【Article】

Atmosphere, Land Surface, Hydrology, Ocean Wave, and Ocean Current Model (ALHOM) in Asia Environmental Simulator

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Abstract

An atmosphere, ocean waves, and ocean current coupled model system is extended to include the atmosphere land surface interactions and to connect the water heat and material circulation between the ocean and terrestrial circulation systems. The models used in this system are the non-hydrostatic atmospheric model (MM5), multi-layer land surface model (SOLVEG2), hydrological simulation program FORTRAN (HSPF), the third-generation ocean wave model of NOAA (WAVE WATCH III), and the Princeton Ocean Model (POM). The modeling system is divided into two main wings; the atmosphere-ocean wing, and the atmosphere-land surface wing. Both wings are combined to give a coupled atmosphere, land surface, hydrology, ocean wave, and ocean current model (ALHOM) that is capable to simulate the hydrological cycle on a regional scale.

The coupled modeling system is a main part of currently running research project Asia Environmental Simulator (AES). Within AES the coupled modeling system will be applied for simulating water circulation and CO2 budgets in Kapuas river basin in Kalimantan Island, Indonesia, and for water circulation and water quality in Haji dam watershed in Hiroshima prefecture, Japan.

Keywords: MM5, POM, WW3, SOLVEG, HSPF, Coupling, Asian Environment Simulator

1. Introduction

There is a growing interest in the field of modeling and quantitative assessment of environmental problems. Results of environmental models and assessment analyses have been influencing the regulations and policies related to the environmental preservation at local, national and international levels. In earth system modeling, the interacting components on the environment which were traditionally modeled in isolation are modeled in unison to understand how feedbacks between the components may ultimately influence the properties of the whole system.

The atmosphere and oceans transfer mass and energy between them at all times and scales. This is a key element of the Global Climate Engine. Energy transfer between atmosphere and ocean takes different forms: heat, water vapor, dissolved gases, and kinetic energy that drive surface ocean currents. Terrestrial ecosystems control fluxes of energy, mass and momentum between the land surface and the atmosphere and therefore influence climate (e.g. Mintz, 1984; Bonan et al., 1992). Changes in climatic conditions can change the structure of the underlying vegetation cover, which may feed back to climate. A need for a single system that connects the atmosphere, ocean, and terrestrial systems is crucial to better understand the interaction between the different components of the earth environment system.

Atmosphere, land surface, hydrology, ocean wave, and ocean current models are coupled together to create a comprehensive earth environment modeling system, ALHOM. ALHOM is a part of a running research project called Asia Environmental Simulator, AES, aiming to create sustainable development plans in East Asian countries. ALHOM will be first applied to the mercury contamination problems in Kapuas River basin in West Kalimantan, Indonesia, and to the environmental effects of the large scale landuse change in Kalimantan due to the wildfires events and the unplanned deforestation activities. Eutrophication problems in Haji dam reservoir in Hiroshima, Japan is the second case study of interest.

2. Overview of Numerical Models in ALHOM

The models used in ALHOM are the non-hydrostatic atmospheric model (MM5), Multi-layer land surface model (SOLVEG2), hydrological simulation program FORTRAN (HSPF), the third-generation ocean wave model (WAVE WATCH III), and the Princeton Ocean Model (POM). A brief description of each of the pre-mentioned models is given in the following paragraphs.

Mesoscale Atmospheric Model (MM5): The PSU/NCAR mesoscale model (known as MM5) is a limited-area, non-hydrostatic, terrain-following sigma-coordinate model designed to simulate or predict mesoscale atmospheric circulation (Grell et al., 1994). The model is supported by several pre- and post-processing programs, which are referred to collectively as the MM5 modeling system. The MM5 modeling system has been developed at Pennsylvania State University, PSU, and National Center for Atmospheric Research of the United States, NCAR, as a community mesoscale model. MM5 allows simulation of wide spectra of real atmospheric processes of the scales from several kilometers to several thousand kilometers. Appropriate computational tools and parameterization methods of the sub-grid scale processes should be selected for a particular application. The choice of the model parameters for a simulation provides useful information for understanding the physics of the processes involved. A variety of meteorological analysis and forecast products can be used as the background analysis data for the meteorological model. Among these data sets are the NCEP GDAS global analysis data, NCEP/NCAR global reanalysis data, NCEP AVN global analysis data, ECMWF global reanalysis data, NCEP FNL global analysis data, and JMA reanalysis data.

Princeton Ocean Model (POM): Princeton ocean model (Mellor, 1998) is a three dimensional coastal ocean model, incorporating a turbulence closure model (Mellor and Yamada, 1982) to provide a realistic parameterization of the vertical mixing processes. POM uses a terrain following sigma coordinates and suitable for coastal regions application. The prognostic variables are the three components of velocity, temperature, salinity, turbulence kinetic energy, and turbulence macro-scale. The momentum equations are nonlinear and incorporate a variable Coriolis parameter. Prognostic equations governing the thermodynamic quantities, temperature, and salinity, account for water mass variations brought about by highly time-dependent coastal upwelling processes as well as horizontal advection processes. Free surface elevation is also calculated prognostically, with some sacrifice in computational time. This is accomplished by use of a mode splitting technique whereby the volume transport and the vertical velocity shear are solved separately.

Third Generation Wind Wave Model: WAVE WATCH III (WW3) has been developed at the Marine Modeling and Analysis Branch (MMAB) of the Environmental Modeling Center (EMC) of the National Center of Environmental Prediction (NCEP) in the United States (Tolman, 2002). It is based on WAVE WATCH I and WAVE WATCH II developed at Delft University of Technology, and NASA Goddard Space Flight Center, respectively. WW3 differs from its predecessors in all major aspects; i.e., overrunning equations, program structure, numerical and physical approaches. WW3 is known as third generation wave model which is phase averaged and stochastic. It simulates temporal and spatial variation of wave growth and decay resulting from surface wind force, dissipation due to white-capping, and the bottom friction on the water column.

Multi-Layer Atmosphere –Soil-Vegetation Model: A new atmosphere-soil-vegetation model named SOLVEG2 (SOLVEG version 2) was developed at the Japan Atomic Energy Research Institute (JAERI) to study the heat, water, and CO2 exchanges between the atmosphere and land-surface (Nagai, 2005, 2003, 2002). The model consists of one-dimensional multilayer sub-models for the atmosphere, soil, and vegetation. It also includes sophisticated processes for solar and long-wave radiation transmission in vegetation canopy and CO2 exchanges among the atmosphere, soil, and vegetation. Although the model usually simulates only vertical variation of variables in the surface-layer atmosphere, soil, and vegetation canopy by using meteorological data as top boundary conditions, it can be used by coupling with a three-dimensional atmosphere model.

The atmosphere sub-model solves prognostic equations for horizontal wind components, potential temperature, specific humidity, fog water, and turbulence statistics by using a second-order closure model. The soil sub-model calculates the transport of heat, liquid water, and water vapor. The vegetation sub-model evaluates the heat and water budget on leaf surface and the downward liquid water flux. The adopted radiation scheme calculate the four solar radiation components (visible and near infrared bands in direct and diffuse components) separately. Using such detailed radiation calculation, the observed albedo is simulated more properly than early versions of the model. Also, it enables the utilization of a more realistic stomatal resistance scheme that considers the spectral band of solar radiation: visible or photosynthetically active radiation. Carbon dioxide (CO2) exchange processes are incorporated into SOLVEG2. It includes the exchange process of CO2 along with those of heat, water, and momentum, which interact with each other.

Hydrologic Simulation Program FORTRAN: Hydrologic Simulation Program FORTRAN (HSPF) is a U.S. EPA program for simulation of watershed hydrology and water quality for both conventional and toxic organic pollutants (Bicknell et al., 2001). The HSPF model uses information such as the time history of rainfall, temperature and solar radiation; land surface characteristics such as land-use patterns; and land management practices to simulate the processes that occur in a watershed. The result of this simulation is a time history of the quantity and quality of runoff from an urban or agricultural watershed. Flow rate, sediment load, and nutrient and pesticide concentrations are predicted.

The HSPF model can simulate the watershed hydrology and associated water quality for both conventional and toxic organic pollutants on pervious and impervious land surfaces and in streams and well-mixed impoundments.

The HSPF model incorporates the watershed-scale Agricultural Runoff Model (ARM) and Non-Point Source (NPS) models into a basin-scale analysis framework that includes pollutant transport and transformation in stream channels.

3. Interactions among Models

To facilitate the construction of a comprehensive coupled modeling system, the interactions among the different models are divided into two wings; the atmosphere-ocean wing, and the atmosphere-land surface wing. For both wings, the interactions occur through an interface medium, WW3 in case of atmosphere-ocean wing, and SOLVEG2 in case of atmosphere-land surface wing. The atmosphere-ocean interactions were already developed in an earlier stage of preparing the targeted coupled modeling system (Kyeongok, 2005). Our focus now on will be on the development of the atmosphere-land surface wing, and on the combination of both wings into a comprehensive coupled model for atmosphere, land surface, hydrology, ocean waves, and ocean currents for mesoscale water, energy, and material circulation.

Atmosphere-Land Surface Wing: The interaction within the atmosphere-land surface wing is briefly shown in Figure. (1) The momentum, energy, and water exchanges between the atmosphere and land surface are considered completely, while only the water exchange is treated in the interaction between the land surface and the hydrology. MM5 sends the surface layer variables: air pressure, solar radiation, long wave radiation, precipitation, horizontal wind speed components, and humidity to SOLVEG2 at every time step, SOLVEG2 calculation initiates and sends its results to MM5: skin temperature, heat fluxes, vapor flux, and surface albedo. MM5 receives theses values in the next time step and uses them as the surface boundary conditions in the planetary boundary layer (PBL) processes. MM5 sends precipitation, temperature, and wind speed to the hydrological model HSPF in a one way interaction process. SOLVEG2 sends interception, evaporation, and transpiration losses to HSPF in a one way interaction. HSPF calculations initiate, but without feed back to neither MM5 nor SOLVEG2.

Atmosphere-Ocean Wing: The interaction within the atmosphere-ocean wing was previously developed in an earlier stage of preparing ALHOM (Kyeongok, 2005). The interactions are briefly shown in Figure. (2), the surface wind from MM5 provides the wind stresses; the wave-induced stress and the turbulence induced stress to generate wind wave in WW3, and the surface stress to generate current in POM. For the wave calculation in WW3, the surface current components and the surface elevation, which are provided from POM, are necessary as well as the wind stress. Calculated wind breaking stress and surface roughness length from WW3 are fed back to POM and MM5 respectively. POM calculates the surface current using the wind stress from MM5 and wave breaking stress from WW3. POM simulates surface water elevation using sea surface pressure from MM5. Sea surface elevation along with surface current components is provided to WW3. Although the energy and water exchanges are considered in the atmosphere-ocean interaction, only the sea surface temperature from POM is provided to MM5 as ocean surface boundary condition, (Kyeongok, 2005).

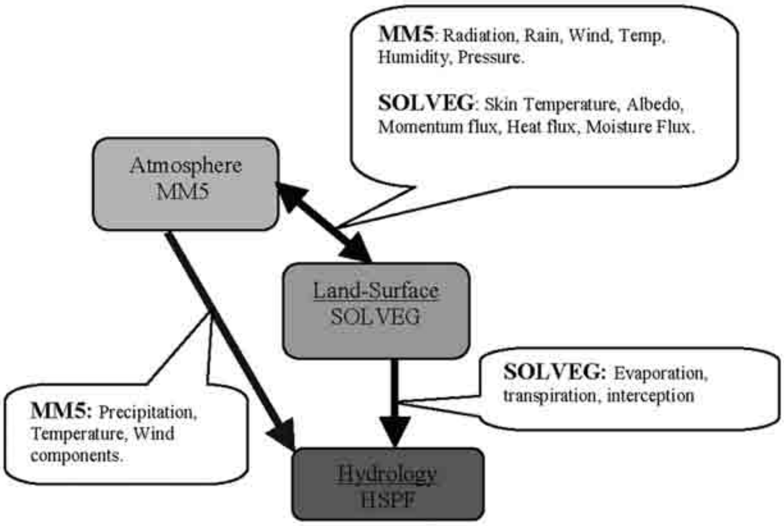

Figure (1): Data Exchange and Interactions in Coupled Atmosphere, Land Surface, and Hydrology Model for Mesoscale Water Circulation and Material Transport.

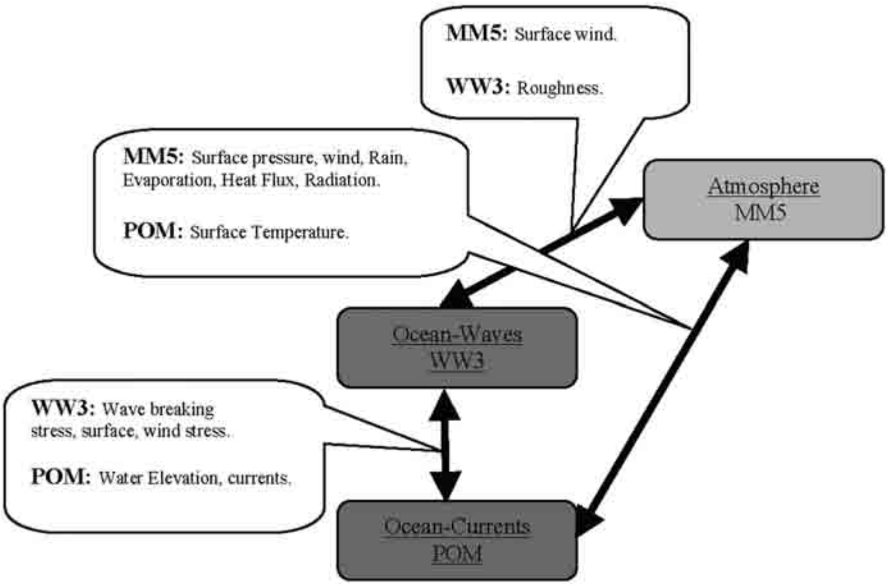

Figure (2): Data Exchange and Interactions in Coupled Atmosphere, Ocean Currents, and Ocean Waves Model for Mesoscale Water Circulation and Material Transport.

Coupled Atmosphere, Ocean, Land Surface Model: Both model wings described in the preceding sections have to be combined together to produce the targeted coupled atmosphere, hydrology, land surface, ocean waves and ocean current model, Figure (3). By combining both wings, a new interaction between HSPF and POM appeared. The river outflow, sediment, and materials are transferred from the river system to the ocean system connecting both aquatic and terrestrial systems and giving a closed loop for the hydrological cycle on the area of interest.

The coupling among the different models can be done using data exchange in parallel computing system. The Multiple Program Multiple Data (MPMD) is already performed for the atmosphere ocean wing by using a model coupler FORTRAN code, (Kyeongok, 2005). The atmosphere land surface wing will be coupled together using a similar scheme. The model coupler starts at first and it calls and controls calculation processes and the message passing interface, MPI, communication of the five models. This coupling procedure has the flexibility to use different resolution and time step for each model.

4. ALHOM within Asia Environment Simulator

Asia Environment Simulator is a running research project at Graduate School for International Development and Cooperation, Hiroshima University. The project aims to link the different components of the earth environment parameters, earth preservation measures, and economics resulting in a sustainable development plan for Asian countries. ALHOM is the main part of AES responsible for simulating the earth system environment including the atmosphere, land surface and ocean interactions.

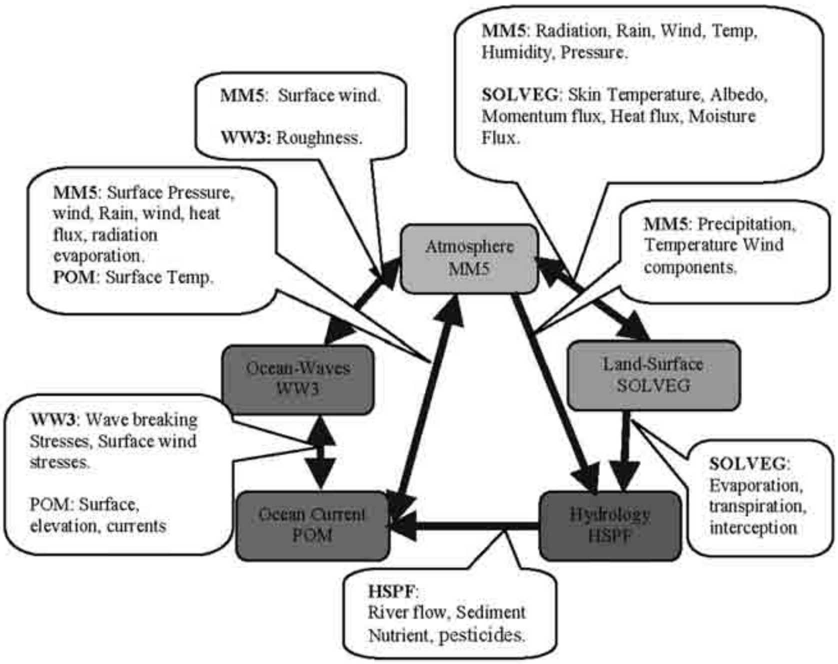

Figure (3): Data exchange and interactions in coupled Atmosphere, Land-Surface, Hydrology, Ocean waves, and Ocean Currents Model for ALHOM.

As a starting point in ALHOM application within AES, we have two case studies. First, studying of water circulation and material transport in Kapuas River basin in West Kalimantan, Indonesia, and secondly, determination of the source of eutrophication in Haji dam reservoir watershed in Hiroshima city, Japan.

Kalimantan and Kapuas River Basin: Kalimantan, the world third largest island, is the Indonesian part of the island of Borneo, Figure (4). It occupies the central and southern regions of the island. Kalimantan, with an area of 540,000 square kilometers, represents nearly 30 percent of the Indonesian land area, but less than five percent of the Indonesian population. The Kapuas River is located in West Kalimantan. At approximately 1,143 km, it is the longest river in Indonesia, and is the major river of the western portion of Borneo. The river rises in the mountains of Kapuas Hulu near the border with Malaysia, and flows west. It empties into the South China Sea about 20 km south of the city of Pontianak. The river drains the extensive Lake Sentarum area, and intermittently flooded forests.

People in Kalimantan considered the gold mining activity in Kapuas river basin as the most promising sector to support their economy, (Adijaya, and Yamashita 2004). As a result, in the last decade the illegal gold mining activities has been dramatically bloomed. In the gold mining, mercury is used as the chemical agent to perform amalgam, which facilitates the separation of gold from undesired materials. The mercury pollution from gold mining and processing plants causes the contamination of aquatic and terrestrial resources by inhalation and uptakes. Hence, Kapuas River is undergoing a severe environmental and social problem due to the poor illegal mining practices and the lack of economic alternatives.

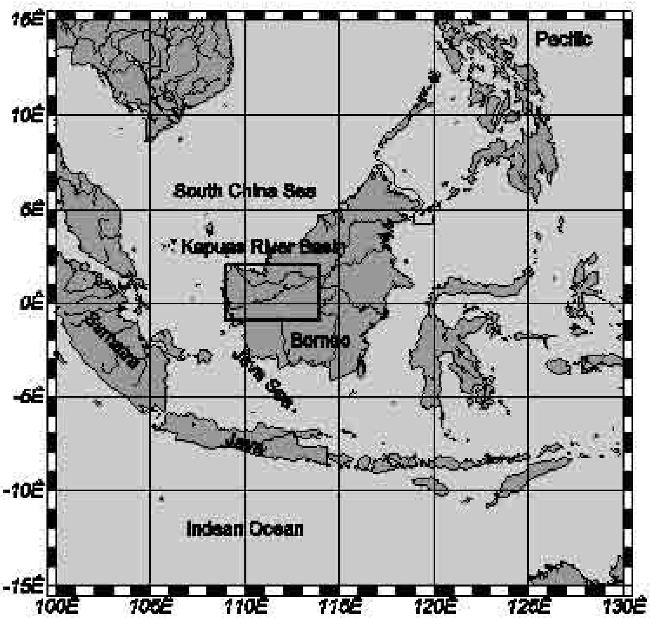

Figure (4): Location of Borneo Island and Kapuas River Basin

After the severe fire episodes during the El Niño-Southern Oscillation (ENSO) events of 1982-83, 1991 and 1994 a prolonged and extremely severe fire season occurred during the ENSO of 1997-98 in South East Asia

(Goldammer, 1999). The Indonesian province of East Kalimantan was the area worst affected by extended wildfires between late 1997 and May 1998. Figure (5) shows carbon dioxide, and NOx emissions at the most affected point in Kalimantan in the period of 1997 to 2004, (Randerson et al., 2006). It is easily noticed that a severe event occurred in the late 1997 and early 1998. In addition to the wildfires effect on the public health not only in Kalimantan, but all over south east Asian countries, a new environmental conditions is expected to appear as a results of the large scale landuse change and to abnormal amounts of fires emissions that is capable to have a regional effect on the climatic conditions in south east Asia. Not only wildfires, but also unplanned deforestation activities in the area are major cause of the large scale landuse change and the expected associated environmental effects.

The landuse change will result in modifying the water and heat exchange between the atmosphere and land surface, modifying the hydrologic budget of the large number of rivers in the area, and changing the water quantities, quality, and material content from rivers to coastal areas. The abnormal amounts of fires emissions of CO2, NOx, and SOx will result in an increase of air temperature.

ALHOM will be applied for simulating the water quantity and quality in Kapuas river basin. The atmosphere-land surface wing of the coupled model is the most important for studying the watershed system. The atmospheric fields from MM5 will be applied as forcing fields in HSPF and SOLVEG2. SOLVEG2 feeds back its moisture and heat fluxes into MM5 while sending interception, evaporation, and transpiration losses to HSPF in one way interaction. The main objective is to find the source points of mercury pollution in the illegal mining sites and proposing countermeasure scenarios to prevent or at least minimize the effect of mercury contamination of aquatic and terrestrial resources on the area. The second application of ALHOM in Kalimantan will be to assess the effect of the large scale landuse changes due to the deforestation activities and due to the wildfires events on the climate change and the possible modifications on the water heat, material, and CO2 circulation in the region. Different scenarios of the landuse change in the future and its effects on the regional environment will be tested using the new modeling system, ALHOM.

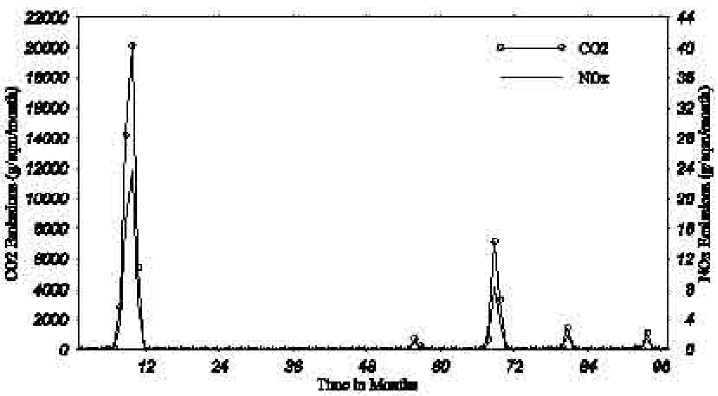

Figure (5): Maximum Fire Emissions in Kalimantan Island in (1997-2004)

Haji Dam Watershed: Haji dam is a multipurpose dam located about 30km northeast of the downtown of Hiroshima city, Japan, 34.6433N 132.6208E, Figure (6). Its construction was completed in 1974 and it was classified as a national project, (Jimenez, et al., 2001). Flood control, power generation, and water storage are its main functions, Haji dam water is one of the main resources for drinking water in Hiroshima city. The effective storage of the dam is 41.10 million m3, and it is a part of the Gono-kawa River system. The total watershed area is 307 square kilometer, Figure (7).

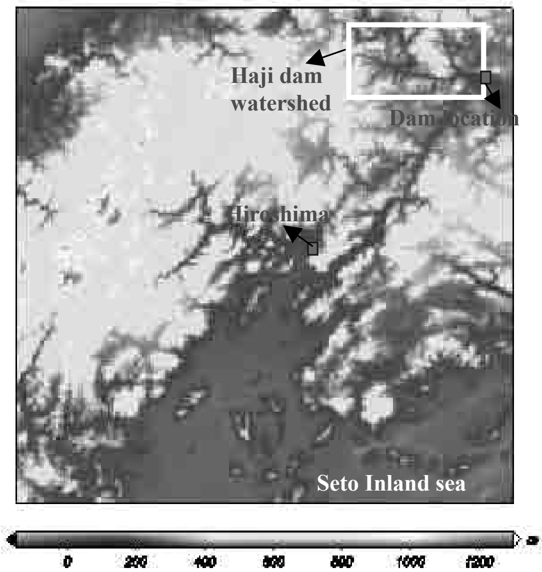

Figure (6): Haji Dam Watershed Location

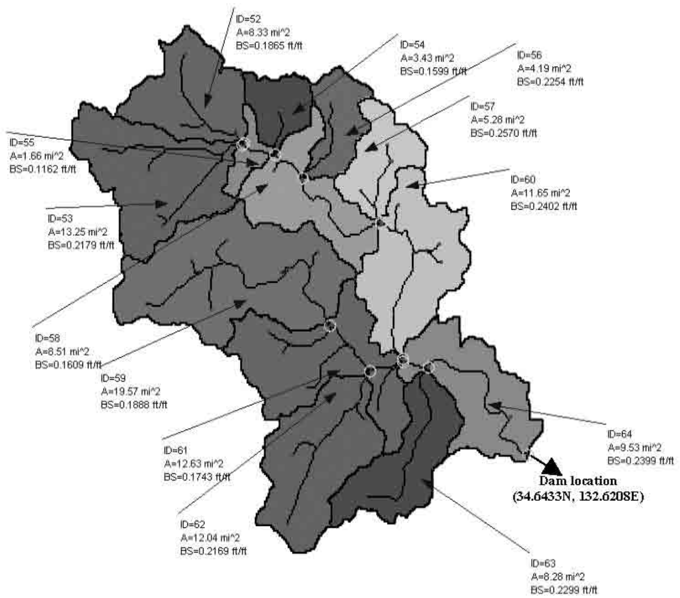

Figure (7): Haji dam watershed with its sub-watersheds (Area=307 km^2)

The most serious water quality problems found in the dam reservoir is the prolonged eutrophication due to large phosphorus loadings. Recently, the influent load, such as nutrient salts, on dam reservoir has increased as a consequence of changes in life styles and productive activities in the watershed. In Haji dam reservoir, eutrophication caused by the massive proliferation of algae has effected the utilization of the water and the recreational use in the dam reservoir.

Eutrophication of dam reservoirs occurs when the quantity of nutrient salts flowing into reservoirs increases, and if the temperature, sunlight, and other conditions are suitable in water areas such as dam reservoirs where water is retained longer than in natural rivers, massive proliferation of algae etc. occurs, causing the growth of water bloom. Consequently, measures to deal with this problem are categorized as follows: measures at the sources of load in the watershed, measures in the influent river of the dam reservoir, and measures in the dam reservoir. The most effective way to reduce the nutrient salt load that causes massive proliferation of algae is to introduce measures to reduce the load from the watershed itself, and here comes the role of ALHOM.

ALHOM will be applied for simulating the water quantity and quality in Haji dam watershed. The main objective is to find the sources of the high loads of nutrients and phosphorus within the watershed. ALHOM is capable of simulating the surface runoff and water quality parameters within the watershed and within the stream network and water and material circulation in the reservoir considering the interaction among water, land surface, and the atmosphere. The simulation results from ALHOM will be verified by runoff and water quality data collected at different stations in Haji dam watershed. The simulation results are expected to identify the eutrophication sources and to assess the applicability of the different scenarios proposed as countermeasures of the eutrophication in Haji dam reservoir.

5. Conclusions

ALHOM is an atmosphere, land surface, hydrology, ocean waves, and ocean current coupled model system that include the atmosphere land surface interactions and atmosphere ocean interactions. The models used in this system are the non-hydrostatic atmospheric model (MM5), Multi-layer land surface model (SOLVEG2), hydrological simulation program FORTRAN (HSPF), the third-generation ocean wave model of NOAA (WAVE WATCH III), and the Princeton Ocean Model (POM). Asia Environment Simulator is a running research project at Graduate School for International Development and Cooperation, Hiroshima University. The project aims to link the different components of the earth environment parameters, earth preservation measures, and economics resulting in a sustainable development plan for Asian countries.

ALHOM will be applied for simulating the water quantity and quality in Kapuas river basin to find the source points of mercury pollution in the illegal mining sites and proposing countermeasure scenarios to minimize the effect of mercury contamination of aquatic and terrestrial resources. The second application of ALHOM in Kalimantan will be to assess the effect of the large scale landuse changes due to the deforestation activities and due to the wildfires events on the climate change and the possible modifications on the water heat, material, and CO2 circulation in the region. ALHOM will be applied for simulating the water quantity and quality in Haji dam watershed to find the sources of the high loads of nutrients and phosphorus within the watershed. The simulation results are expected to identify the eutrophication sources and to assess the applicability of the different scenarios proposed as countermeasures of the eutrophication in Haji dam reservoir.

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