Hydrol. Earth Syst. Sci. Discuss., 11, 2825–2874, 2014
www.hydrol-earth-syst-sci-discuss.net/11/2825/2014/
doi:10.5194/hessd-11-2825-2014

Hydrology and Earth System Sciences
Open Access
Discussions

Satellite radar altimetry for monitoring small river and lakes in Indonesia

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Received: 17 January 2014 – Accepted: 21 February 2014 – Published: 10 March 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Remote sensing and satellite geodetic observations are capable for hydrologic monitoring of freshwater resources. For the case of satellite radar altimetry, limited temporal resolutions (e.g., satellite revisit period) prohibit the use of this method for a short (< weekly) interval monitoring of water level or discharge. On the other hand, the current satellite radar altimeter footprints limit the water level measurement for rivers wider than 1 km. Some studies indeed reported successful retrieval of water level for small-size rivers as narrow as 80 m; however, the processing of current satellite altimetry signals for small water bodies to retrieve accurate water levels, remains challenging.

To address this scientific challenge, this study tries to monitor small (40–200 m width) and medium-sized (200–800 m width) rivers and lakes using satellite altimetry through identification and choice of the over-water radar waveforms corresponding to the appropriately waveform-retracked water level. This study addresses the humid tropics of Southeast Asia, specifically in Indonesia, where similar studies do not yet exist and makes use Level 2 radar altimeter measurements generated by European Space Agency's (ESA's) Envisat (Environmental Satellite) mission.

This experiment proves that satellite altimetry provides a good alternative, or the only means in some regions, to measure the water level of medium-sized river (200–800 m width) and small lake (extent < 1000 km^2) in Southeast Asia humid tropic with reasonable accuracy. In addition, the procedure to choose retracked Envisat altimetry water level heights via identification or selection of standard waveform shapes for inland water is recommended and should be a standard measure especially over small rivers and lakes. This study also found that Ice-1 is not necessarily the best retracker as reported by previous studies, among the four standard waveform retracking algorithms for Envisat radar altimetry observing inland water bodies.

1 Introduction

Water level (also called stage) and discharge are essential parameters in monitoring the quantity of fresh water resources. A tremendous number of small to medium-sized rivers (defined as 40–200 m width with 10–100 $m^3 s^{-1}$ average discharge and 200–800 m width and 100–1000 $m^3 s^{-1}$ average discharge, respectively, according to Meybeck et al., 1996) around the world are poorly gauged for various reasons (Alsdorf and Lettenmaier, 2003). In contrast, despite the installation and operation of in-situ measurement, such permanent gauging is often considered costly and less important while the need for continuous hydrological monitoring of small rivers is increasing. Therefore, it is a scientific and social challenge to provide reliable water level and discharge information given the absence of continuously operating in-situ measurement efforts.

Space geodetic and remote sensing from space has proven to be one viable source of observation to complement or replace field measured data, which is lacking for many parts of the world, in efforts to monitor watershed hydrology. Copious research has demonstrated the capability of remotely-sensed data to provide continuous estimation of a number of hydrological variables (Tang et al., 2009). A number of initiatives to develop global rivers' and lakes' water level database exist to date, but very limited if not none of them count small to medium-sized rivers and lakes in the humid tropics.

Satellite altimetry missions were introduced to support studies of oceanographic phenomenon (Brown and Cheney, 1983) even though at the later stage scientists found a way to study large inland water bodies (Fu and Cazenave, 2001). Numerous efforts had been made since a couple decades ago to utilize early satellite altimetry missions (Wingham and Rapley, 1987; Koblinsky et al., 1993; Morris and Gill, 1994), as well as the recent satellite altimetry missions (e.g. Birkett, 1998; Benveniste and Defrenne, 2003; Kouraev et al., 2004; Calmant and Seyler, 2006; Frappart et al., 2006; Cretaux et al., 2011) to monitor the hydrology of large river and lake systems. However, various limitations of space geodetic observation systems hampered the advancement of hydrology studies; for example, the current radar altimeters footprints limit the

measurement into only rivers with ~ 1 km width (Birkett, 1998; Birkett et al., 2002). Even some studies present successful retrieval of water level of small-sized rivers down to ~ 100 m width (e.g. Kuo and Kao, 2011; Michailovsky et al., 2012), satellite altimetry signals processing for small water bodies still remains challenging. Therefore, even with significant improvement on the measurement accuracy, limited spatial and temporal resolutions of the current satellite altimeter missions still prevent scientist and government from relying to this method to monitor rivers.

The early use of satellite altimetry to retrieve water level of the river utilized waveform shape to match the specular characteristics, which exclusively belongs to the signals returned by the river (Koblinsky et al., 1993). Along with this principle, the development of retrackers for non-ocean studies were completed in the last decade, which includes the Offset Center of Gravity (OCOG) (Wingham et al., 1986), also known as Ice-1, volume scattering retracker (Davis, 1993), Sea Ice retracker (Laxon, 1994), NASA β-retracker (Zwally, 1996), surface/threshold retracker (Davis, 1997) and Ice-2 (Legresy and Remy, 1997).

The Offset Center of Gravity (OCOG) or Ice-1 (Wingham et al., 1986) is a simple but robust retracker, which requires only the statistics of the waveform samples and does not require any model; hence it is later called model-free retracker (Bamber, 1994). This algorithm, which later called as Ice-1, was still carried out as one standard retracker for Envisat radar altimeter sensor ntil Envisat was decommissioned in June 2012 and claimed the best available retracker for medium to large-sized rivers (Frappart et al., 2006). Some notable recent developments of inland water retracking methods include threshold retracker (Davis, 1997) and its improvements (e.g. Lee, 2008; Bao et al., 2009), sub-waveform analysis (e.g. Hwang et al., 2006 and Fenoglio-Marc et al., 2009) and sub-waveform filtering and track offset correction (Tseng et al., 2012).

After all, there is no "one size fits all" method for satellite altimetry waveform retracking available up to now, especially those devoted to measuring near-real time water level of small (40–200 m width) and medium-sized (200–800 m width) rivers and lakes. This led to the integration of geospatial information, remote sensing and satellite altimetry measurement to monitor important water bodies and therefore, and comprises the motivation of this study. In this study, standard waveform retracking procedures (i.e. Ocean, Ice-1, Ice-2 and SeaIce for Envisat radar altimetry system) are applied to observe water level of one small river and one medium-sized river and two lakes in the humid tropics. In addition, careful spatial and waveform shape selection and outlier detection are involved to further screen out low quality data. The results are then evaluated to assess their reliability and accuracy.

2 Study area

This study takes place in Mahakam and Karangmumus Rivers (one tributary downstream of Mahakam River) in East Kalimantan, Indonesia and Lakes Matano and Towuti which are part of Malili Lakes Complex in South Sulawesi, Indonesia. The study areas oriented in Figs. 1 and 2 represent typical humid tropics in Asia with different geomorphology, climate and anthropogenic settings.

2.1 Mahakam and Karangmumus Rivers

Mahakam watershed is located between 113°40′ to 117°30′ E longitude and 1°00′ S to 1°45′ N latitude. Mahakam is its main river that stretches a length of ~ 920 km and drains an area of 77 095 km^2, which declares this river as the second longest river both in Borneo Island and the Republic of Indonesia. The river rises in the mountainous forest ranges with dramatic elevation drops in the first hundreds kilometres of the main stem, which led to the formation of rolling hills and steep slopes in the upstream part of this basin. Then forms up the Middle Mahakam Lake and Wetlands starting from the fifth hundreds kilometres of its length and transforming into the Mahakam Delta estuary in its last hundred kilometres (MacKinnon et al., 1996). In terms of the channel physical characteristics and the land use, the upstream part of Mahakam River presents narrow channel width of 40–100 m with depth varies from 5 to 10 m and slope greater than 2 %,

with forest and small patches of subsidence agricultural farms dominate the land use. The middle part presents channel width of 100–300 m, 10–24 m depth and 0.5–2 % slope, with extensive lowland and agricultural areas spread out everywhere along with country-style residential areas and vast distribution of lakes and swampy shrubs. The lower part and the Mahakam Delta present wide channel of 500–850 m width, 10–24 m depth and 0–0.5 % slope while with regard to land use, the lower sub-basin is a typical developed area with lots of residential areas, very scarce forest patches and heavily inhabited land (Estiaty et al., 2007).

Karangmumus River is a very narrow channel (3 to 45 m width), which is very important for the residents of Samarinda City in East Kalimantan. Due to poor land cover and its short distance to the ocean, this sub-watershed often experiences gradually increasing and steady high discharge during heavy rainfall. This small channel is also affected by ocean tide that intrudes through the Mahakam Delta. These factors led to the occurrence of slow-paced flood that inundated most of the residential areas two to three times a year.

2.2 Lake Matano and Lake Towuti

Lake Matano is located between 121°12′ to 121°29′ E longitude and 2°23’ to 2°34′ N latitude. This lake counts as the seventh deepest lake of the world (Herdendorf, 1982) despite its small extent (i.e. only 164 km^2). With its maximum depth of 595 m and mean water surface elevation measured at only 392 m, Lake Matano represents a cryptodepression which essentially means its bed is dropped below the mean sea level (Hehanussa and Haryani, 1999). Originated by tectonic process since 2–3 million years ago, this lake is included as one of the oldest lakes of the world and hosts endemic faunas that provide remarkable examples of ecological diversification and speciation (Cristescu et al., 2010). In terms of its geomorphology, the basins in the surrounding of Lake Matano formed by the hardness of the rocks and the softness of uplift tectonic fault that forms very limited number of alluvial plain. Regarding the bed topography, Lake Matano has two flat depressions separated by a saddle. Lake Matano drains through the Petea River into Lake Mahalona, still in the same Malili Lakes complex (Vaillant et al., 1997).

Lake Towuti is recognized as the largest tectonic lake in Indonesia (Russel and Bijaksana, 2012). Located at the downstream end of the Malili Lakes Complex, this lake covers an extent of 562 km^2 with 206 m depth, and similar to Lake Matano, also carries locally endemic fauna due to its nature as one of the ancient lakes.

3 Materials and methods

3.1 Envisat radar altimetry

This study utilizes satellite radar altimeter measurements provided by The European Space Agency (ESA)'s Envisat Radar Altimeter (RA-2). The RA-2 determines the two-way delay of radar echo from the Earth's surface to a very high precision of less than a nanosecond. In addition, it also measures the power and shape of the reflected radar pulses. The RA-2 telemetry provides averaged 18 range measurements per second (i.e. 18 Hz) which corresponds to an along-track sampling interval of $\sim$ 350 m (ESA, 2011). The averaged 18 Hz waveforms are arranged into 128 gates with 3.125 nanosecond time resolution and presents the default tracking gate at #46 (ESA, 2007). Specifically, this study uses the Envisat RA2/MWR SGDR product that contains parameters for time tagging, geo-location, output from retrackers (range, wind speed, significant wave height, etc.) at 1 Hz, plus some 18 Hz parameters such as range and orbital altitude. In addition, the RA2/MWR SGDR also contains the 18 Hz waveforms to use in the waveform shape selection procedure. The dataset covers the period of July 2002 to October 2010, corresponding to cycle 6 to 93 (ESA, 2007). Table 1 describes Envisat RA-2 pass, cycles and observation period for each study sites.

Satellite radar altimetry measures the geocentric water surface elevation with respect to the reference ellipsoid. However, due to uncertain relationship between the elevation of the field gage benchmark relative to the local vertical datum, this research

took out the mean water surface elevation measured by satellite altimetry during the period of observation and therefore consider only the water level anomaly for further processing. Water level anomaly represents the fluctuation of water level relative to its mean level during the period of observation. It is obtained by removing the mean of the water surface elevation measured by altimeter and in-situ gage. To prove the current assumption on the Ice-1 as the best retracking algorithm for inland waters (Frappart et al., 2006), this study compares the water level anomaly obtained from water surface elevation measured by the Ocean, Ice-1, Ice-2 and Sea Ice retrackers with the water level anomaly obtained from the in-situ gage measurement. Geophysical corrections (i.e. inverse barometer, sea state bias, ocean tide, polar tide, Earth tide), propagation corrections (i.e. ionospheric correction, wet tropospheric correction, dry tropospheric correction) and instrument error corrections (i.e. Doppler correction, time delay due to flight and time delay due to ground corrections and antenna center of gravity) are applied as it is described as the standard procedure to obtain Level-2 products (ESA, 2011).

3.2 Optical remote sensing and geospatial dataset

Optical remote sensing and geospatial data processing play an important role in this study, especially in the determination of physical characteristics and spatial boundary of water bodies to observe by satellite geodetic techniques. For instance, measurements of the river and lake width are carried out through (1) visual interpretation of remote sensing image, i.e. through dark-blue color reflected by the water bodies in the red-green-blue combination of band #5-4-3 on Landsat-5 and Landsat-7, or band #6-5-4 on Landsat-8, or (2) medium-scale (1 : 50 000) topographic maps released by the Indonesian Geospatial Agency.

Standard optical remote sensing data processing techniques include geometric correction, development and contrast of pseudo-natural colour composite (e.g. red-green-blue colour composite using bands 5, 4 and 3 for Landsat 5 and 7 and bands 6, 5 and 4 for recently launched Landsat 8) were applied to obtain imageries with precise position with good contrast between land and water.

Once the lake boundaries are identified, a buffer with different distances (i.e. 500 m and 1000 m for lakes) are generated and included in the spatial processing so that the altimeter measurements can be analysed based on the distance between its projected ground track to the lakeshores. As for the river, a 5 m buffer is created to reduce the contamination of land surface to the analysed waveforms.

3.3 In-situ water level data

Indonesia's Ministry of Public Works provided the datasets used for validation of water level of Mahakam River at Melak site (2002–2004) and Karangmumus River (2008–2010) while PT Vale Indonesia provides validation data for Lake Matano and Lake Towuti (2002–2012). Similar with the satellite altimetry data, the water level time series were transformed into water level anomaly by removing the mean water surface elevation during the period of observation, due to uncertain relationship between the elevations of the field gage benchmark relative to the local vertical datum.

3.4 Waveform shape analysis

The diameter of pulse-limited footprint of the Envisat RA-2 over a smooth surface is about 1.7 km (Rees, 1990; ESA 2007). Therefore, it is necessary to analyse the waveform shapes considering that the radar pulse reflected by the water surface might be influenced by other surface along with different distance from projected radar footprint to the land surface. For the lakes, 1 km distance to the lake shore should be enough consider that the radius of the Envisat footprint (half of its diameter) is about 850 m. In the case of small and medium-sized rivers (19–300 m width), this becomes very challenging, and the waveform produced by the processed radar pulse reflection might be unpredictable.

Considering the fact that inland water surface is smoother than the ocean (Birkett, 1998), the (quasi) specular shape is declared as the standard waveform shapes for radar pulse returns that reflected by inland water bodies, in contrast to the ocean-reflected diffuse shape (Koblinsky, 1993). Additional shapes of Envisat RA-2 returned radar pulse over inland water include quasi-Brown, flat patch, and complex (Berry et al., 2005), which generally represent a transition from land to water, an intermediate surface, and a mixture between water and vegetation, respectively (Dabo-Niang et al., 2007). In this study, the (quasi) specular, quasi-Brown and flat-patch shapes are considered as qualified waveform to perform reliable range measurement while the complex and other non-classified shapes are considered as non-qualified waveform and therefore, discarded from further process. Some examples of these categorized waveforms from this study are presented in Fig. 3.

3.5 Outlier removal, validation and performance evaluation

Even after the exclusion of non-qualified waveform shapes, some observations are still outlying from the most value range. In order to obtain the dataset with minimum influences from outliers, the mild outliers were excluded from each data array following the definition of the inter-quartile-range (IQR) (Kenney and Keeping, 1947; Panik, 2012).

$$\mathrm{IQR} = Q_{0.75} - Q_{0.25}$$

Therefore,

$$\begin{aligned} \mathrm{WSE}_{\mathrm{min}} &= Q_{0.25} - 1.5\,(\mathrm{IQR}) \\ \mathrm{WSE}_{\mathrm{max}} &= Q_{0.75} + 1.5\,(\mathrm{IQR}) \end{aligned} \tag{1}$$

Consequently, any measurements below the $\mathrm{WSE}_{\mathrm{min}}$ and above the $\mathrm{WSE}_{\mathrm{max}}$ threshold were not involved in the further processing. WSE represents the water surface elevation as measured by Envisat radar altimetry.

Validation and statistical evaluation performance of satellite altimetry water level measurements are carried out for some of the virtual stations where in-situ measurements are available by root-mean-square error (RMSE) and the coefficient of correlation (r). The RMSE is a measure on how well estimation performs over the "truth" value and calculated following the standard statistical notation (e.g. Nagler, 2004 and Li, 2010).

$$\mathrm{RMSE} = \sqrt{\sum_{i=1}^{n} \frac{(x_i - y_i)^2}{n}} \quad (2)$$

where:

x_i is the Envisat water level anomaly

y_i is the in situ measured water level anomaly.

The correlation coefficient is the standard measure of association for continuous type of data (deSa, 2007); therefore, it is used to measure the association between satellite altimetry and in-situ water level measurements as described in the following equation.

$$r = \frac{S_{xy}}{S_x S_y} \quad \text{with} \quad S_{\mathrm{xy}} = \sum_{i=1}^{n} \frac{(x_i - \bar{x})(y_i - \bar{y})}{(n-1)} \quad (3)$$

With S_x and S_y are variances for each measurement and n is the number of observations, r value falls within the interval [−1, 1], where coefficient of 0 indicates no correlation between two measurements, +1 indicates total correlation in the same direction and −1 indicates total correlation in the opposite direction.

To provide a comprehensive understanding on the data processing sequences in this study, Fig. 4 shows each data processing step and their relationship.

4 Results and discussion

4.1 Mahakam River

The waveforms resulted from processed returned radar pulses were carefully selected, and only those matching with the standard waveform shape of water surface were processed (e.g. waveforms with complex shape or no obvious peak were discarded). As described in Table 2, most of the radar pulse returns produce qualified and useful waveforms that reflect water level trend at all virtual stations, regardless the width of the river. One particular virtual station, i.e. UM03, even indicates the water level fluctuation despite the narrow width of the channel (i.e. 54 m), as indicated by 46 qualified measurement and longer period of coverage as depicted in Fig. 5. Unfortunately, there is no in-situ gage water level data available for validation of this extracted water level anomaly.

After all, this finding becomes the second successful satellite radar altimetry exploitation toward very small water bodies (e.g. 80 m width or less) after Michailovsky et al. (2012), who extracted 13 useful water level measurements from a river with 40 m width, also without validation. By the time of this write up, no other studies indicated successful exploitation of the river with 100 m width or less, except Kuo and Kao (2011), who revealed the water level of Bajhang River in Taiwan with less than 100 m width with remarkable accuracy. Successful retrieval of qualified satellite radar altimetry measurement in this research is very much supported by detailed geographic masking, which carefully excludes all altimetry measurements with projected nadir position outside of the water bodies.

Once the range measurements that carry non-qualified waveforms excluded, water surface elevation at different virtual stations in Mahakam River and its middle sub-basin tributaries retracked using the Ocean, Ice-1, Ice-2 and Sea Ice waveform retrackers on the GDR are then selected. The outliers are defined and excluded from the water surface elevation dataset and subsequently the water level anomalies are calculated by removing the mean. The results of water level anomaly observations for each site are presented Figs. 5–7.

Figures 5–7 indicate that river width limits the ability of Envisat RA-2 satellite radar altimeter to measure water level, especially considering its spatial and temporal resolution, i.e. ~ 1.7 km projected pulse-limited footprint diameter and 35 days revisit period. While 1 km seems a favorable width to expect typical altimetry radar returns from the water surface (Birkett, 1998; Birkett et al., 2002), this study reveals that medium size rivers as narrow as 240 m can still be monitored and validated satisfactorily, given the water surface boundary is identified accurately through medium-resolution optical imageries with a ground resolution of ~ 30 m, such as Landsat. In addition, satellite altimeter measurement over a virtual station with river width of 54 m (Fig. 5) shows a good temporal coverage between the study periods (2002–2010). Still, with the absence of validation dataset for this particular virtual station, alternative validation is needed to support previous studies that found that through careful treatment, satellite radar altimetry can still measure the water level of the river with width less than 100 m (Kuo and Kao, 2011; Michailovsky et al., 2012). Table 2 also shows various number of missing cycles, which indicates the variation in temporal coverage from one site to another due to the availability of the qualified measurements,. This confirms the temporal resolution problem in using satellite altimetry for monitoring inland waters.

With regard to virtual stations at Melak (i.e. Melak01 and Melak02), these virtual stations are combined since they are only separated by 14–40 km distance and there is no drastic change in terrain and configuration of the channel (e.g. no reservoir or steep gradient). Having two different satellite tracks nearby in fact increases the spatial and temporal sampling intensity for this particular location. The combined water level anomaly from both virtual stations is plotted in Fig. 8 along with the water level anomaly observed by the gage station. The Ministry of Public Works' gage station is actually installed right in the middle between these two virtual stations as shown in Fig. 9. Figure 9 actually also indicates dynamic channel morphology in this area. The channel is heavily meandering just before and along the virtual station Melak01, which then

changes into 13 km straight channel along the heavily populated Melak Town before it is back into lightly meandering channel. In addition, topographic map and digital elevation model show no drastic changes neither in channel slope, nor the terrain.

To facilitate visual investigation, the correlation between the satellite altimetry observed and gage-measured are presented in Fig. 10 as scatter plots between each retracking algorithm and the gage-measured water level anomaly.

With regard to the retracking algorithm inter-comparison, this study reveals that Ice-1 is not necessarily the best retracking algorithm for inland water body elevation measurement, since SeaIce retracking algorithm performs best compared to other standard retrackers (i.e. Ocean, Ice-1 and Ice-2), according to Table 3.

With the coefficient of correlation up to 0.97, the satellite radar altimetry presents very convenient alternative for monitoring of the medium-sized river (200–800 m width), even for poorly-gauged basin such as the Mahakam Watershed. Referring to other studies, the magnitude of root-mean-square error (RMSE) reflected in this study, i.e. 0.69, is just about the average of RMSE obtained from other studies deal with medium sized rivers (200–800 m width), as summarized in Table 4.

It is important to note however, that this study did not adjust the magnitude of the satellite altimetry range measurements in any way. Beside a careful spatial selection of the range measurements with the projected nadir footprint center within the water body and the removal of outliers, the only intervention applied to the dataset was the selection of the range measurements based on its waveform shape to strictly follow the standard waveform shape for inland water body as described in the previous studies (Koblinsky et al., 1993; Birkett, 1988; Berry et al., 2005; Dabo-Niang et al., 2007). Therefore, there must be ample room for improvement to increase the accuracy of the satellite altimetry measurement of river water level, especially for this study area.

4.2 Karangmumus River

The northeast-southwest orientation of this river makes it difficult to find the crossing Envisat ground tracks. However, high resolution IKONOS image (1 m ground resolution) allows detailed selection of the altimeter ground tracks that fall within its narrow channel. Still, the narrow channel width (between 8 and 45 m) seriously hampered successful satellite radar altimetry measurement of this study site. After careful spatial filtering and waveform shape selection procedure, there are only 11 water surface elevation extracted from Karangmumus River. Figure 11 depict the location, while Table 5 summarizes the qualified measurements. Due to unknown relationship with the vertical datum, only water level anomaly is presented.

One important note from the effort of satellite altimetry measurement of this study site is, given the limitation on its spatial and temporal resolution, the satellite altimetry measurement still indicates the inter-annual water level fluctuation of the Karangmumus River during 2004 to 2006, as compared to the magnitude of precipitation. In addition, the in-situ measurement record from the nearest available gage stations (i.e. Pampang, Muang, Gununglingai, and the outlet of the Karangmumus River) are available only during 2008–2010 so that the performance of satellite altimetry measurements over this very small river cannot be evaluated. Figure 12 shows the truncated time series of the water level anomaly along with TRMM estimated precipitation for the area. The trend of the water level time series seems linearly related with the rainfall and the plot also shows lags between the rainfall and the water level peak. These results conclude that it seems not viable to monitor water level of this class of river (width < 40 m) through satellite altimetry technique, especially due to limited numbers of valid measurements.

4.3 Lake Matano and Lake Towuti

Inland water has been known to produce different, sometimes irregular waveform shapes and pattern compared to the ocean with respect to their response to radar pulse signal transmitted by satellite based active sensor. Some examples of distinguished waveform shapes from Lake Matano and Lake Towuti at different buffer distances from the lakeshore are presented in Fig. 13. Clearly, the waveform shapes resulted from satellite altimetry measurement over the lakes are more variable compare to those over the small to medium-sized rivers. From Fig. 13, one can see the

typical ocean-like, multi and low peaks, gradually rising and many other kinds of irregular patterns. Considering the dynamic of the water surface of the lake and river, this is understandable, since lake has much larger extent and much more influenced by wind that may develop wave with some height. With the absence of verified categorization of waveforms shapes especially those occur on inland waters, other than Dabo-Niang et al. (2007), further study on this field might worth to consider in the future.

The waveforms from qualified measurements are further screened out based on the acceptable waveform shape, while the outliers are also excluded. Table 6 summarizes the results of satellite altimetry waveform qualification over Lake Matano and Lake Towuti.

Similar to the result of satellite altimetry measurements to the small to medium-sized river in the previous section, most of the radar pulse returns produced qualified waveforms that were used to compute water level anomaly at these two lakes. It is also noticed that separation of distance to the lakeshore seems does not significantly affect the number of qualified waveforms. For instance, from Table 6 one can see the percentage of qualified waveforms for the lake surface with distance more than 1 km in Lake Matano and Lake Towuti is lower than those closer to the lakeshore. This complex result calls for further investigation in the field of satellite altimetry application for small and medium lakes in the tropics, given the fact that the land cover does not necessarily influence the shapes of the returned altimeter waveform. One possible cause is the lake surface roughness, which is caused by the range of crest and trough of the wave, which is mainly driven by the wind.

Upon the completion of waveform sorting, the range measurements as performed by Ocean, Ice-1, Ice-2 and Sea Ice retrackers were processed and evaluated against observed water level from in-situ gage station. Figures 14 and 15 show the satellite altimetry derived and in-situ gaged water level anomaly at Lake Matano and Lake Towuti and indicates the best match among the three lakes studied. On the other hand, it is also obvious that the Envisat radar altimetry measurements present considerable noises, especially those inferred by the Ocean retracker.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

Physically, the two lakes being studied possess slightly different characteristics. Lake Matano is a very gentle and ultra-deep lake, which regulates a maximum annual precipitation of 2800 mm into very low mean discharge of 133 $m^3 s^{-1}$ at its outlet. Other research indicates that nearly half of the water within the catchment upstream of Lake Matano circulates through groundwater interaction, which explains why this particular lake outflows less discharge compared to its inflow (Hehanussa, 2006). As the result, the water level profile fluctuates very gently and ranges in the magnitude of 1.2 m.

Lake Towuti is the largest lake among all lakes in Malili Lakes Complex but possesses less depth compared to the Lake Matano. Considering its surface area, this lake is influenced by wind that comprises the lake breeze, which blocks the cloud propagation and pushes the precipitating cloud over the lakeshore (Renggono, 2011). The water level profile of this lake also fluctuates gently in the ranges of 1.4 m.

To provide an idea on how the satellite altimetry measurements correlate with the in-situ field gage data, Figs. 16 and 17 illustrate the correlation between the Envisat radar altimeter measurements as processed by Ocean, Ice-1, Ice-2 and Sea Ice retrackers with the gage measured water level anomaly for Lake Matano and Lake Towuti, respectively.

In terms of performance, Envisat radar altimetry measurements over Lake Towuti outperform those on Lake Matano, considering the lower RMS error obtained by the best retracker for each lakes (0.27 for Lake Towuti compared to 0.33 for Lake Matano, see Table 7). This fact is further confirmed by the scatterplots of the correlation between the altimetry measured and gage measured water level anomaly in Figs. 16 and 17.

The result of performance evaluation shows that the initial assumption regarding the effect of distance from lakeshore to the accuracy of satellite altimetry measurement is in-consistent. The satellite altimetry measurement of water level anomaly over Lake Matano indicates lower RMS error and higher correlation coefficient relative to the in-situ gaged water level anomaly with the increase of distance from the altimeter footprint to the lakeshore, while the satellite altimetry measurement over Lake Towuti shows the opposite. Two statistical measures (i.e. RMS error and correlation coefficient) resulted

from the performance evaluation over different distance to the lakeshore are illustrated in Figs. 18 and 19. Considering the complicated results from splitting the altimeter measurements by the distance from the lakeshore, this study does not recommend such classification of samples based on the distance to the lakeshore. Table 7 presents all statistical measures resulted from the performance evaluation over different distance to the lakeshore.

Inter-comparison between the available retrackers (i.e. Ocean, Ice-1, Ice-2 and Sea Ice) cannot suggest any single retracker to infer water level of the small lakes, since Ice-2 performed best for Lake Matano, but Ice-1 retracker performed best for Lake Towuti. An important conclusion that could be drawn from this part of research is that Ice-1 is not necessarily the best retracker to measure water level anomaly over small to medium lakes in Southeast Asia humid tropics.

Compared to other studies, the best RMS error obtained from measurements of water level anomaly in this study, i.e. 0.29 m at Lake Towuti, is close to the lowest one among the small lakes being studied throughout the world. Table 8 clearly states that satellite altimetry measurements over the small lakes give the RMS error magnitude in the range of 30 to 50 cm, as compared to large lakes that produce RMS error as low as 3 cm. Lake Matano is in fact the smallest among all lakes listed in Table 8.

5 Conclusions

This study demonstrated that satellite altimetry is capable to monitor the water level of medium-sized (200–800 m width) rivers in the Southeast Asia's humid tropics, as indicated by the high correlation between the water level measured by satellite altimetry and the validation dataset measured on the ground. Even the results vary in terms of the performance; water level anomaly inferred by Envisat radar altimetry through standard waveform retracking method has been validated and therefore, capable to represent the fluctuations of water level of medium rivers. Aside from the medium-sized rivers, this study also found that small rivers (40–200 m width) are

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potentially observable through satellite altimetry, as indicated by reasonably good altimetry-derived water level anomaly recovered for a river with 54 m width, given the water surface boundary is identified carefully through medium-resolution optical imageries (e.g. Landsat with 30 m ground resolution). Even this measurement was not validated due to absence of in-situ gage station, the water level anomaly generated in this study provides good indicators of the satellite altimetry reability for small rivers. It is important to note however, that this situation might be different from one region to another; therefore a specific approach should be developed for each region, as part of the development of permanent monitoring effort of those regions.

In contrast with the common assumption as summarized by Frappart et al. (2006), Ice-1 is not necessarily the best retracker for monitoring small water bodies, especially for the Southeast Asia humid tropics area. It is obvious though, that the Ocean retracker performs worst as it is compared to other retrackers. Ice-1, Ice-2 and Sea Ice alternately produced the best results in various locations of this study.

The RMS errors of satellite altimetry measurement of Lake Matano and Lake Towuti relative to validation measurement, i.e. 0.33 m and 0.27 m, respectively, are about the average of small lakes being studied throughout the world. It is worth noting that the extent of Lake Matano, which has been investigated in this study, is the smallest water bodies among any other studies of satellite altimetry measurement of water level involving lakes and reservoirs.

On the other hand, by learning from obstacles and problems encountered during the experiment, this study recommends the following to advance future studies: (1) the selection of the range measurements based on its waveform shape to strictly follow the standard waveform shape for inland water body (Koblinsky, 1993; Birkett, 1988; Berry et al., 2005; Dabo-Niang et al., 2007) is proposed for future studies involving small (40–200 m width) to medium rivers (200–800 m width), as well as small lake (e.g. those with extent less than 1000 km^2), and (2) over lakes, classification of distance from the satellite altimetry measurements to the lakeshore is not recommended since it did not suggest significant difference in the number of qualified altimetry measurement.

Acknowledgements. This research is primarily supported by the Fulbright PhD Presidential Scholarship administered by American Indonesian Exchange Foundation (AMINEF) and the Institute for International Education (IIE). In addition, this study is partially funded by grants from NASA's Application Science Program under the SERVIR project (NNX12AM85G), and by the Chinese Academy of Sciences/SAFEA International Partnership Program for Creative Research Teams (Grant No. KZZD-EW-TZ-05). The authors greatly appreciate the Ministry of Public Works of Republic of Indonesia and PT Vale Indonesia, Tbk for providing in-situ water level data used in this research.

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Table 1. Envisat RA-2 pass, cycles and observation period for each study sites.

Site #	Site Name	Longitude	Latitude	Pass	River/Lake Width	In-Situ Data	Cycle	Period
	Mahakam Watershed							
1	UM03	114°35′10″ E	0°50′02″ N	89	54 m	No	6-93	2002–2010
2a	Melak01	115°53′20″ E	0°17′08″ S	46	247 m	Yes	6-93	2002–2010
2b	Melak02	115°47′58″ E	0°11′03″ S	297	294 m	Yes	6-93	2002–2010
3	Karangmumus	117°11′20″ E	0°24′21″ S	3	8–45 m	Yes	6-93	2002–2010
	Malili Lakes Complex							
4	Matano	121°24′6″ E	2°28′59″ S	397	8,159 m	Yes	6-93	2002–2010
5	Towuti	121°23′57″ E	2°30′10″ S	397	28 818 m	Yes	6-93	2002–2010

Table 2. Number of qualified and non-qualified altimeter measurements and outliers for study sites at Mahakam River.

Site Name	Cycles	# of Missing Cycles	Measurements in water body	Qualified Measurement		Non-qualified Measurement		# of Outlier	River width (m)
				(#)	(%)	(#)	(%)		
UM03	9–93	34	51	46	90.2	5	9.8	N/A	54 m
Melak01	7–93	8	225	220	97.8	5	2.2	8	247 m
Melak02	7–93	11	148	134	90.5	14	9.5	0	294 m

Table 3. Performance evaluation of Envisat RA-2 radar altimetry measurements over Melak virtual stations at Mahakam River (width 247 m).

Site Name	Cycles Covered	Validated Measurement	Number of Pass	Retracker	RMSE (m)	Correlation Coefficient
Melak	7–33	46	2	Ocean	0.885	0.955
				Ice-1	0.720	0.962
				Ice-2	0.724	0.966
				SeaIce	0.685	0.970

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Table 4. Summary of studies on satellite radar altimetry for water level over river.

Reference	Location	River Width	Satellite/Sensor	Reported Error (m)
Koblinsky et al. (1993)	Amazon Basin	N/A	Geosat	STDE: 0.31–1.68 m
Birkett et al. (1998, 2002)	Amazon Basin	1.5 km	T/P	RMSE: 0.60 m
Kouraev et al. (2004)	Ob' River	3 km	T/P	%: 8 %
Frappart et al. (2006)	Mekong River	450 m	Envisat, T/P	RMSE: 0.23 m, RMSE: 0.15 m
Kuo and Kao (2011)	Bajhang River	100 m	Jason-2	STDE: 0.31 m
Michailovsky et al. (2012)	Zambezi River	80 m	Envisat	RMSE: 0.72 m
Sulistioadi (2013)	Mahakam River	279 m	Envisat	RMSE: 0.69 m

STDE (Standard Deviation of Error), % (% difference), RMSE (Root Mean Square Error).

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Table 5. Qualified Envisat RA-2 altimetry measurements for Karangmumus River.

Cycle	Date	ID	Longitude	Latitude	Water Surf Elevation	Remarks
8	23 Jun 2002	KM08	117.181540	−0.404124	59.63 m	
9	27 Aug 2002	KM10	117.194581	−0.408362	55.18 m	Benanga Reservoir
13	13 Jan 2003	KM11	117.195384	−0.407573	62.64 m	Benanga Reservoir
23	30 Dec 2003	KM01	117.157190	−0.507934	57.77 m	
23	30 Dec 2003	KM02	117.157910	−0.504634	57.38 m	
28	22 Jun 2004	KM09	117.188367	−0.405981	63.33 m	47 m to field gage
37	3 May 2005	KM06	117.169721	−0.448573	59.59 m	
37	3 May 2005	KM07	117.170441	−0.445263	59.57 m	
39	12 Jul 2005	KM03	117.158610	−0.503317	57.42 m	
42	25 Oct 2005	KM05	117.171486	−0.452076	63.81 m	
49	27 Jun 2006	KM04	117.159139	−0.501533	58.76 m	

RMSE (Root Mean Square Error).

Table 6. The number of qualified and non-qualified altimeter measurements and outliers over Lake Matano and Lake Towuti.

Location	Width	Cycle	Distance to Shore	Measurement Within water body	Qualified		Non-Qualified		No of Outlier
					#	%	#	%	
Lake Matano	8159	8–79	< 500 m	453	416	91.8	37	8.2	68
			500 m–1 km	253	215	85.0	38	15.0	27
			> 1 km	989	805	81.4	184	18.6	115
Lake Towuti	28 818	8–79	< 500 m	1314	786	59.8	528	40.2	79
			500 m–1 km	1328	764	57.5	564	42.5	64
			> 1 km	2450	1353	54.3	1137	45.7	156

Table 7. Performance evaluation of Envisat RA-2 radar altimetry measurements over Lake Matano and Lake Towuti.

Site	Lake width (m)	Cycles	Validated measurement	Retracker	Correlation coefficient	RMSE (m)	No/% of Outliers
Lake Matano	8159	8–79					
0–500 m			75	Ocean	0.202	0.995	68/416
				Ice-1	0.221	0.858	16.35 %
				Ice-2	0.276	0.836	
				SeaIce	0.341	0.760	
500–1000 m			71	Ocean	0.605	0.554	27/215
				Ice-1	0.538	0.624	12.56 %
				Ice-2	0.723	0.458	
				SeaIce	0.745	0.417	
> 1000 m			73	Ocean	0.692	0.493	115/805
				Ice-1	0.647	0.535	14.29 %
				Ice-2	0.667	0.517	
				SeaIce	0.666	0.518	
Merged			75	Ocean	0.884	0.317	210/1436
				Ice-1	0.858	0.346	14.62 %
				Ice-2	0.876	0.322	
				SeaIce	0.750	0.526	
Lake Towuti	28 818	8–79					
0–500 m			75	Ocean	0.851	0.416	79/786
				Ice-1	0.886	0.348	10.05 %
				Ice-2	0.867	0.369	
				SeaIce	0.880	0.342	
500–1000 m			71	Ocean	0.920	0.275	64/764
				Ice-1	0.884	0.337	8.38 %
				Ice-2	0.864	0.375	
				SeaIce	0.859	0.380	
> 1000 m			73	Ocean	0.689	0.611	156/2490
				Ice-1	0.780	0.521	6.27 %
				Ice-2	0.761	0.514	
				SeaIce	0.761	0.529	
Merged			75	Ocean	0.920	0.274	299/4040
				Ice-1	0.924	0.269	7.40 %
				Ice-2	0.910	0.289	
				SeaIce	0.908	0.294	

Table 8. Summary of studies on satellite radar altimetry for water level over lakes.

Reference	Location	Lake Extent	Satellite/Sensor	Reported Error
Morris and Gill (1994a)	Superior, Ontario	Large	Geosat	RMSE: 0.09 m
	Michigan, Huron	Large	Geosat	RMSE: 0.11 m
	Erie		Geosat	RMSE: 0.13 m
	Lake St Clair		Geosat	RMSE: 0.17 m
Morris and Gill (1994b)	Great Lakes		Topex/Poseidon	RMSE: 0.03 m
Korotaev et al. (2001)	Black Sea	436 402 km^2	T/P, ERS-1	RMSE: 0.03 m
Mercier et al. (2002)	Victoria, Tanganyika Malawi and Turkana	131–390 × 10^3	TOPEX/Poseidon	RMSE: 0.10 m
	Rukwa and Kyoga	75–80 × 10^3	TOPEX/Poseidon	RMSE: 0.50 m
Coe and Birkett (2004)	Lake Chad	2.5 × 10^6 km^2	TOPEX/Poseidon	RMSE: 0.21 m
Zhang et al. (2006)	Dongting Lake	2623 km^2	TOPEX/Poseidon	RMSE: 0.08 m
Medina et al. (2008)	Lake Izabal	717 km^2	Envisat	RMSE: 0.09 m
Munyaneza et al. (2009)	Lake Kivu	2400 km^2	Envisat	RMSE: 0.30 m
Cai and Ji (2009)	Poyang Lake	20 290 km^2	Envisat	Mean Error: 0.31 m
Guo et al. (2009)	Hulun Lake	2339 km^2	TOPEX/Poseidon	RMSE: 0.13 m
Troitskaya et al. (2012)	Gorki Reservoir	1358 km^2	T/P, Jason-1	RMSE: 0.15 m
Tseng et al. (2013)	Qinghai Lake	4186 km^2	Envisat	RMSE: 0.06 m
Sulistioadi (2013)	Lake Matano	164 km^2	Envisat	RMSE: 0.32 m
	Lake Towuti	562 km^2	Envisat	RMSE: 0.29 m

* RMSE (Root Mean Square Error).

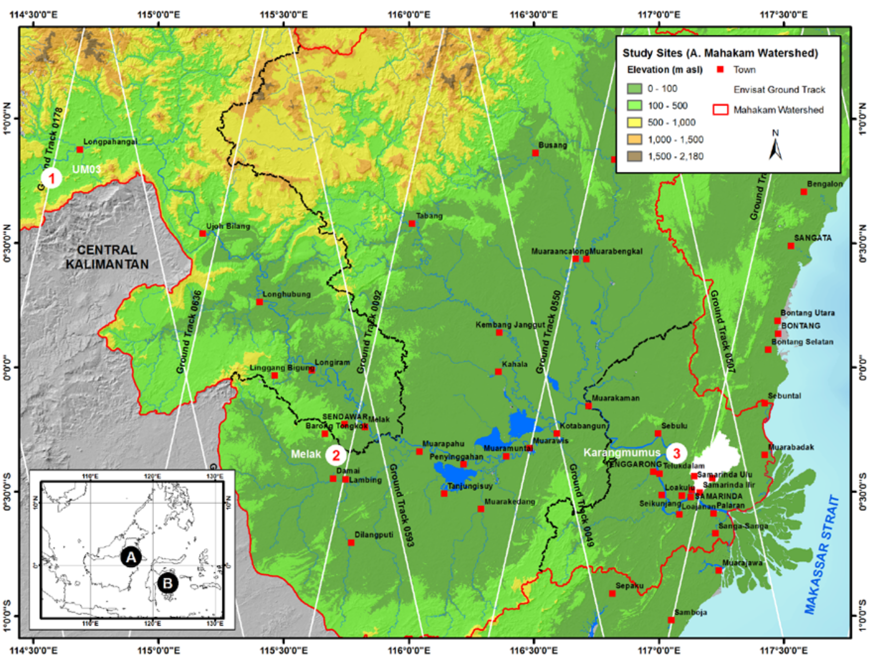

Fig. 1. Study Sites at Mahakam Watershed, East Kalimantan, Indonesia.

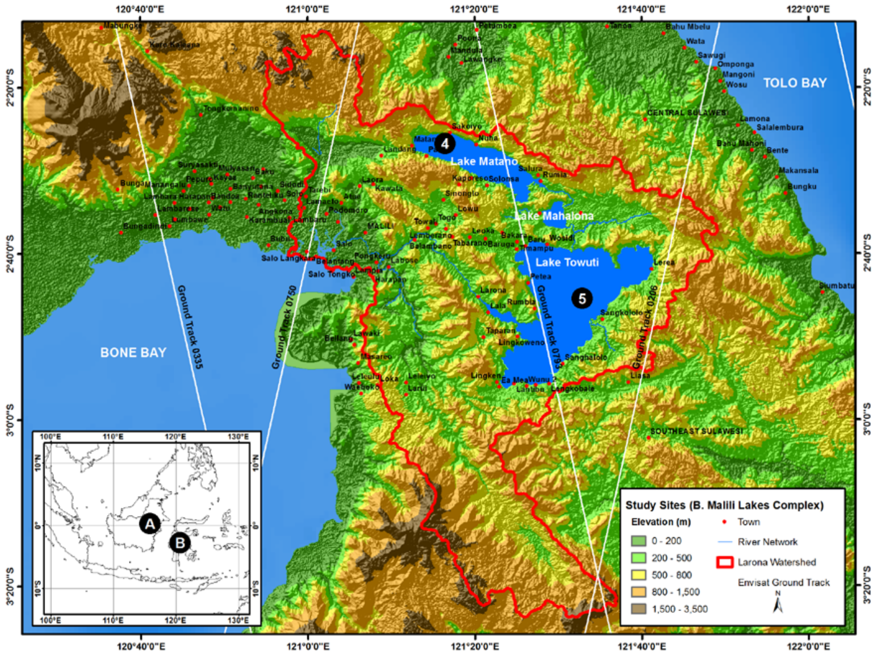

Fig. 2. Study Sites at Malili Lakes Complex, South Sulawesi, Indonesia.

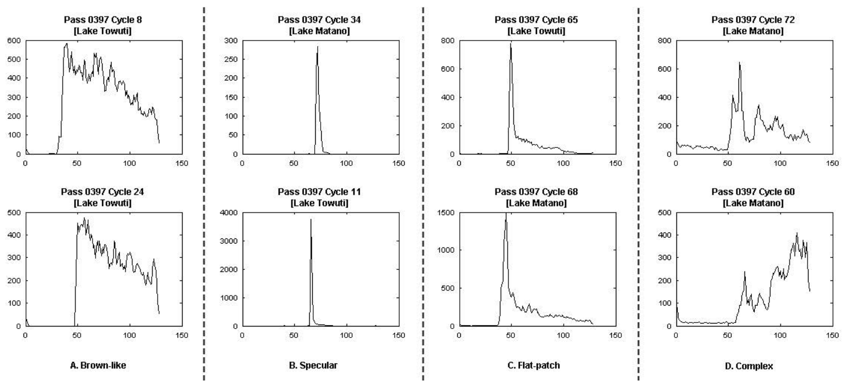

Fig. 3. General categories of waveform shapes.

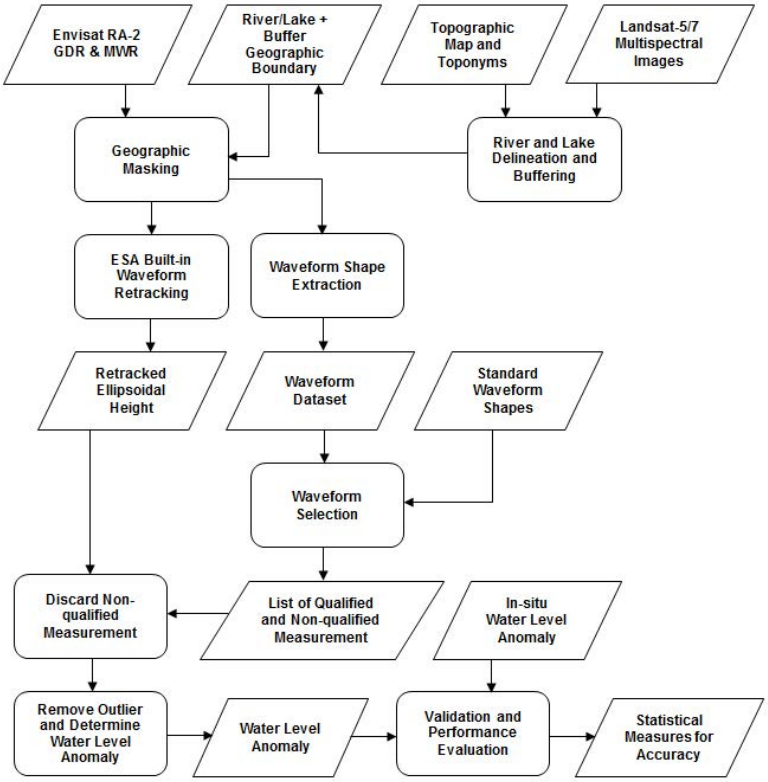

Fig. 4. Data processing workflow.

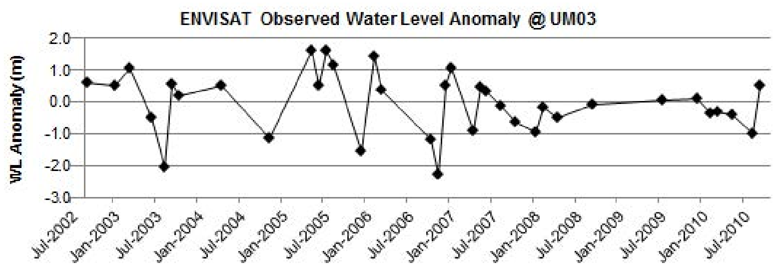

Fig. 5. ENVISAT Observed Water Level Anomaly at Site UM03 (river width 54 m) as measured by Envisat RA-2 and processed by Ice-1 retracker.

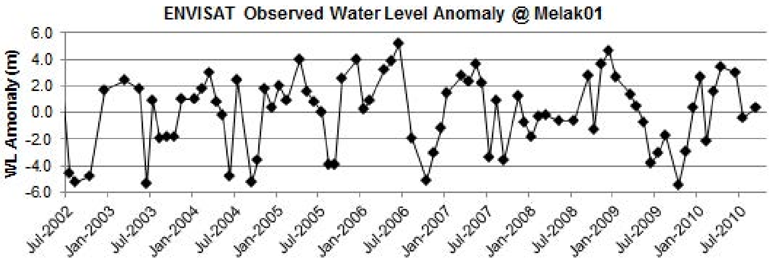

Fig. 6. ENVISAT Observed Water Level Anomaly at Site Melak01 (river width 247 m) as measured by Envisat RA-2 and processed by Ice-1 retracker.

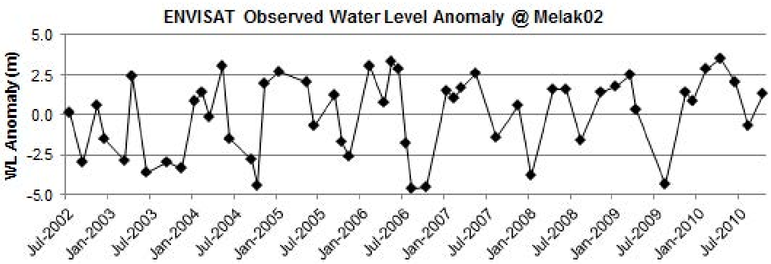

Fig. 7. ENVISAT Observed Water Level Anomaly at Site Melak02 (river width 294 m) as measured by Envisat RA-2 and processed by Ice-1 retracker.

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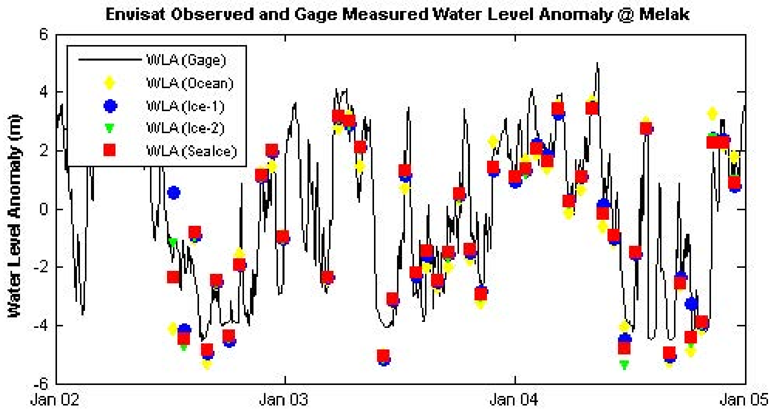

Fig. 8. Water level anomaly at Melak as observed by two Envisat passes and retracked by four retrackers; compared with in-situ water level anomaly.

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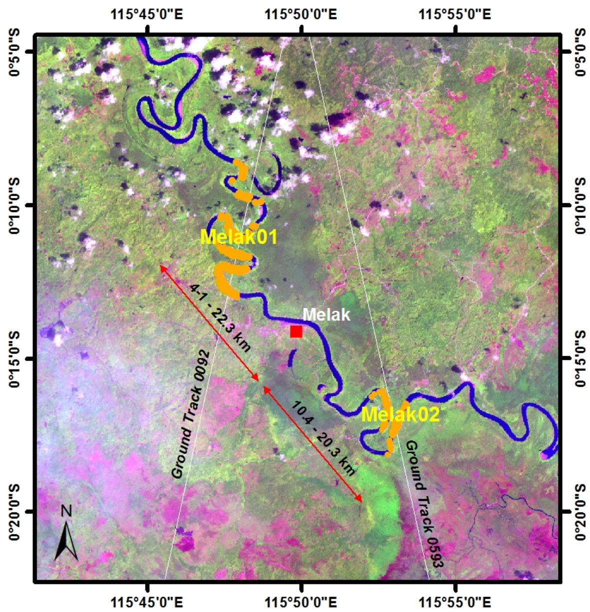

Fig. 9. Location of Envisat virtual stations and in-situ water level gage stations at Melak Town.

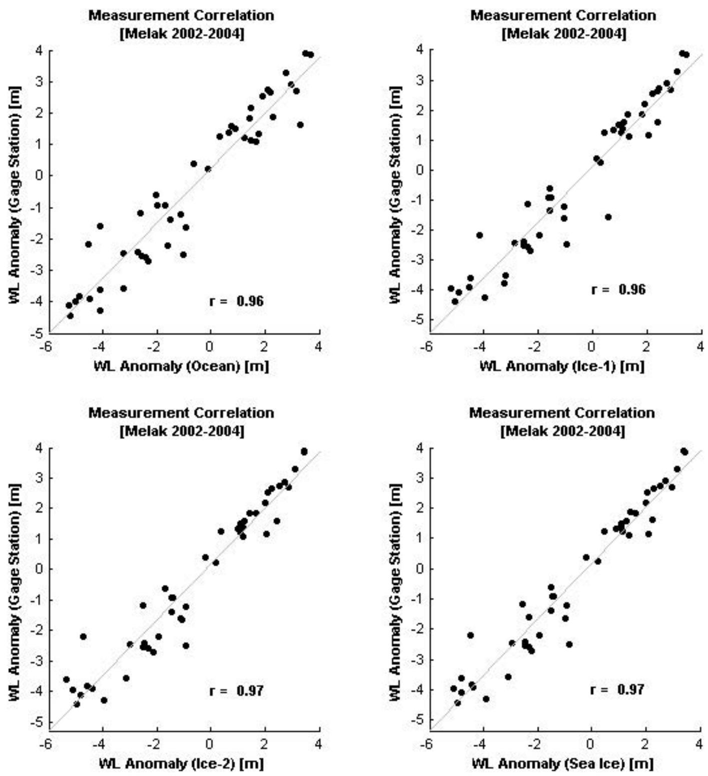

Fig. 10. Correlation between water level anomaly measured by Envisat altimeter and processed with Ocean (top left), Ice-1 (top right), Ice-2 (bottom left) and Sea Ice (bottom right) retrackers and in-situ water level measurement over Melak.

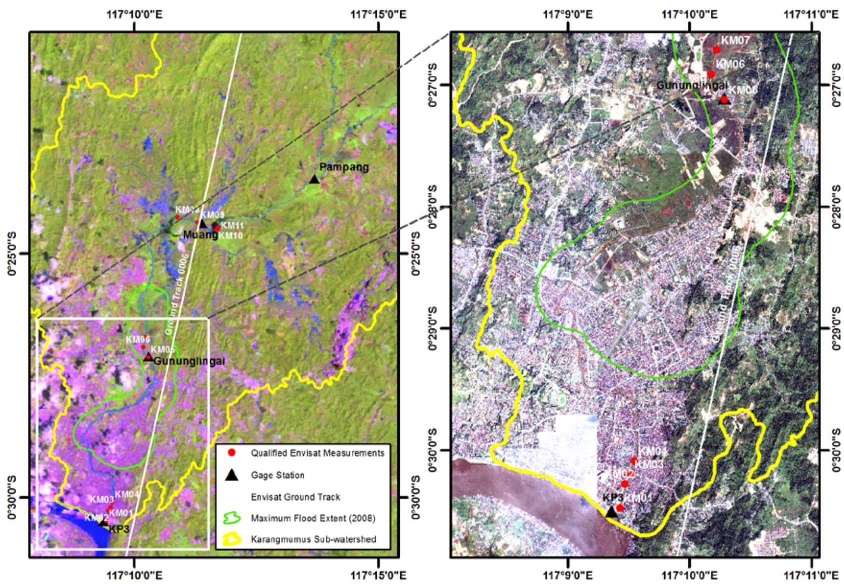

Fig. 11. Overview of Karangmumus Sub-watershed and Envisat ground track with background of Landsat-7 image of January 2007 (left) and IKONOS of February 2002 (right, in the extent of white box of the left image).

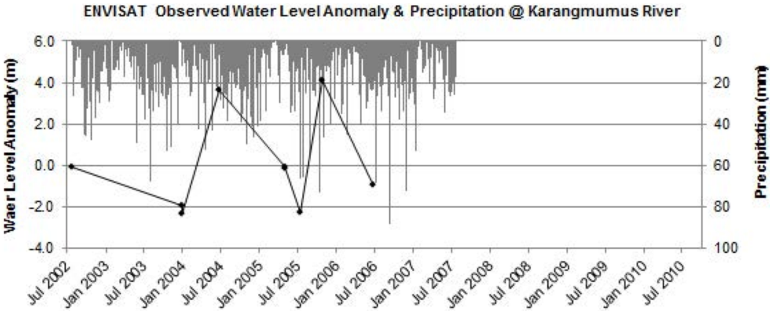

Fig. 12. Water level anomaly of Karangmumus River from Envisat RA-2.

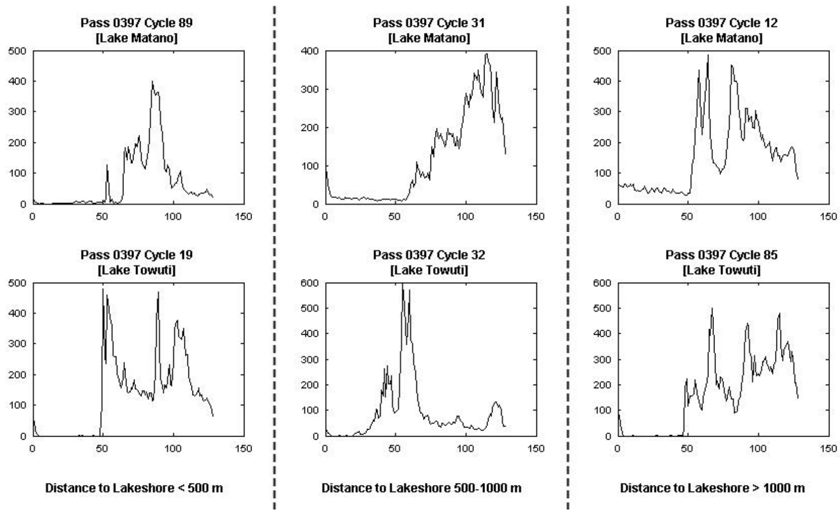

Fig. 13. Distinguished waveform shapes as reflected by Lake Matano and Lake Towuti at different buffer distances to the lakeshore.

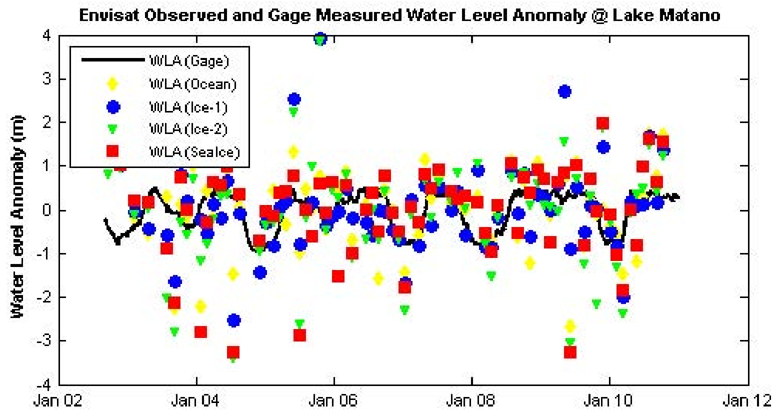

Fig. 14. Water level anomaly at Lake Matano as measured by Envisat RA-2 and processed by all retracker, compared with in-situ measurement.

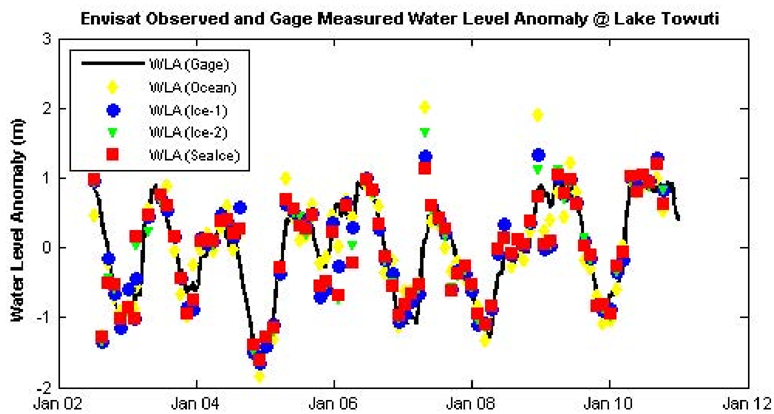

Fig. 15. Water level anomaly at Lake Towuti as measured by Envisat RA-2 and processed by all retracker, compared with in-situ measurement.

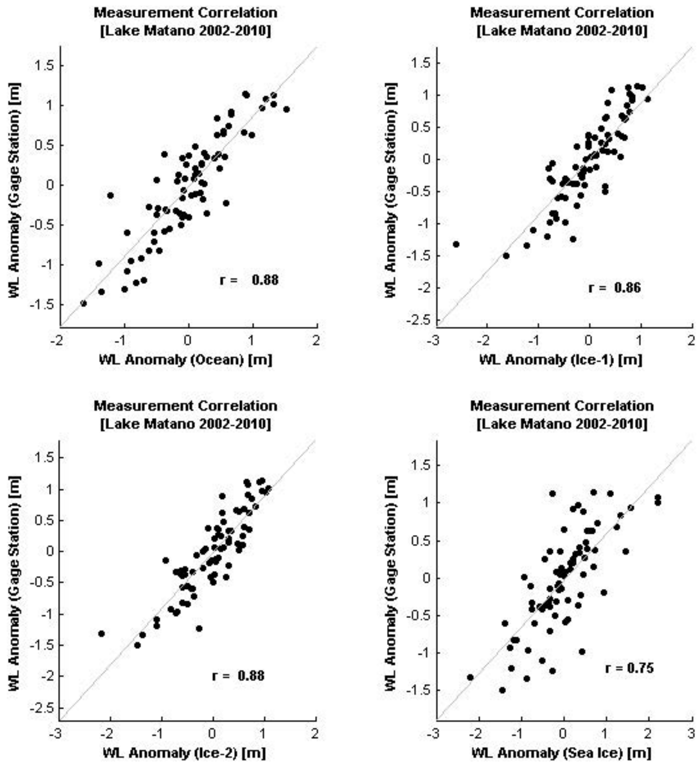

Fig. 16. Correlation between water level anomaly at Lake Matano as measured by Envisat RA-2 altimeter and processed with Ocean (top left), Ice-1 (top right), Ice-2 (bottom left) and Sea Ice (bottom right) retrackers.

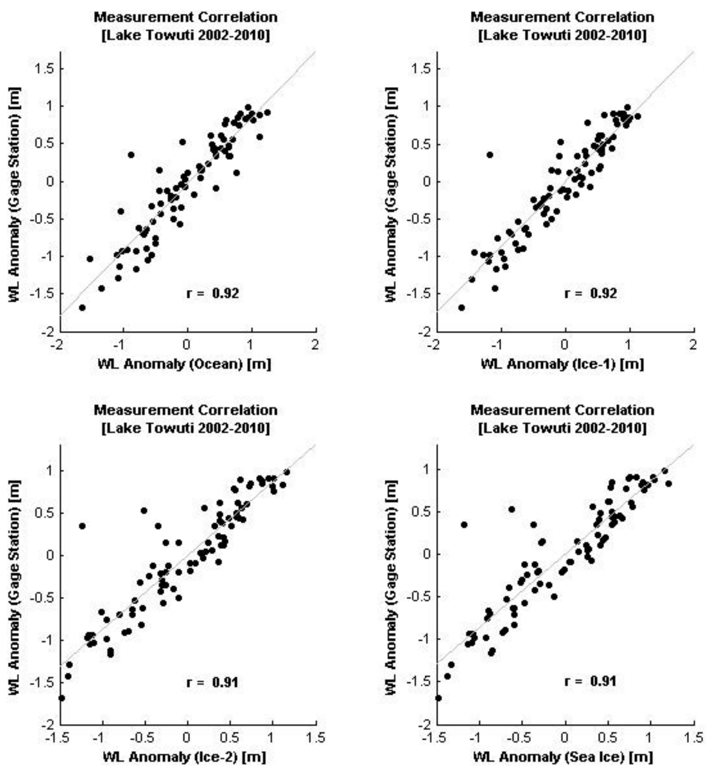

Fig. 17. Correlation between water level anomaly at Lake Towuti as measured by Envisat RA-2 altimeter and processed with Ocean (top left), Ice-1 (top right), Ice-2 (bottom left) and Sea Ice (bottom right) retrackers.

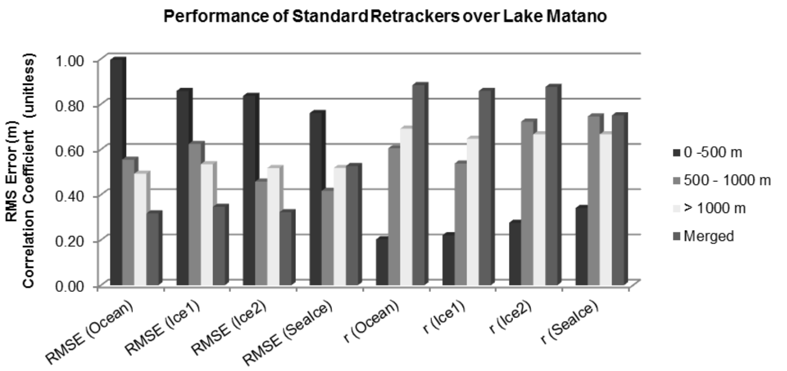

Fig. 18. The performance of Envisat RA-2 radar altimetry measurements over Lake Matano, classified by the distance to the lakeshore.

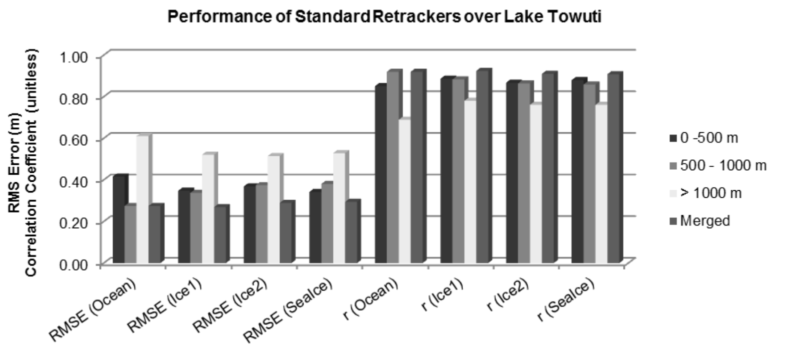

Fig. 19. The performance of Envisat RA-2 radar altimetry measurements over Lake Towuti, classified by the distance to the lakeshore.