論　文　の　内　容　の　要　旨

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論文題目　Estimation of Evapotranspiration in Cultivated and Uncultivated Paddy Field in Tropical Watershed
(熱帯流域の水田における耕作および非耕作水田からの蒸発散量の推定)

Watershed management can be mentioned as region development plan which placing watershed as a natural resource management unit which generally to reach target of optimally increasing production in the field of forestry and agriculture in the sustainable way. The need to allocate water resource correctly is the objection of water resource management. Thus it is necessary to optimize it for each region or watershed not only for water-deficit region. Water resource management in an optimal fashion, is basically exploiting of water resource efficiently in accordance to its allotment. Various activity which planned in the field of industry, agriculture, domestic utilization, and forestry initially require water resource data. As Industrial area, agriculture farm, residential area are progressively mounting from year to year, so that also the amount of water required that is needed, and the competition usage of water unavoidable. This condition coercively bring obligation to manage watershed with effort to depress damage as minimum as possible in order to have equal distribution of water from the river during the year.

In present study, the existence of paddy field and its role on controlling water resource in the watershed is evaluated. Evapotranspiration in the paddy field is the main concern on this study. Several field measurement were conducted to have basic

information on paddy field. Several methods were also applied to estimate evapotranspiration in paddy field. The importance of this research is to answer questions such as whether paddy field increase or decrease water resource and how can it contribute to decrease water loss in the atmosphere.
Cidanau watershed was taken as study area. It located in Java Island, Indonesia on the geographic coordinate of East 6° 8' - 6° 17' and North 105° 52' - 106° 03'. The watershed land use has an area of 220 km^2 comprises mountain and forest (58%), swamp (5%), swamp forest (5%), village (4%), and paddy field (28%). This area is part of tropical monsoon region, in which the rainy season and the dry season are explicitly distinguishable. Rainy season lasts from October to April while Dry season from May to September. The unique of this watershed are firstly because of the existence of Rawa Danau swamp forest which designed as natural preservation in 1921 for its richness in endemic plant and animal species. Secondly, this watershed is topographically isolated which create restriction of commodity exchange across watershed. It enables the assumption of closed system for many fields of research.

Basic information on hydrology in this watershed is necessary start point. Daily discharge and rainfall data within the last ten years give brief description on dry season and wet season in every year. It also informs how dry season could be difference on certain years and when the extreme drought occurred. Through these data yearly actual evapotranspiration across the watershed is extracted. The main idea is water balance concept which put evapotranspiration occurrence as necessary factor which influence to river discharge and water storage across the watershed. Water balance concept on estimating actual evaporation is based on hydrological water balance equation in watershed scale. The basic equation is $\Delta S = P - Q - E$, which means change in storage is happen due to precipitation subtracted by river discharge and evaporation. If within one certain period there is no storage change ($\Delta S = 0$), it means during the period, actual evaporation can be calculated only by subtracting river discharge from precipitation ($E = P - Q$). Calculation shows that on yearly base, actual evapotranspiration in the watershed is about 80.16% of reference evapotranspiration. In a very dry condition where annual rainfall is small for example in the beginning of dry season of 1997 to the end of rainy season in 1998 (1340 mm), actual evaporation has value less than 2 mm/day.

Field survey was conducted to observe surface temperature in the watershed especially in the paddy field area. Access to water is not the same for all paddy field in watershed area, which is become one important factor for starting cultivation. In dry season, crop growth stages are various and disperse spatially in the watershed. Therefore, even though the meteorological condition is the same for the whole area, this condition creates spatially differ in surface temperature and evaporation rate

Temperature of paddy field in both bare surface and cultivated surface were measured. For cultivated surface, growth stage was also noted and recognized using classification introduced by Yoshikawa and Shiozawa (2006). By applying microlysimeter method, evaporation was also measured. Thin wall samplers were inserted into wet soil to take sample; but for dry soil, soil blocks were taken and wrapped the bottom with plastic bag to make the samples. After weighing each sample by electric balance, returned them to field as they were to allow evaporation, and then measured how much they loose weight. Water evaporation is also measured by putting water into 1053 cm^3 (13 cm x18 cm x 4.5 cm) plastic container. The amount of evaporation from water surfaces is used as reference.

Other data needed was acquired from nearest meteorological office which are solar radiation and average wind speed. Incoming solar radiation was estimated by using Amstrong formula which take into account extraterrestrial radiation and relative sunshine duration.

The important fact in this survey is the comparison of surface temperature and evaporation in wet soil and dry bare soil. Evaporation measurement shows amount of 1.63 mm for 10.00 – 17.00 in dry bare soil and 4.49 mm in wet soil for 9.30-18.00. Maximum temperature in wet soil was about 40^{o} C, while that for dry soil was 53^{o}C. Surface temperature at 10.00 a.m. is also noted. It is the time when Landsat overpass the watershed. They are 45.5^{o} C in dry bare soil and 36.6^{o} C in wet soil.

Thermal conductivity of soil was measured using Thermal Conductivity Probes. This sensor consists of a length of resistive wire (heating element) and a copper-constantan thermocouple in a stainless steel hypodermic needle that is in the center of a cylindrical ceramic matrix (Scanlon et al., 2002). Thermal conductivity probe used in this measurement is made by Decagon Device, Inc. Soil was prepared from wet condition in small chamber (12 cm x 5 cm x 5cm). Thermal conductivity probe was inserted to the soil. During wet condition, the thermal conductivity probe can be inserted easily into the soil. As the soil drying, the probe should be keep inside the soil. The measurement interval should ensure that the water content is reduced significantly and the heat in the soil from oven-drying to reduce its water content is totally removed. This paddy field soil is swelling soil which has distinct characteristic. Measured thermal conductivity shows slight decrease with increase in water content due to bulk density increase, except for very dry condition (water content less than 0.2). Thermal conductivity of each wet and dry field during field observation recognize to have almost similar value. From the figure 7, it can be examine that the value is 1.16 W/m.K for dry paddy field and 0.99 W/m.K for wet paddy field.

To assess the relation between surface temperature and evapotranspiration rate, physical model is used. The objective of this study is to estimate evapotranspiration from several type of land use within paddy field. Focus is on bare soil (uncultivated) in paddy field and several rice growth stage which spatially dispersed in Cidanau watershed. The model is a numerical model to calculate heat exchange and vapour between surface and atmosphere. Due to remote sensing application of this model, it should be simple. It takes into account surface parameters and meteorological parameters. Heat transport equation coupled with energy balance equation considered sufficient to explain how the parts of system interact. In bare soil, evaporation as energy balance component, calculated from vapour concentration gradient between soil surface and atmosphere. For vegetated surface, Penman-Monteith equation is used. The result of this study is the temperature-evaporation graph which mapping surface temperature into amount of evaporation in bare paddy field soil and cultivated paddy field soil in several type of crop growth stage.

Another field survey was conducted to measure actual evaporation from wet paddy field and dry paddy field. Accurately quantify evaporation and evapotranspiration is urgent to perform better estimation in larger scale of paddy field within the watershed. Direct observation was performed in representative paddy field. The coexistence of dry and wet paddy field during dry season make this observation possible to conduct. This study compares energy balance component of wet (cultivated) and dry (uncultivated) paddy field in Cidanau watershed when both is under the same meteorological condition. Further it also examines the distinction in surface temperature of both fields in comparison to evaporation rate and soil surface condition. Weather station instrument consist of net radiation sensor, solar radiation sensor, sonic anemometer, fine wired thermocouple, infrared thermometer, air temperature and humidity sensor were installed at location. Bowen ratio method is used to calculate sensible heat flux and latent heat flux. Net radiation was measured, and ground heat flux calculated using heat storage function which utilized profiled soil temperature data. Result shows that from latent heat flux component, dry bare field (2.6 mm/day evaporation) has evaporation value about half (48.9%) from wet cultivated field (5.3 mm/day evapotranspiration). Significant difference between surface temperature pattern at dry bare field and wet cultivated paddy field appears obviously. Directly measured temperature using thermistor shows maximum temperature of 51oC for dry bare field and 32°C for wet cultivated paddy field. The maximum surface temperature difference of both field is 19°C correspond to amount of evaporation difference 2.7 mm/day. This significant difference shows that it is possible to estimate evaporation from surface temperature.

In plastic container/microlysimeter (13 cm x18 cm x 4.5 cm), dry soil gives evaporation about half from wet soil. Both bowen ratio method and microlysimeter method obviously shows that wet soil or cultivated soil resulting higher evaporation from dry soil. Converting bowen ratio value to evaporation fraction (EF) resulting value of 0.57, 0.53, and 0.54 for dry bare paddy field and 0.78, 0.85, and 0.84 for cultivated wet paddy field. Dry bare field has less fraction of available energy used for evaporation rather than in cultivated wet field. In other words dry soil has low energy availability (low albedo in wet or cultivated soil) and also it has low less water availability. The early conclusion could deducted from this result. That is; during dry season, paddy field left uncultivated in the watershed increase water resource for downstream by decreasing evaporation.

To obtain amount evapotranspiration in paddy field at regional scale remote sensing technology was utilized. Recent methods in surface process quantification offer regional based evapotranspiration calculation by using remote sensing image. High temperature observed in low-evaporation surface is proven in the field survey. Surface process along this relation is complex and required many parameters especially related to vegetated surface. Various assumption should be incorporate so that one-time captured image could describe daily value of evapotranspiration. However, unlike hydrological models, remote sensing techniques compute evapotranspiration directly from the energy balance equation without the need to consider other complex hydrological processes. This could be the strong advantage of this technique, because the error in the quantification of other hydrological processes is not propagated into calculated evapotranspiration. Major limitation of remote sensing data is that the temporal distribution of satellite-based estimates is poor, and that interpolation techniques are necessary to define evaporation between satellite overpasses.

Actual evaporation assessed using SEBAL algorithm (Bastiaanssen, 2000). Evaporation from vegetative surface, bare soil, or open water are calculated based on surface reflectance and emittance from difference spectrum of remote sensing images. Since the satellite image provides information for the overpass time only, SEBAL computes an instantaneous ET flux for the image time. Instantaneous components of ET can be extrapolated into daily value by using crop coefficient data. Finally, the result of physical model previously constructed is also used for comparison. The benefit of physical model is that the inputs use information measured in the field survey. Thus it considered more accurate rather than relying most of calculation process from spectral information in satellite image. Result of this study gives spatial information on land use, surface temperature and evapotranspiration in paddy field during dry season.