Upsetting the balance in the Mahakam delta: Past, present and future impacts of sea-level rise, climate change, upstream controls and human intervention on sediment and mangrove dynamics.

Acronym: MAHAKAM (www.eastkalimantan.org)

Prof. Dr. Salomon B. Kroonenberg - Delft University of Technology - s.b.kroonenberg@tudelft.nl
Prof. Dr. H.H.T. Prins - Resource Ecology Group - Wageningen University - herbert.prins@wur.nl
Dr. Jajang Sukarna - Geological Research and Development Centre jajang sukarna@hotmail.com; jajang sukarna@grdc.esdm.go.id
Prof. Dr. Wawan Kustiawan - Faculty of Forestry - Mulawarman University Samarinda - lemlit_unmul@yahoo.com

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Summary
More than 70% of the terrigenous sediment entering the world oceans comes through river deltas in southern Asia and Oceania. The sedimentary and ecological balance in deltas is delicate, however. Increased sediment supply through soil erosion upstream may lead to delta progradation, but construction of storage lakes upstream has the opposite effect. Subsidence in the delta by tectonic processes or groundwater subtraction and sea-level rise triggered by global warming may also lead to increased flooding. Ecosystems in deltas and elsewhere, driven by non-linear processes, can be exploited until a certain threshold level is reached after which the ecosystem changes from a stable productive to another stable, but unproductive state. Such changes can be sudden and unpredictable, and often very difficult to reverse. Governance systems should aim at preventing the system to leave its productive state.

The Mahakam delta is a textbook example of a mixed fluvial-tidal delta. Past and present sediment dynamics show an almost perfect separation between fluvial and tidal sediment pathways. Mangrove ecosystems in the delta play a particularly important role. Mangroves slow down tidal flow, stabilize tidal channels and attenuate wave energy. Mangroves trap sediment, enhancing the space available for expansion of the population, but ultimately the mud surface grows above mean high tide and mangrove is replaced by other communities. Also here the balance between construction and destruction is delicate. Mangrove vegetation along the Kalimantan coast has been able to cope with sea-level rise during the last 5000 years, but human intervention is now rapidly changing the picture.

In the Mahakam delta up to 70% of the mangroves were converted to shrimp-ponds between 1980 and 2000. In an ecological sense, this is a dramatic state change, and now that some of the oldest ponds in the delta are currently being abandoned because of deteriorating conditions, it is questionable whether the alternative stable state of the mangrove ecosystem can be restored.

The cluster aims to understand the integrated impact of human interference and natural processes such as sea-level rise, climate change and ecological changes on the Mahakam delta in different time scales. The research cluster focuses on the ongoing deterioration and destruction of the mangrove ecosystem and identifies specific indicators of such imminent changes as a tool for ecosystem managers. The cluster
contains the following components WP1 studies the balance between fluvial and tidal processes during the last 5000 years of postglacial sea-level rise. WP2 studies the same balance for the last 50 years using remote sensing data, focusing on spectral characteristics of suspended sediment plumes. WP3 studies the record of marine terrestrial changes for the last 200 years using annual growth increments in molluscs and radionuclide dated shallow sediment cores. WP4 studies water and sediment distribution at lowland river junctions in the upstream Kutei lakes, crucial for the functioning of the delta itself; WP5 studies the hydraulic geometry of tidal channels in the delta. WP6 monitors stress in mangrove canopies as a result of natural and anthropogenic disturbance using hyperspectral techniques. WP8 studies the conflicts of interest between the main stakeholders and the relevant property rights regimes in the Mahakam delta and the (socio-legal) requirements for sustainable coastal management in the context of decentralisation.

The cluster as a whole will provide a comprehensive tool that enables spatially explicit modelling of past changes in millennial to annual time scales, and is capable to visualise scenarios for future functioning of the delta under different values for external controls, on time scales relevant both for the present population and for future generations. The impact of good governance in environmental management will be assessed by comparing the role of governance in East Kalimantan with that of Queensland, Australia.

Deltas are among the most diverse landforms on earth. They greatly differ from each other in hydrology, morphology, geographical and tectonic setting, age, sediment characteristics, compaction and subsidence, onshore- and offshore gradient, bifurcation rate, delta-front length, water density contrast, impact of river outflow, wave processes and tide, three-dimensional sedimentary structure. Although in an empirical way we understand the rationale behind this variability, predicting the quantitative impact of changes in any of the forcing factors such as water and sediment discharge, climate, sea-level change and human interference has proven exceedingly difficult so far. The sedimentary and ecological balance in deltas is delicate. Increased sediment supply through soil erosion upstream may lead to delta progradation, but construction of storage lakes upstream has the opposite effect (Syvitski et al., 2005). Three-dimensional modelling of delta hydrology, morphology and sedimentary architecture is still in its infancy, and requires consideration of a whole range in time scales, ranging from daily (tides), annual (monsoons), decadal (El Niño climatic effects) and centennial and millennial (post-glacial sea-level rise) time scales.

More than 70% of the terrigenous sediment entering the world oceans comes from rivers in southern Asia and Oceania, including also the Mahakam river (Milliman and Meade, 1983; Nummedal et al., 2003). The Mahakam delta is a textbook example of a mixed fluvial-tidal delta (Galloway, 1975, Allen & Chambers, 1998). It has not only the classic fanlike shape of a delta onshore, but also the offshore bathymetry shows a very regular bulge form, largely undeformed by erosional processes or slump scars (Roberts & Sydow, 2003, Darlan et al., 2004). The Mahakam delta has been able to prograde in spite of rapid post-glacial sea-level rise during the last 5000 years (Storms et al., 2005). Past and present-day sediment dynamics show an almost perfect separation between fluvial and tidal sediment pathways (Budhiman, 2004). Fluvial channels bring sandy-clayey sediments seawards, tides redistribute the muddy part of the sediments again landwards in tidal channels virtually unconnected with fluvial distributaries (Storms et al., 2005). On a smaller (e.g. ENSO, monsoonal) time scale, subtle fluctuations in the balance between terrestrial and marine influences are discernable in annual growth increments in molluscs in the Nypa zone in the delta (Troelstra et al, 2003). The Kutai Peatlands further upstream (Hope et al., 2005) play a crucial role in the functioning of the delta, as they effectively buffer all peaks in water and sediment discharge, and prevent annual flooding of the interfluvies between the delta distributaries.
Deltas are also the most important sites in the world for wetland biodiversity (Nijland, 1998). Mangrove vegetation and its associated ecosystems play a particularly important role in the Mahakam delta. Mangroves slow down tidal flow, stabilise tidal channels and attenuate wave energy (Augustinus, 1995; Furukawa et al., 1997; Mazda et al., 1997; Winterwerp et al., 2005). To some extent mangroves make and break their living conditions themselves: they trap sediment, enhancing the space available for expansion of the population. At the same time, if sediment trapping continues, the mud surface grows above mean high tide and mangrove is replaced by other communities. Also here the balance between construction and destruction is delicate. Mangrove vegetation along the Kalimantan coast has been able to cope with postglacial sea-level rise during the last 5000 years (Yulianto et al., 2003), but human intervention is now rapidly changing the picture. Man-made degradation may easily tip the delicate balance between the different processes active in the delta into unwanted directions, and it is of utmost importance to be able to forecast the consequences.

The Mahakam delta was a pristine delta covered with primeval mangrove forest until twenty years ago, but between 1980 and 2000 up to 70% of the mangroves were converted to shrimp ponds. This conversion has had large consequences for both sediment and ecosystem dynamics. Some of the oldest ponds in the delta are currently being abandoned because of deteriorating conditions, and the restoration of mangrove is being considered there, with uncertain perspectives.

Most ecosystems are looked at with a myopic view. Specialists study ‘their’ systems with an ever increasing detail, and define ever-smaller pieces of the Earth’s surface as an ecosystem to be studied with endless precision and an infinite number of facets. Yet, ecosystems are nested and linked, but most ecosystem studies ignore nutrient fluxes between systems and thus the potential cascading effects from a higher scale level to a lower one. In a recent Science paper Rietkerk et al. (2004) hypothesised that spatial self organisation (e.g., patterning and patchiness) can be used as an indicator of imminent ecosystem catastrophe in terrestrial systems. If that is indeed the case, it should be possible to identify processes at a detailed, eco-physiological scale that induce pattern formation, also in non-terrestrial systems. We hypothesize that indicators of pending ecosystem collapse can be identified at ecological and the eco-physiological levels, and that they can serve as early signs of collapse; this may help taking counter-measures in time.

Neither local people nor local industries are forewarned when an ecosystem nears collapse. No indicators exist that can predict whether and when anthropogenic stress induce sudden, irreversible shifts from healthy to degraded ecosystem states. Ever reduced densities of harvested products make local resource extraction cumbersome, but this is generally not seen as an indicator of system collapse. Local stakeholders will therefore literally not see a reason to cooperate with either government or upstream stakeholders. Devolution of authority to the appropriate level, aligning of incentives, or co-management (see the “Ecosystem Approach” of the CBD1) are impossible in this insidious context.

Managers and government agencies dislike micro-management, and economists have pointed out that profits at a small-scale level can be more than offset by societal loss at an aggregated level. Individual local and indigenous people cannot see potential catastrophes lurking simply because the states-and-transitions that govern ecosystem processes (Scheffer et al., 2001) operate at another, more detailed scale level. The export-driven upstream, local resource use is based on economic policies that do not include costs that are incurred in downstream ecosystems. Subsidies and other governmental support provided to such industries often lead to catastrophic changes in local and linked ecosystems. Decentralization has led to growing interactions between state actors and civic and commercial actors,
ultimately resulting in ‘multi-actor governance’, and ‘multi-level governance’ (Kersbergen & Waarden, 2001). We hypothesize that, if the optimal scale of governance matches the one of ecosystem functioning, there is a maximum potential for developing tools to internalise externalities, for aligning extraction incentives, and possibly for co-management structures to develop prior to ecosystem collapse. We furthermore evaluate the costs and benefits of (good) governance, through cooperation with a similar programme run by CSIRO in tropical Queensland (Australia).

Objectives
The objective of the cluster is to study the impact of external forcing factors such as sea-level rise, climate change, upstream sediment, as well as human interference on past, present and future development of the Mahakam delta in different time scales. We will pay special attention to determine the resilience and restoration potentials of mangrove ecosystems and develop models forecasting catastrophic changes in coastal ecosystems, and understand issues of governance across scales, and how ecosystem nestedness and governance nestedness can be linked. The cluster will use the Delft3D model (Delft Hydraulics) as a tool to integrate data into scenarios and will extend it from its present decadal time scale limitation to millennial time scales, enabling to better predict future changes in the Mahakam delta.

Multidisciplinary composition of cluster

- Simulating the Holocene development of the mixed tidal-fluvial Mahakam delta (TUDelft and GRDC Bandung)
- Quantifying sediment fluxes in the Mahakam Delta using remote sensing (ITC and LAPAN)
- Impact of decadal climatic cycles on sedimentation in the modern Mahakam Delta, Indonesia (TUDelft and GRDC Bandung)
- Water and sediment distribution at lowland river junctions: the Mahakam Lakes region (WUR and LIPI Limnology)
- Discharge regimes, morphometry and tides in the Mahakam delta channel network (WUR and ITB)
- Searching the brink: assessing indicators for system change through hyper-spectral analyses of mangrove systems (ITC and Mulawarman University)
- Stakeholder interests and potential for sustainable coastal management through rights regulation practices in the context of decentralisation in the Mahakam Delta, East Kalimantan (Leiden University and Padjadjaran University)

Simulating the Holocene development of the mixed tidal-fluvial Mahakam delta.
Prof. Dr. Salomon B. Kroonenberg - Delft University of Technology - s.b.kroonenberg@ta.tudelft.nl
Dr. Jajang Sukarna - Geological Research and Development Centre - jajangsukarna@hotmail.com; jajangsukarna@grdc.esdm.go.id

Existing models predicting the behaviour and stratigraphy of large delta systems are of two kinds:

- morphodynamic models such as Delft3D that predict the behaviour of sediment in distributaries and along delta fronts, with usually great hydraulic accuracy but with limited time depth (decades at most) and without a vertical dimension that predicts how 3-D sediment bodies are being formed; and
- stratigraphic models such as SEDFLUX and Deltasim, that simulate the building of delta architecture as a function of sea-level change, subsidence and sediment supply in geological time
scales, but with limited hydraulic accuracy, usually 2-D at most, and not allowing for the inclusion of essential subenvironments of river-dominated, wave-dominated and tide-dominated deltas. Yet, a full understanding of the impact of future sea-level rise and changing sediment input on large delta systems requires integration of both approaches into a single model. In this proposal we intend to bridge the gap for mixed fluvial tidal deltas, and test the enhanced model against a classical example: the Mahakam delta.

The late-Holocene Mahakam delta, located along the tropical eastern shore of Kalimantan, Indonesia, prograded during the past 5000 years. This has resulted in the development of a distinct network of distributary and tidal channels. Local wave action is low and the Mahakam river discharge is characterized by absence of any flood surges, allegedly due to the presence of large upstream lakes that regulate discharge. The tides are semi-diurnal and the tidal amplitude ranges from < 1 m in neap tides to 3 m during spring tides. These specific regional settings provide an excellent opportunity to focus specifically on the effects of tide on distributary deposition during the Holocene without the complicating depositional effects of flood surges, wave action and channel switching.

To that end, we will study the interaction between tidal and fluvial processes in distributary channels, and how their depositional patterns and stratal signatures changed as a result of sea-level rise during the late Holocene. Shallow geophysical surveys, corings, and radiometric datings will be used to construct a conceptual sedimentary model describing the evolution of mixed tide-fluvial processes in time and space. This concept will be used for the further development of DELFT3D enhancing its capabilities for modelling large time scale processes and should result in simulating long term delta evolution of the Mahakam delta.

**Quantifying sediment fluxes in the Mahakam Delta using remote sensing**

Dr. Zoltán Vekerdy - International Institute for Geo-Information Science and Earth Observation - vekerdy@itc.nl
Dr. Orbita Roswintiarti - National Institute of Aeronautics and Space – LAPAN - Remote Sensing Application and Technology Development Center - oroswin@indo.net.id

Sedimentation processes in the Mahakam Delta are governed by the discharge and sediment transport of the Mahakam River, the tide and the coastal currents. The presence of mangroves set a natural boundary condition for theses complex processes, and the human activities (especially by converting mangroves into fish ponds) express the socio-economic pressure on the delta. Remote sensing allows to monitor sedimentation processes in time and space as was demonstrated in the pilot phase of the East Kalimantan Programme. The main objective of this proposal is to quantify sediment fluxes by fluvial and tidal processes in the Mahakam delta over the last 50 years using data from aerial photographs, optical and microwave remote sensing techniques, in combination with field data on sediment concentration in the delta distributaries. In this way a better reconstruction of delta development in the last fifty years can be obtained, and future trends may be predicted.

Only optical remote sensing allows the direct study of total suspended sediments (TSM) in the water, but this tool fails in case of cloud cover. Microwaves penetrate clouds, but do not penetrate the water body. Therefore, an innovative synergy of the different remote sensing image types with ancillary data is planned for the reconstruction of the history of delta development. In the cloudy wet season, when most of the sediment is produced from the basin, indicators of sedimentation and the dynamics of the branches will be analysed based on microwave images, in combination with the results of sediment yield studies by in-situ measurements, modelling and catchment analysis.
Imaging spectrometry using bio-optical models is feasible for mapping TSM in the cloud-free periods. Spectra of water-leaving radiance are of importance to test bio-optical model closure. Therefore field measurements, research and laboratory analyses are needed. Based on the determination of the inherent optical properties of the water constituents a bio-optical model will be calibrated. Model inversion techniques will be used to obtain water quality parameters from remote sensing images in order to monitor water quality.

The results will allow the analysis of changes attributable both to natural processes (e.g. climate change) and human interactions.

**Impact of decadal climatic cycles on sedimentation in the modern Mahakam Delta, Indonesia**

Prof. Dr. Salomon B. Kroonenberg - Delft University of Technology - s.b.kroonenberg@ta.tudelft.nl
Dr. Jajang Sukarna - Geological Research and Development Centre - jajangsukarna@hotmail.com; jajangsukarna@grdc.esdm.go.id

The project aims to reconstruct changes in sedimentation and geochemical environment in the Mahakam Delta in the last 200 years, on the basis of

- biogeochemistry of long-living molluscs, especially *Polymesoda*, and
- granulometry, geochemistry and paleoecology of 210Pb-dated cores from the different subtidal sedimentary environments.

The geochemical signal preserved in the shells of molluscs is an exciting new tool to study rapid climate/environmental change. The laser ablation and microdrill technique, coupled with state of the art geochemical analyses (stable oxygen/carbon isotopes, trace elements, ICP-MS, ICP-AES) opens a detailed record of precipitation/evaporation variability, environmental change, and run-off patterns which can be directly related to monsoonal, ENSO variability and human impact. Sampling molluscs along fresh/brackish-water transects in the Mahakam area enables us to link the effects of specific ENSO cycles and anthropogenic induced environmental change. Preliminary geochemical analysis of the shell of the brackish water species *Polymesoda* showed a detailed climatic/environmental archive extending ~120 years back. Systematic variations in Sr/Ba ratio suggest important variations in the influence of marine and terrestrial processes during its growth, possibly caused by ENSO and/or human interference. Now we propose to carry out a monitor program to calibrate our data, to complete our analyses on both fossil and recent brackish/freshwater material and to achieve a correlation with other biota such as corals. ENSO variability over the past centennia will be studied using museum material.

We hypothesize that the changes in Sr/Ba ratio in the molluscs reflect changes in the delicate balance between fluvial and tidal processes in the delta. We want to test this hypothesis by dating cores from the different sedimentary environments with 210Pb and other radionuclides, and study granulometry, geochemistry (including Sr/Ba as well) and paleoecology (palynology) in those parts of the cores that according to the radionuclide data have been deposited in the last 200 years. Special attention will be given to the distribution and thickness of sand-mud couplets thought to represent neapspring tide cycles. These data will be compared with data on delta development during the last 5000 years and from the last 50 years from remote sensing imagery and will be used to refine the scenarios for future development of the delta using the Delft3D model.

**Water and sediment distribution at lowland river junctions: the Mahakam Lakes region**
River junctions are nodal points where river channels confluence or diverge. Over the past decades much research has been focused on channel junctions in braided rivers. These are morphologically highly dynamic alluvial environments, which occur typically in steep upstream river reaches. Physical analyses of channel junctions in lowland rivers are relatively few. Especially bifurcation processes controlling the water and sediment distribution over lowland distributaries are not well understood. The distribution function of river bifurcations is captured in nodal point relations used for one-dimensional morphodynamical models, which relate water and sediment flow rates. These relations can be used to analyze the stability of a bifurcation, which can be defined as the likeliness that both the downstream branches remain open. The present objective is to include more physical processes in existing nodal point relations, and to analyse the effect of local morphodynamic changes on the stability of a bifurcation.

It is proposed to analyze river junctions in the Mahakam Lakes region, which is an extremely flat area that seldom reaches 10 m above mean sealevel. As a result of the small bed level gradient the Mahakam River is meandering with a tendency to anastomose. On opposite sides the Mahakam is connected to about 30 shallow lakes, which modulate the water discharge. Although no evidence exists to date, it is assumed that the Mahakam Lakes alternately feed and drain the Mahakam, preventing extreme floods or low flow conditions. Accordingly, river junctions may alternately be regarded as a bifurcation (divergence) and a confluence. The functioning of the channel junctions in the Mahakam Lake region will be analysed ultimately aiming to establish the vulnerability of the hydraulic connection between the lakes and the Mahakam River, which discharges into the economically important Mahakam Delta.

The proposed methods include field measurements, satellite radar remote sensing for observation of water surface elevation and width, theoretical analysis and morphodynamic modelling. The proposed field campaign encompasses bathymetric surveys, installation of water level gauges and ADCP measurements of flow and sediment transport. A two-dimensional morphodynamic model will be used after calibration to simulate morphometric changes of the bifurcations between the Mahakam river and the connecting channels to the three main lakes. The nodal point relations will be used in the network model setup in WP10 of the research cluster.

Discharge regimes, morphometry and tides in the Mahakam delta channel network (Hoitink, Gadis)
Dr. A.J.F. Hoitink - Hydrology and Quantitative Water Management Group - Wageningen University - ton.hoitink@wur.nl
Dr. Gadis Sri Haryani - Research Centre for Limnology - Indonesian Institute of Science - gadis@limnologi.lipi.go.id

Relations between river discharge and channel characteristics such as mean depth, surface width and surface slope are known as the hydraulic geometry (HG). The so-called at-site HG concerns channel properties at an individual location, whereas the downstream HG relates channel properties from different downstream locations through some characteristic discharge of constant frequency of exceedance (e.g. bankfull discharge). Tidal rivers are intrinsically more complex than alluvial rivers, since the river discharge interacts nonlinearly with the tide. The present proposal is to formulate new HG relations that can be applied to the freshwater part of a tidal river network. In specific, the objective is to establish and explain at-site and downstream HG relations between discharge, tidal and morphometric
variables in the Mahakam delta distributary system, which can be regarded as a lowland tidal river network. The proposed methods include field measurements, remote sensing for observation of water surface width and height, and hydrodynamic modelling. The field campaign encompasses bathymetric surveys, installation of water level gauges, ADCP discharge measurements, sediment sampling and characterisation of riparian vegetation. Discharges obtained from ADCP surveying are expected to be function of mean depth and longitudinal surface slope from level gauging. A hydrodynamic model will be used after calibration to establish downstream HG relations, and to investigate the physical mechanisms that result in the HG relations found.

The relations between sediment and freshwater discharges, tides and morphometry in the Mahakam delta will allow to evaluate and anticipate effects of sealevel rise, climate change and ongoing human interference. Issues relevation for society include the risk of flooding and navigability of channel sections. Appropriate scenarios will be setup in collaboration with the other research groups in the cluster. Understanding the hydraulics of the delta is important to each of the other research groups within the cluster, as the alluvial flows in the tributaries under the influence of tides are the principal agents of sediment dispersal. The remote sensing component in this proposal is based on PALSAR L-band radar aboard the ALOS satellite, which covers peninsular Southeast Asia. The use of radar water surface measurements in hydraulic research broadens the application domain of ALOS satellite.

Searching the brink: assessing indicators for system change through hyper-spectral analyses of mangrove systems

Prof. Dr. A.K.Skidmore – ITC - skidmore@itc.nl
Prof. Dr. Wawan Kustiawan - Faculty of Forestry - Mulawarman University Samarinda - lemlit_unmul@yahoo.com

Mangroves provide ecosystem services and economic values in many tropical coastlines. The mangroves of East Kalimantan are threatened by two anthropogenic disturbances. Firstly, upstream deforestation causes a washing out of nutrients and soils, which have mainly negative ecological effects on downstream mangrove communities. Secondly, the building of shrimp ponds results both in a loss and fragmentation of mangrove forests, and in a subsequent increase of pollution. Although mangrove communities appear to be resilient to low and moderate disturbances, the transition from an undegraded to a degraded state can be very fast. Such transitions from a desirable to an undesirable state are difficult to predict and show the hallmarks of an associated hysteresis effect. Since degraded states are stable, they are difficult or even impossible to restore. Therefore, finding indicators to detect early signs of degradation may help taking counter measures in time to prevent further degradation of the desirable state past the point of no return.

A desirable state looses its resilience when the associated feed-back mechanisms fail to operate. This is when e.g., closed mangrove canopies form open patches, recruitment lags behind, and seedlings fail to establish themselves. We hypothesize that early signs of disturbance-induced stress in mangrove plants may be found in changes in the chemical composition of foliage. We furthermore hypothesize that relevant leaf physiological changes can be studied with hyperspectral remote sensing.

Our objectives are:

- To detect hyperspectral wavebands sensitive to changes in chemical levels in mangrove foliage that are linked to disturbance-induced plant stress.
• To understand how the chemical composition of mangrove foliage responds to deforestation-induced sediment increase, and shrimp farming effluents, i.e. separate from natural fluctuations in the environment.
• To test early changes in disturbance-induced chemical composition of mangrove foliage as an indicator of system change.

The research project will focus on the detection of the sediment- and shrimp-farm-induced changes in canopy cover and leaf physiology in mangrove stands in the Mahakam delta (disturbed) and the results will be compared with other estuaries with less (Balikpapan bay) or no disturbance (Berau delta), supported by experiments in the field (Mahakam) and in the Netherlands. An important component will be the use of hyperspectral remote sensing together with artificial neural networks, which have recently been applied in the retrieval of canopy variables and for classification routines. Results will be crosslinked with peer projects in the research cluster.

Stakeholder interests and potential for sustainable coastal management through rights regulation practices in the context of decentralisation in the Mahakam Delta, East Kalimantan
Dr. G.A. Persoon - Institute of Environmental Sciences (CML) persoon@cml.leidenuniv.nl
Prof. Dr. J.M. Otto - Van Vollenhoven Instituut - Leiden University - vollenhoven@law.leidenuniv.nl
Prof.dr. H. Martodirdjo - PPSDAL Universitas Padjadjaran
Dr. Johan Iskandar - PPSDAL Universitas Padjadjaran,

Inland deforestation and aquaculture (shrimp farming) in the Mahakam delta has resulted in loss of productive functions of the coastal ecosystem. Fish catches and productivity of shrimp farms are declining, which affect the livelihood of coastal users. Unregulated access to and lack of ownership over resources further enhances resource degradation. Decentralisation forms the context in which developments in the coastal zone take place, while responsibilities for management under the new legal framework sometimes are unclear and laws largely undefined.

Within the research cluster this project tries to answer the following question:

What are the main conflicts of interests between the main stakeholders and the relevant property rights regimes in the Mahakam delta (East Kalimantan) related to forestry, shrimp farming and fishing and what are the (socio-legal) requirements in terms of property rights arrangements for sustainable coastal management in the context of decentralisation?

To answer this question the research will focus on the main actors involved in shrimp farming and forestry (activities that have the most detrimental effect on the environment) and the potential role they could play in the conservation of the Mahakam delta. The researchers will study the current legal and extra-legal property rights arrangements and the rules determining access to natural resources relevant to the situation of the Mahakam Delta. Special focus will be on the role legal processes and legal institutions play in dealing with the many conflicting interests in the region, before and after the decentralisation law of 1999.

The study of legal aspects of sustainable management draws on the interdisciplinary theory developed in the framework of neo-law and development studies. The project will define how and under what conditions law can be made more effective, in particular those elements of the legal system that are associated with the rule of law.
The managerial aspects of resource use are inspired by theories of co-management. Comanagement is considered to represent a more democratic, equitable and efficient governance system as it involves participatory and collaborative processes of decision-making and power sharing. These theories have so far paid relatively little attention to socio-legal issues, in a context of complex interests. This research helps to further expand the theories on common property, co-management and sustainable coastal management by integrating them with socio-legal theories on how to make law more effective when trying to implement the former theories in practice.