, the results of the experiments running the two models showed not very good results. Both models have inconsistencies in PCC and high error values (between 8 to 32 mm/hour). This weakness is very reasonable because the two models also produce the unevenly spatial distribution of rainfall. Both models did not predict heavy rains in the central and western areas of the modelling domain. Meanwhile, based on statistical tests, WRF/WRF-Hydro has better skills than conventional WRF. Judging from the PCC value, the WRF/WRF-Hydro capability is better than conventional WRF, especially at the Jatiasih observation station in which the correlation value between WRF/WRF-Hydro with observations reaches 0.94. This indicates WRF/WRF-Hydro has a better skill in predicting the timing of rainfall. In addition, the error test showed that WRF/WRF-Hydro performed better than conventional WRF. In Jatiasih, Citeko, Halim, and TMII stations, the conventional WRF RMSE value is slightly greater than the WRF/WRF-Hydro. Thus, conventional WRF tends to produce larger outliers. For more details, see the chart in Figure 18.



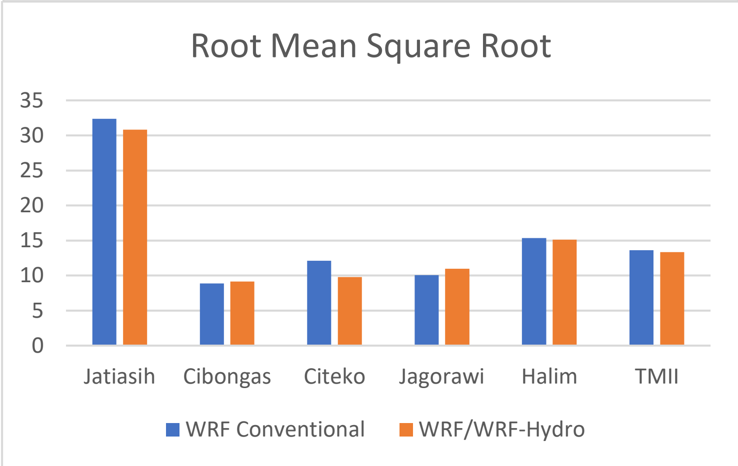


Figure 18 PCC Values and RMSE Values between the Two Models and Observation Data

4.6. Best Use of WRF-Hydro

First of all, the employment of WRF-Hydro in simulating atmospheric conditions and generating streamflow predictions can be utilized by competent and authorized agencies. WRF-Hydro has the potential to be employed operationally by the BMKG as a weather service and the Directorate General of Water Resources under the Ministry of Public Works and Public Housing as a hydrological service. In addition to being used operationally, WRF-Hydro also has the potentials to be employed in research and development in meteorology and hydrology. In optimally utilizing the WRF-Hydro hydrometeorological modelling, this study first reviews the uncertainties of the hydrological and meteorological modelling used in decision making.

Hydrological modelling in predicting discharge, flood depth, and inundated areas with an extended forecast lead time is highly dependent on the input. As input for hydrological modelling, the accuracy of meteorological modelling in generating precipitation determines the accuracy of hydrological modelling (Liu, 2012). Also, the uncertainty of hydrological modelling depends on spatial input data such as digital elevation models, land use, and land maps used both globally and regionally (Camargos et al., 2018). However, this writing mainly addressed more the precipitation input generated by weather modelling to produce flood predictions with a lead time of several days. This is in accordance with IN-7 suggestion that improving the weather prediction skill is of the most importance.

As with other models, weather modelling also has uncertainties. The longer the forecast lead time, the greater the uncertainty (Leutbecher & Palmer, 2008). Moreover, Gill et al. (2008) mentioned that the uncertainty in meteorological modelling is caused by four factors: atmospheric uncertainty, the uncertainty of data interpretation, uncertainty in composing forecasts, and interpretation of forecasts. To support a better decision-making process, a way to reduce uncertainty is needed, one of which is ensemble forecasting. Ensemble forecasts can dissolve forecast uncertainty from modelling either by the initial perturbation method or by the multi-model/multi-physical method (Zhu, 2005). Zhu also asserted that the mean of ensemble forecast could improve forecast skill of 1-2 day forecast lead time. Based on probability density function, moreover, ensemble forecast can provide users with probabilistic forecasts.

The IN-5 highlighted that there are necessities to shift from deterministic forecast to probabilistic forecast. The importance of delivering probability information seamlessly in planning and decision making in civil protection has been proven by Wastl et al., (2018). Changes in information on how much rain intensity can cause flooding to become informed on what percentage of confidence floods occur due to rainfall exceeding a particular threshold. Numerous models are required to implement probability theory. The more employed models, the more choices, so the agreement between models can be used as a better reference. If the number of models is only one, then the uncertainty is substantial. Therefore, WRF-Hydro has the potential to become a member of the ensemble forecast through the multi-model method. As a member of the weather forecast ensemble, WRF-Hydro can also offer water discharge predictions and as a member of flood forecast ensemble. BMKG may include WRF-Hydro as a member of the regional operational modelling in addition to those mentioned in section 4.3.1.

However, it will be a long process to operationalize WRF-Hydro and make WRF-Hydro a member of the forecast ensemble. Before being used operationally, IN-7 explained that WRF-Hydro users could define the level of prediction accuracy in terms of timing and spatial distribution they want to achieve. Therefore, WRF-Hydro can be used in research beforehand to test its system and its reliability, including model environment settings. The IN-5 suggested that research on the use of WRF-Hydro be carried out for at least one year. The recommendation for approximately one year is reasonable, acknowledging the monsoon, which causes wet and dry seasons in Indonesia. During the experimental period through this research, researchers will identify the deficiencies and strengths of WRF-Hydro in predicting rain and streamflow. Opportunities to improve WRF-Hydro's capabilities will also be very open during the research period. Generally, there are two main ways to improve WRF-Hydro's hydrometeorological modelling capabilities. First, test the sensitivity of the model through model tunning. This is done by making certain combinations of model parameterization. Researchers will determine which parameterization combinations are closest to reality by conducting an extensive sensitivity analysis to increase modelling capabilities. WRF-Hydro, which has hydrological and meteorological components, allows sensitivity tests for both streamflow simulations and daily rainfall production as Liu et al. (2021) and Arnault et al. (2018) did, respectively. Second, like other numerical predictions, IN-6 said that WRF-Hydro's ability to predict future hydrometeorological conditions could be improved by assimilating observational data into the model. The assimilation process can involve multiple observation data such as rain gauge data, weather radar data, weather satellite data, streamflow data, and other weather data obtained from ground stations. Research conducted by Abbaszadeh, Gavahi, & Moradkhani (2020) explicated that assimilation of soil moisture data and streamflow observations can improve WRF-Hydro's ability to predict streamflow.

Furthermore, the delivery of output information from hydrometeorological modelling is expected to be well received and perceived by end-users. Therefore, selecting information visualization of forecasts and warnings is essential in empowering the community to mitigate hydrometeorological disaster risks timely. WRF-Hydro users have many options in displaying WRF-Hydro output, such as images, maps, charts, graphs, and text. According to IN-1, currently, the community has understood the delivery of early warning information from the BMKG and KP2C in the form of texts on which areas have the potential for hydrometeorological disasters. Like BMKG, WRF-Hydro output can be presented in the form of a precipitation map image that depicts the concentration of rainfall. Moreover, the output of weather modelling as input for hydrological modelling can produce inundation maps. However, pluralistic societies with different educational backgrounds hardly understand map information. Most people still do not have full awareness of reading maps. The IN-1 preference for the style of visualization also represents the NGO KP2C under his auspices, that information in the form of maps is still challenging to follow. However, WRF-Hydro users can choose graph as an option for displaying, particularly hydrograph. A hydrograph can illustrate when the peak of the discharge is and how the water level is in a watershed. The IN-1 stated that hydrograph is more beneficial because it is clearer to read. Figure 19 shows an example of hydrograph.

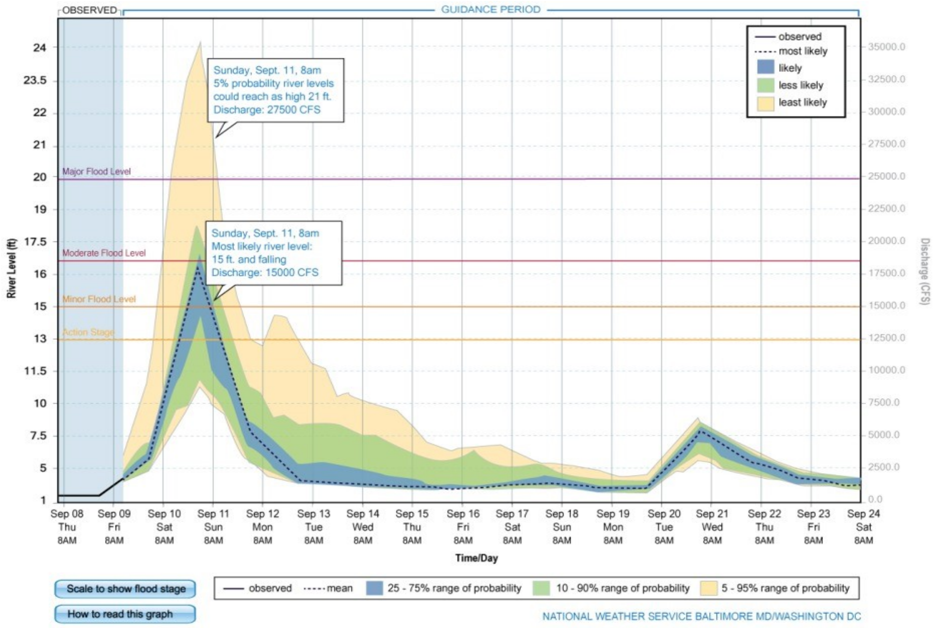


Figure 19 A Probabilistic Hydrograph Served by NOAA and NWS
(Source: Nurture Nature Center & East Carolina University, 2018)

Last but not least, this study explored the employment of WRF-Hydro to implementing the four elements of effective early warning systems based on the results of interviews and desk research. In addition to expert judgment, the potential use of hydrometeorological modelling such as WRF-Hydro also involves assessing the community and disaster management agencies. The opinion of the community and disaster management agencies is critical because they must understand the early warning provided by the monitoring and warning services. Thus, the early warning can empower communities and disaster management agencies to respond appropriately and quickly to such warnings. The following is the elaboration:

1. **Risk knowledge:** As with other mesoscale models, WRF-Hydro can be used to assess risk. Several researchers have conducted risk studies using mesoscale weather modelling. For instance, Kasai et al. (2017) overlayed predicted hazard index uses WRF with vulnerability and exposure maps to generate heat stroke risk. Wang et al. (2021) paired the WRF with the Community Multiscale Air Quality model to assess health risks in the petrochemical industry. Putra, Halik, & Wiyono (2021) used Artificial Neural Network modelling to downscale global reanalysis climate data to the mesoscale to generate drought risk based on the Standardized Precipitation Index. Likewise, the hydrometeorological WRF-Hydro model can also be employed for risk analysis. Not only flooding, but WRF-Hydro can also project hydrological drought risk as Lee, Kim, & Chae (2020) did with the Threshold Level Method.

2. **Monitoring and warning services:** Authorities can use WRF-Hydro to monitor atmospheric conditions and generate weather threat warnings for up to several days. However, how operationally employing WRF-Hydro for both weather forecasting and streamflow forecasting has been discussed previously.

3. **Communication and Dissemination:** One of the advantages of mesoscale weather modelling such as WRF, WRF-Hydro or other modelling is composing forecasts with prolonged lead times. Thus, in general, the results of hydrometeorological modelling forecasts that can detect catastrophic events early will enable authorities and the public to disseminate this information more widely. Hopefully, broader and faster acceptance of information will reduce the risk of hydrometeorological disasters.

4. **Response action:** As discussed above, WRF-Hydro can generate forecasts up to one day or two days before a catastrophe. Therefore, each actor who has a different role in the early warning system will respond to the output of WRF-Hydro. Table 12 summarized the response actions taken by each actor in response to the early detection of hydrometeorological disasters. In addition, the potential of WRF-Hydro as a member of the forecast ensemble is highly expected to encourage further a paradigm shift in the presentation of forecasts, from deterministic forecasts to probabilistic forecasts. Pappenberger et al. (2015) affirmed that probabilistic forecasts that receive response actions consistently earn monetary gain if calculated based on cost-benefit analysis. This can be the primary consideration for changing the paradigm of delivering forecast information.

Table 12 Response Actions Taken by Actors based on Prolonged Forecasts

No	Actor	Action
1	BMKG and Directorate General of Water Resources	- Disseminate the potential for extreme events that could lead to disaster - Observe dynamic conditions of natural hazards and update the information in real-time - Coordinate with disaster managers
2	BPBD Bekasi Municipality and BPBD Bogor Regency	- Redistribute received information to diverse stakeholders and the wider community - Develop disaster management plans together with other stakeholders - Allocate personnel and equipment to vulnerable areas - Educate the community so that people can make decisions calmly, precisely, and directed - Specifically for the Bekasi City BPBD, coordinate with the Bekasi Mayor to determine the opening of the Bekasi weir gate by considering the tradeoffs
3	KP2C	- Conduct regular water level monitoring and prohibit water level monitoring officers from taking leave - Update river water level - Redistribute received information to members, disaster managers, local community leaders through established networks - Coordinate with various stakeholders including volunteers and youth organizations
4	Community at risk	- Prepare for self-evacuation - Evacuate vulnerable groups to safer areas - Re-evaluate long-distance travel plans to be able to mitigate flood risk

4.7. Discussion

This study reveals that the community at risk are well prepared for flooding by responding appropriately to early warnings disseminated by government agencies and NGOs. Although early warnings have been disseminated several hours in advance, exceptional hydrometeorological events steadfastly have considerable impacts. The use of hydrometeorological modelling with proper tuning through extensive research can be considered so that extraordinary events can be predicted several days in advance. Thus, the important actors of decision-makers and implementers can be more broadly reached with prolonged forecasts. This section further discusses some aspects that need to be underlined from the research findings.

Despite frequent flooding, residents prefer to stay for several reasons: financial conditions, close social relations with the community, and homeownership (Ahaliati, 2013). For those staying, the current early warnings are helpful in diminishing the impact of floods. Even more, the IN-1 stated that there were never fatalities, including vulnerable groups, during the flood after residents received flood early warnings. Community act accordingly after receiving early warnings can indicate that the early warning system is reliable and trustworthy.

The system built by KP2C is a form of community-based flood early warning. KP2C is a bridge between top-down weather early warnings designed on a national scale and bottom-up micro-scale early warnings detailing potential flood areas to the residential level. Practical experience from KP2C is the basis for calculating the lag time between rising river water levels and overflowing rivers in the downstream area. Community-based flood early warning in Indonesia is rarely studied even though it has broad benefits for the community. A study on community-based flood early warning is critical so that it can be a pilot. To build a similar early warning system in other places requires at least a strong motivation, knowledge of the landscape, and knowledge of social interactions. Regarding the role of the social system, Rahayu et al. (2020) emphasized that local community leaders and the mosque community are important figures for disseminating early warnings locally. However, it will need other considerations if applied in other communities with different social and cultural systems.

Although early warning from KP2C has been proven to reduce flood risk in many flood events, the community and disaster management agencies still certainly demand flood forecasts with long lead times for decision-making purposes. For example, the decision of opening the Bekasi weir gate that will reduce the water level. Based on Sriyono et al. (2020) calculations, the Bekasi River can only accommodate 391.79 m3/s of water discharge, while during a major flood, the discharge can reach more than 700 m3/s. When the Bekasi dam is opened, the river water level will fall, and the dam's opening must obtain the Bekasi mayor's approval. The IN-3 explained that this is because there is a trade-off here, namely the possibility that the northern part of Bekasi will also be submerged even though the flood is not too deep. Therefore, the performance of hydrometeorological modelling is crucial to predict floods with long lead times.

Even though newly-developed numerical weather prediction models have been operationally used to predict rainfall up to three days lead time in many parts of the world (Ashrit et al., 2020), there should be experiences regarding the timing, location, and intensity of forecasting precipitation (Tardy, 2015). Especially for meteorological modelling because the Quantitative Precipitation Forecast product is an input for hydrological modelling, the IN-4 emphasized that improving the atmospheric condition analysis skills at Indonesia Maritime Continent is still very important considering that the forecast basis is mostly still using high latitude references. It is evident from the experimental results in this study that the models' results can detect extreme rainfall but are not sound at describing the spatial distribution of rain, so that statistical tests with ground observations are also lacking.

Researchers encourage the delivery of probabilistic forecasting information because it has been shown to yield several advantages. For example, Buizza (2008) explained that probabilistic forecasts are better than single deterministic forecasts because decision-makers can assess which events are most likely to occur and extreme events can be detected. Pappenberger et al. (2015) reassured that another benefit for flood forecasting in Europe is that probabilistic forecasts can bring monetary benefits. However, probabilistic forecasts are only widely known by hydrometeorological scientists and rarely come out into the public domain. This may be due to two reasons: the lay public is suspected of resisting to utilize probabilistic forecasts and the complexity of communicating this information to them (Fundel et al., 2019). This also prevails in the study area, where probabilistic forecasts are still in the domain of scientists. Based on the interviews with BPBD, the institution responded splendidly to early warnings issued by both BMKG and KP2C a few hours before the disaster. However, the potential for extreme hydrometeorological events detected for the next few days is only accepted by BPBD without any decision-making process. This indicates that decision-makers still rely on the authorities' deterministic forecasts even though the forecast's uncertainty is still notable. Therefore, the readiness of the community and decision-makers in the study area to understand probabilistic forecasts well should also be known before there is a shift in delivering forecast information from deterministic to probabilistic.

Embracing, implementing, and enhancing hydrometeorological modelling is also very important. Losses due to devastating flooding triggered by heavy rains that lasted for a long time are still inevitable. Many people are not ready to face the extreme rain event, so the IN-1 stated that the community also demands information on the duration of the severe rain event. Therefore, technical affairs such as improving the performance of hydrometeorological modelling need to be scrutinized to provide duration information. In addition, to be responded accordingly, BMKG and related response agencies as early warning disseminators are deemed necessary to carry out multidisciplinary collaboration, experience social systems, and establish solid partnerships with various stakeholders, including academics. This is done so that the agencies can meet the needs of end-users.

CHAPTER V CONCLUSIONS

This chapter provides concluding remarks based on the research results presented in the previous chapter to answer the research sub-questions and provide recommendations for improving early warning systems using hydrometeorological modelling. Furthermore, suggestions for future research based on the limitations and findings of this study are provided.

5.1. Answers to Research Questions

Question 1: What are the main characteristics in the selected flood-prone areas related to flood risks, flood preparedness and response action?

The devastating flood disaster on 1 January 2020 caused enormous losses even though valuables had been secured. Floods have damaged hundreds of homes and vehicles, wasted important documents, forced thousands of residents to flee, and halted economic activity for several weeks to clean up flood mud. Meanwhile, the potential for flood losses calculated by the BPBD Bekasi Municipality and BPBD Bogor Regency in flood-prone areas is estimated to reach approximately 85 million USD. The community-based flood early warning provided by KP2C in conjunction with the extreme weather early warning provided by BMKG for the study area is sufficient to mitigate flood risk. After the early warning is disseminated, the community and disaster management agencies take response actions according to their capacity. Residents evacuated all property, including vehicles, to a safer place while the disaster management agency dispatched personnel and prepared evacuation and flood pumps equipment.

Question 2: Is the meteorological and hydrological simulation-based WRF-Hydro model capable of providing better flood risk warnings and guidance to response action than systems in place? (cf. flood occurred on 1st January 2020).

It is imperative to know the atmospheric conditions in catastrophic flooding events following extreme precipitation to detect similar events earlier. Therefore, this study analyzes extreme rain events that last for more than 12 hours from 31 December 2019, based on numerical weather prediction simulations. The results show that heavy rains are preceded by shear winds blowing in opposite directions between the surface and the high level, convective instability due to dry air in the middle layer, and high relative humidity supply at the surface. Due to hardware limitations, timeframes, and the researcher's ability, the study was not carried out to comprehend the presence of a persistent northerly monsoon wind for approximately a week as Wu et al. (2007) did. Also, the study did not observe the anomaly values of specific weather parameters, which usually play an essential role in forming a solid storm system like what Siswanto et al. (2017) did. Therefore, I suggest that meteorologists examine this event more comprehensively.

The weather service responsible for monitoring atmospheric conditions employs several weather models to generate early warnings, one of which is WRF. The researcher compared the WRF's capability with that of WRF-Hydro. Based on the experimental procedure, both models can detect the presence of extreme rainfall. However, both models also lack precision in producing the spatial distribution of rain. The statistical test results show that WRF-Hydro is slightly better in generating time series data, as indicated by the slightly smaller RMSE value and slightly larger PCC value. A more extensive sensitivity test is needed in order to prepare better forecast results.

Question 3: How could WRF-Hydro best be embraced and implemented by authorities and communities in the selected flood prone areas?

The current use of WRF-Hydro is better focused on various researches, both for meteorological and hydrological research. Because the model has uncertainty, research can improve the model's capabilities and reduce the uncertainty in the model. In addition, based on interviews with experts, WRF-Hydro also has the potential to be a member of the prediction ensemble so that the forecast information communicated is a probabilistic forecast. Furthermore, WRF-Hydro can also be embraced and implemented in each of the four elements of the early warning system.

5.2. Directions for Future Research

Early warning systems play essential roles in reducing the risk of hydrometeorological hazards. However, there are still gaps and challenges to optimize the early warning system to create a robust and resilient community. Therefore, three directions are identified for future research from the technical and non-technical sides of hydrometeorological early warning. Firstly, efforts are needed to close the gap between scientists and the general public and decision makers regarding probabilistic forecasts, for example by conducting surveys or workshops. Secondly, a study of impact-based forecasts in specific sectors is necessitated. For example, in the energy sector, hydrometeorological disasters often cut the power grid. These impacts can be immediately mitigated and recovered if the impacts are predicted to build reliable and resilient energy. Thirdly, a WRF-Hydro sensitivity analysis should be carried out from the hydrological configuration and the meteorological configuration to produce better streamflow and rainfall forecasts.

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APPENDICES

Appendix A. Total Area and Demographics of Bogor Regency

No.	Sub-districts	Total Area (km^2)	Population (thousands)
1	Nanggung	159.30	98.49
2	Leuwiliang	91.03	124.67
3	Leuwisadeng	35.40	77.38
4	Pamijahan	124.86	157.11
5	Cibungbulang	38.45	145.70
6	Ciampea	33.04	168.35
7	Tenjolaya	41.35	63.64
8	Dramaga	25.29	110.37
9	Ciomas	18.65	170.48
10	Tamansari	34.32	108.91
11	Cijeruk	47.92	91.66
12	Cigombong	96.07	97.65
13	Caringin	47.16	131.01
14	Ciawi	77.55	114.85
15	Cisarua	47.07	127.09
16	Megamendung	73.97	107.13
17	Sukaraja	62.43	206.32
18	Babakan Madang	43.76	114.64
19	Sukamakmur	92.38	85.56
20	Cariu	170.17	51.61
21	Tanjungsari	85.43	57.2
22	Jonggol	158.86	143.51
23	Cileungsi	133.31	288.34
24	Klapanunggal	70.57	127.56
25	Gunungputri	60.87	298.08
26	Citeureup	68.81	214.66
27	Cibinong	46.62	363.42
28	Bojonggede	28.34	287.55
29	Tajurhalang	30.78	123.45
30	Kemang	33.61	104.87
31	Rancabungur	22.67	60.71
32	Parung	25.74	123.07
33	Ciseeng	41.29	110.59
34	Gunung SIndur	49.39	126.83
35	Rumpin	136.84	146.00
36	Cigudeg	177.61	133.93
37	Sukajaya	156.18	66.92
38	Jasinga	144.54	106.34
39	Tenjo	83.22	73.27
40	Parung Panjang	71.34	118.17

Appendix B. Questionnaire

1. Questions for NGO

a. Are you aware of the existing extreme weather early warning system, particularly torrential rain warnings?
b. Do you often receive early warning of extreme weather? If so, then how do you receive the early warning, and how long does it take between the early warning information you receive until the extreme weather actually occurs?
c. Do you also often receive warning information about flooding due to overflowing rivers? If yes, then how do you receive the warning information about the occurrence of the flood, and how long does it take for the flood warning that you receive when the flood event actually occurs?
d. What obstacles do you face in receiving early warning information?
e. Do you re-disseminate the early warning information that you received? If so, then to whom do you disseminate the information and through what media?
f. What obstacles do you experience in re-disseminating the early warnings?
g. Were you at home when there was heavy rain and floods on January 1, 2020? Please explain briefly about the floods on January 1 2020
h. In general, what losses did the community suffer when floods on January 1, 2020? What caused this flood incident to be more detrimental than the flood events commonly experienced by the local community?
i. Did you receive early warning information about heavy rain and flooding when flood when floods on January 1, 2020, occur?
j. What is the time period between receiving the early warning information and the incidence of heavy rains and floods on January 1, 2020?
k. In that timeframe, what preparations have you made to reduce the negative impact of flooding when you receive the early warning information of heavy rains and floods?
l. If you receive flood early warning information with a longer time span (for example 1 day or 2 days before the incident), will you take action to reduce the risk that occurs due to heavy rains and flooding? If so, then what preparations will you do to reduce this risk? If not, then why won't you make preparations?
m. Do people in the study area have a special role to play in reducing the risk of flooding when heavy rains cause flooding?

2. Questions for meteorological and hydrological services

a. What are the main duties and functions of the meteorological/hydrological service, specifically regarding public services?
b. Does the meteorological/hydrological service monitor atmospheric conditions/river levels before issuing advance warnings regarding extreme weather/flooding? If so, how was the monitoring carried out?
c. Based on monitoring result, how are early warnings disseminated to affected communities?
d. What are the obstacles experienced when monitoring the atmosphere/river water level before generating early warnings?
e. What are the obstacles in disseminating the early warnings that have been created based on the monitoring results?
f. Is there a collaboration with disaster management agencies on the current early warning system? Could you briefly explain this collaboration?
g. Generally, is there an integrated flood prediction and early warning system in Indonesia? If so, how flood forecasts in Indonesia are generated? If not, what are the obstacles to the integration of flood forecasts and early warnings?

h. What are your recommendations for overcoming obstacles to integrating flood forecasts and early warnings?
i. Regarding the effectiveness of the early warning system, has there been risk assessments of flood in the study area?
j. How do meteorological/hydrological services view community involvement in early warning systems? Has there been some form of community involvement in the early warning system?

3. Questions for disaster managers

a. What are the duties and functions of disaster management agencies in an early warning system, in particular, a flood early warning system?
b. In your opinion, how important is the role of early warning in reducing damage and reducing casualties?
c. Is there an extreme weather early warning system and/or flood early warning system currently in place in the study area? If so, how does the early warning system work?
d. In the case of the flood on January 1, 2020, in particular, was the early warning system able to reduce damage and reduce casualties? If not, what factors have caused the system not to be able to reduce damages and reduce casualties?
e. What response actions do disaster management agencies take when receiving early warning information on extreme weather/water levels?
f. What response actions do the disaster managers take when there was a flood in the study area?
g. Are there any efforts by the disaster management agency to prevent flooding in the study area? If so, how do the flooding prevention take place?
h. In the case of floods on January 1, 2020, specifically, what response actions were carried out by the disaster management agency to reduce the risk of flooding in the study area?
i. If you receive flood early warning information with a longer time span (eg 1 day or 2 days before the event) from the meteorological/hydrological service, what response actions will the disaster managers take to reduce the risk of flooding?
j. Regarding the effectiveness of the early warning system, has there been risk assessments of flood in the study area?
k. Are early warnings of both extreme weather and water levels from relevant agencies received in a timely manner? If not, what were the constraints that caused the delay?
l. Who actors have important roles in communicating and disseminating extreme weather and flood early warnings?
m. Is there community involvement in the early warning system in the study area? What is the form of coordination with local communities in efforts to prevent and reduce flood risk?
n. What advice is given to the community at risk to reduce the risk of flooding in the study area?

4. **Questions for meteorological and hydrological modelling experts**

a. Are there any models employed operationally to predict floods in Indonesia? If so, what models are used and how are they be operated?
b. What meteorological/hydrological models are currently used operationally to predict extreme weather or floods in Indonesia?
c. Is there an operational use of meteorological/hydrological models to predict extreme weather/flooding on a local/regional scale? If yes, how does it work?
d. Can meteorological/hydrological modelling be used for risk analysis of flooding? If so, how is it done?

e. What are the roles of meteorological/hydrological modelling in reducing the risk of flooding caused by extreme weather?
f. How can we improve your meteorological / hydrological modeling capabilities to reduce the risk of flooding?
g. For urban landscape such as the study area, how can we optimize the use of meteorological / hydrological modeling to reduce flood risk?
h. Do you know about hydrological and meteorological modeling that can be run fully-coupled such as WRF-Hydro? If yes, is to improve the hydrometeorological modeling capability the same in principle as other weather modeling?

Appendix C. Two Versions of Consent Form

CONSENT TO TAKE PART IN RESEARCH STUDY INTERVIEW

ENHANCING EARLY WARNING SYSTEM IN BEKASI THROUGH THE EMPLOYMENT OF HYDROMETEOROLOGICAL MODEL

	Yes	No
- I, ……. ………., agree to take part in this research study interview of my own volition.	☐	☐
- I understand that even if I agree to participate now, I can withdraw at any time or refuse to answer any question without any consequences of any kind.	☐	☐
- I accept that I have the right to refuse to allow data from my interview to be used after it has taken place, in which case the content will be deleted.	☐	☐
- I have had the purpose and nature of the study explained to me and I have had the opportunity to ask questions about the study.	☐	☐
- I agree to my interview being audio-video-recorded.	☐	☐
- I understand that all information I provide for this study will be treated confidentially.	☐	☐
- I understand that in any report on the result of this research my identity will remain anonymous if preferred to be so. This will be done by not explicitly mentioning my name and disguising any details of my interview which may reveal my identity or the identity of people I speak about.	☐	☐
- I understand that I am entitled to access the information I have provided after the interview.	☐	☐
- I understand that I am free to contact any of the people involved in the research to seek further clarification and information.	☐	☐

The names of the people involved in this study who guarantee the agreed-upon use of this consent and the answer provided during the interview are mentioned below.

Researcher:

Nizam Mawardi

Project Supervisor:

1. Dr. Kris Lulofs
2. Dr. Gül Özerol
3. Prof. Chay Asdak

Participant:

Signature of participant

Date:

PERSETUJUAN UNTUK MENGAMBIL BAGIAN DALAM WAWANCARA STUDI PENELITIAN

PEMANFAATAN PEMODELAN HIDROMETEOROLOGI UNTUK PENGEMBANGAN SISTEM PERINGATAN DINI DI DAS BEKASI HULU

	Ya	Tidak
- Saya yang bernama, ……. ………., setuju untuk mengambil bagian dalam wawancara studi penelitian ini atas kemauan saya sendiri.	☐	☐
- Saya memahami bahwa meskipun saya setuju untuk berpartisipasi sekarang, saya dapat membatalkan kapan saja atau menolak menjawab pertanyaan apa pun tanpa konsekuensi apa pun.	☐	☐
- Saya menerima bahwa saya memiliki hak untuk menolak memberikan izin data dari hasil wawancara saya digunakan setelah wawancara tersebut dilakukan. Jika saya menolak memberikan izin maka konten akan dihapus.	☐	☐
- Saya telah diberikan penjelasan mengenai tujuan dan sifat studi tersebut kepada saya dan saya memiliki kesempatan untuk mengajukan pertanyaan tentang studi tersebut.	☐	☐
- Saya setuju wawancara saya direkam baik dengan audio maupun audio-video.	☐	☐
- Saya memahami bahwa semua informasi yang saya berikan untuk penelitian ini akan dijaga kerahasiaannya.	☐	☐
- Saya memahami bahwa dalam laporan apa pun tentang hasil penelitian ini, identitas saya akan tetap anonim jika diinginkan. Ini akan dilakukan dengan tidak secara eksplisit menyebutkan nama saya dan menyembunyikan detail wawancara saya yang dapat mengungkapkan identitas saya atau identitas orang yang saya bicarakan.	☐	☐
- Saya memahami bahwa saya berhak mengakses informasi yang saya berikan setelah wawancara berlangsung.	☐	☐
- Saya memahami bahwa saya bebas untuk menghubungi siapa pun yang terlibat dalam penelitian untuk mendapatkan klarifikasi dan informasi lebih lanjut.	☐	☐

Peneliti:

Nizam Mawardi

Pembimbing Penelitian:

1. Dr. Kris Lulofs
2. Dr. Gül Özerol
3. Prof. Chay Asdak

Peserta:

Date: