# Mangrove rehabilitation under climate change: towards a hydrological tool for quantifying the effect of expected sea level rise on mangroves

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**ABSTRACT**

Mangroves are complex ecosystems in delta regions. Mangrove species have developed tolerance for environmental stress factors, such as an unstable soil profile, water salinity and inundation. Vast quantities of mangrove forest have deteriorated or disappeared due to human migration, wood exploitation, fishing and shrimp farming. Another threat is sea level rise, since Southeast Asia is already experiencing sea level rise due to climate change.

Comprehensive programs that combine measures to control deforestation and improved techniques for tree plantation development are expected to contribute to a sustainable combination of forest exploitation and ecosystem rehabilitation. Examples are the Mahakam Delta at Kalimantan, Indonesia, and the Dong Tranh delta, Vietnam. Field research in mangrove forests at both deltas proved that micro-topography highly determines the duration of inundation and inundation frequency. Basins with impeded overland flow are inundated longer than might be expected from just their elevation. This makes the often used hydrological classification, developed by Watson (1928) less reliable. Therefore, starting from the Watson classification, a new classification was developed to relate hydrological properties to some characteristic mangrove species (such as *Avicennia spp*., *Rhizophora spp*., *Acrosticum aureum*, *Phoenix paludosa*).

Relatively simple field measurements produce highly relevant information on inundation characteristics. These characteristics can be used by local authorities for determining which species can be used for wood exploitation, for determining the potential for ecosystem rehabilitation (i.e. high biodiversity), and for quantifying the effect of expected sea level rise scenarios on mangroves.

Key words: Mangrove; Hydrology; Ecosystem restoration; Vietnam; Indonesia; Hydrological classification

## 1. Introduction

Mangroves are unique, but very vulnerable and complex ecosystems (Tabuchi, 2003). Human migration, wood cutting, fishing, and shrimp farming have deteriorated vast quantities of mangrove forest (Kairo *et al*., 2001; Dijksma *et al*., 2010). Rehabilitation projects in degraded forests often fail to restore the high ecological values of the original forests (Sanyal, 1998; De Leon and White, 1999; Lewis, 2005). Sometimes restoration projects result in monospecific mangrove plantations, predominantly *Rhizophora spp*. (Lewis, 2001).

Hydrological site characteristics are the most important determinant for the establishment of mangroves (Hughes *et al*, 1998). The only common hydrological tool in mangrove rehabilitation projects is the general classification for mangrove forests by Watson (1928) where the tidal range is considered in five inundation classes, as shown in Table 1. Watson developed his classification for mangrove systems with regular semi-diurnal tides and a gradually rising surface elevation. He indicated that the classes are chosen arbitrarily, so that the classification only hold for a rough comparison.

Table 1 Hydrological classification 1928 (Watson, 1928)

| **Inundation class** | **Tidal regime** *flooded by* | **Elevation** *above admiralty datum* | **Flooding frequency** *times per month* | **Vegetation** *species* |
|---|---|---|---|---|
| 1 | all high tides | Below 244 cm | 56 to 62 | none |
| 2 | medium high tides | 244 to 335 cm | 45 to 59 | *Avicennia spp., Sonneratia* |
| 3 | normal high tides | 335 to 396 cm | 20 to 45 | *Rhizophora spp., Ceriops, Bruguiera* |
| 4 | spring high tides | 396 to 457 cm | 2 to 20 | *Lumnizera, Bruguiera, Acrosticum aureum* |
| 5 | equinoctial tides | 457 cm and above | - to 2 | *Ceriops spp., Phoenix paludosa* |

This paper shows the result of intensive field studies on the hydrology of mangrove forests and proposes an adapted classification. Also a simple tool for the implementation of the adapted classification is shown.

## 2. Site description

The hydrological properties of two extensive mangrove forests in the southern part of Vietnam were studied: Can Gio in the province of Ho Chi Minh City and Ca Mau province in the southernmost part of the country. Despite restoration efforts, conversion of forest to agricultural land, shrimp ponds and fish farms and the increasing population pressure hampered the ecological redevelopment of these areas.

Can Gio measures 35 km from north to south and 30 km from east to west (Tuan *et al*., 2002). The creek system in Can Gio experiences an irregular semi-diurnal tidal regime (Hong and San, 1993). The maximum amplitude of the tides in Can Gio ranges from 3.3 to 4.1 m (Vietnam National Committee, 1998).

Ca Mau National Park is situated at the Ca Mau peninsula. The tidal regime is influenced by the South China Sea and by the Gulf of Thailand. In the South China Sea the tidal regime is irregular semi-diurnal, where the Gulf of Thailand has a diurnal tidal regime. The amplitudes range between 2.5-3.8 m and 0.5-1.0 m, respectively.

The Mahakam Delta is located on the east coast of Kalimantan, Indonesia. The delta has a length of approximately 50 km, and stretches along the coast for 100 km (Gastaldo, 2010). The mangrove system suffered from uncontrolled and controlled wood logging, the development of shrimp ponds and agricultural land. Figure 1 shows the tidal regime at the Mahakam Delta, also an irregular semi-diurnal regime.

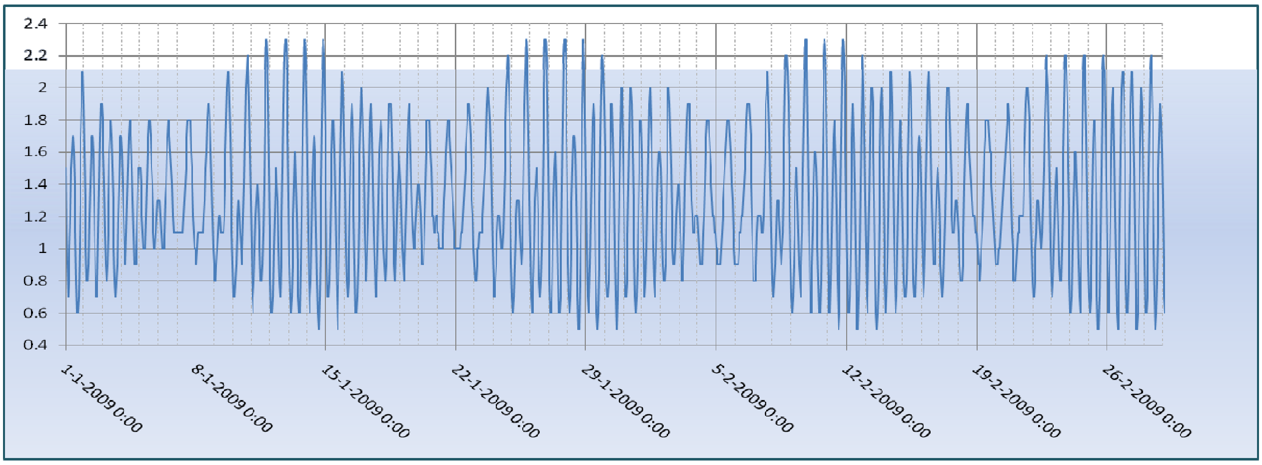


Figure 1 Tidal prediction of Samarinda (Indonesia) for January 2009

## 3. Methods

During the intensive field campaigns in Gan Gio and Ca Mau, Vietnam, representative plots were selected. On these plots the elevation profile was studied, the groundwater and surface water levels were measured and the species were determined. Groundwater and surface water level was measured in stilling wells by means of automatic devices with a 5 min recording interval. Figure 2 shows a stilling well and an automatic recording device called 'Diver' (Van Loon, 2005). Also the impact of creek systems in the mangrove areas on the inundation frequency and duration was studied.

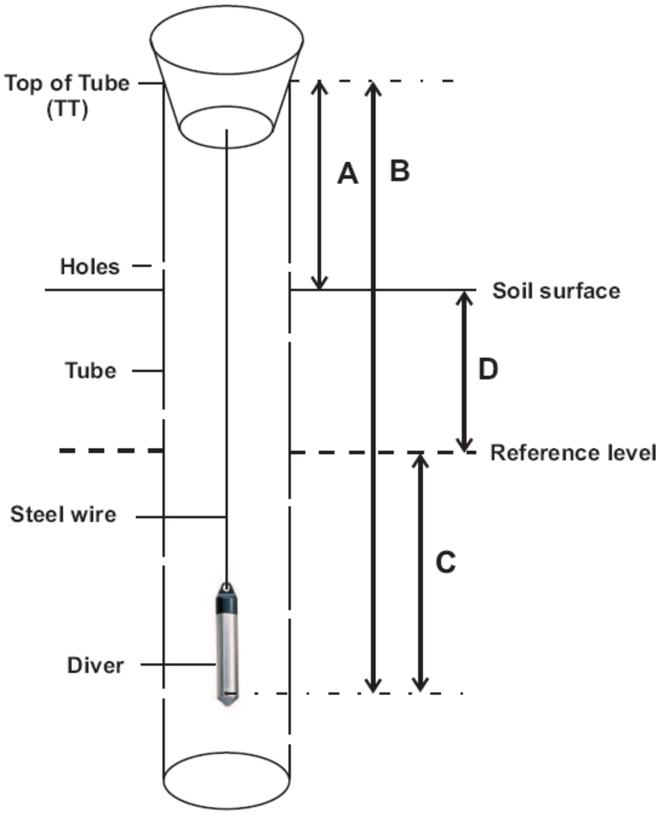


Figure 2 Automatic water level recording device in a stilling well (Van Loon, 2005)

## 4. Results and discussion

Measured water levels in open water were compared with predicted water levels. Figure 3 shows the measured water level in the Dongh Tranh river at Gan Gio and the predicted water levels for the nearby open water location Vung Tau (Vietnam) for the period 11 April to 18 April 2007. Measured and predicted levels are highly correlated. In the mangrove forest, a strong correlation between surface level and inundation characteristics (frequency, depth and duration of inundation) was expected. However, small ridges and basins have a significant effect on the frequency and duration of inundations. The ridges form a barrier to overland flow, so water has to be discharged through the creek system. This causes a higher hydraulic resistance and therefore longer flow routes. These factors are, however, not part of the Watson classification.

Based on this study in 2004 in Can Gio, the hydrological classification according to Watson (1928) was modified. Surface elevation in m+admiralty datum was modified to the easier applicable m+MSL. Also the duration of inundation was included. This modified classification (Hydrological Classification 2004) is shown in Table 2 (Van Loon *et al.*, 2007).

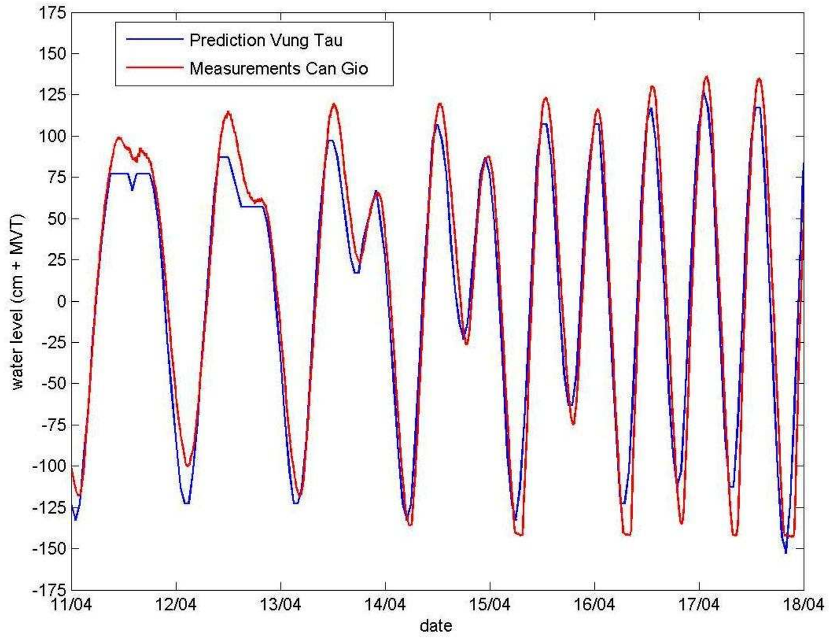


Figure 3 Comparison of predicted water levels for Vung Tau (Vietnam) and measured water levels in the Dongh Tranh river for the period 11 April to 18 April 2007

Table 2 Hydrological classification 2004 (Van Loon *et al*., 2007)

| **Inundation class** | **Tidal regime** *flooded by* | **Elevation** *cm+MSL* | **Flooding frequency** *times per month* | **Duration of inundation** *min per day* | **Duration of inundation** *min per inundation* | **Vegetation** *species* |
|---|---|---|---|---|---|---|
| 1 | all high tides | < 0 | 56 – 62 | > 800 | > 400 | none |
| 2 | medium high tides | 0 – 90 | 45 – 56 | 400 – 800 | 200 – 400 | *Avicennia spp., Sonneratia* |
| 3 | normal high tides | 90 – 150 | 20 – 45 | 100 – 400 | 100 – 200 | *Rhizophora spp., Ceriops, Bruguiera* |
| 4 | spring high tides | 150 – 210 | 2 – 20 | 10 – 100 | 50 – 100 | *Lumnizera, Bruguiera, Acrosticum aureum* |
| 5 | equinoctial tides | > 210 | < 2 | < 10 | < 50 | *Ceriops spp., Phoenix paludosa* |

This Hydrological Classification 2004 gave a better correlation between the hydrological classification and observed species in Can Gio, Vietnam. Especially the new criteria ‘duration of inundation’ proved to be useful. The original Watson (1928) criteria ‘tidal regime’ and ‘flooding frequency’ gave variable results. Additional field research was done in Can Gio and Ca Mau to evaluate the Hydrological Classification 2004. Figure 4 shows the water level fluctuation on the mudflat (A1) to 700 m inland (A6) in Can Gio (Vietnam), from 21 March 13:00 to 22 March 13:00, 2007 (Te Brake and Van Huijgevoort, 2008). When a measurement location is inundated by a rising tide, a clear and direct water level change is visible. Water discharge form the plot is hampered by microtopography, resulting in a delayed water level drop. This delay had no effect on the criteria ‘flooding frequency’, but does have significant effect on the ‘duration of inundation’. Since ‘duration of inundation’ gives more reliable results, the criteria ‘frequency of inundation’ was removed from the hydrological classification.
Several lists of requirements of species with regard to inundation characteristics are given by Watson (1928), Hong and San (1993) and MAB Vietnam National Committee (1998). Mixed zones with both *Avicennia Alba* and *Rhizophora apiculata* were frequently observed during the field campaigns. Although optimum conditions for both species are not in exactly the same range, conditions where they both occur seem sufficient for natural establishment and development of a rather natural ecosystem. As shown in Figure 5, the conditions for such a zone with a higher

biodiversity lies between Hydrological Class 2 and Class 3. This leads to the conclusion that the five classes, as published by Watson (1928) is relatively broad and that the classification could benefit from an additional class. Therefore Class 2* is introduced. Table 3 shows the Hydrological Classification 2008. In this classification, ‘frequency of inundation’ is removed, Class 2* is added, including accompanying species.

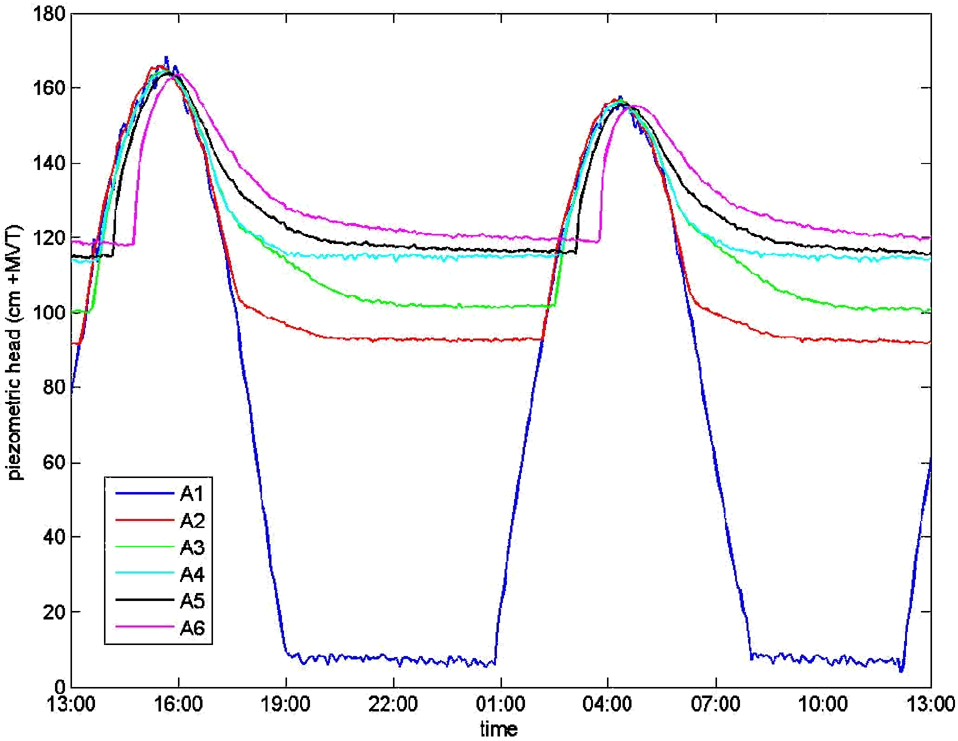


Figure 4 Water levels in Can Gio plot A form 21 March 13:00 to 22 March 13:00, 2007 (Te Brake and Van Huijgevoort, 2008)

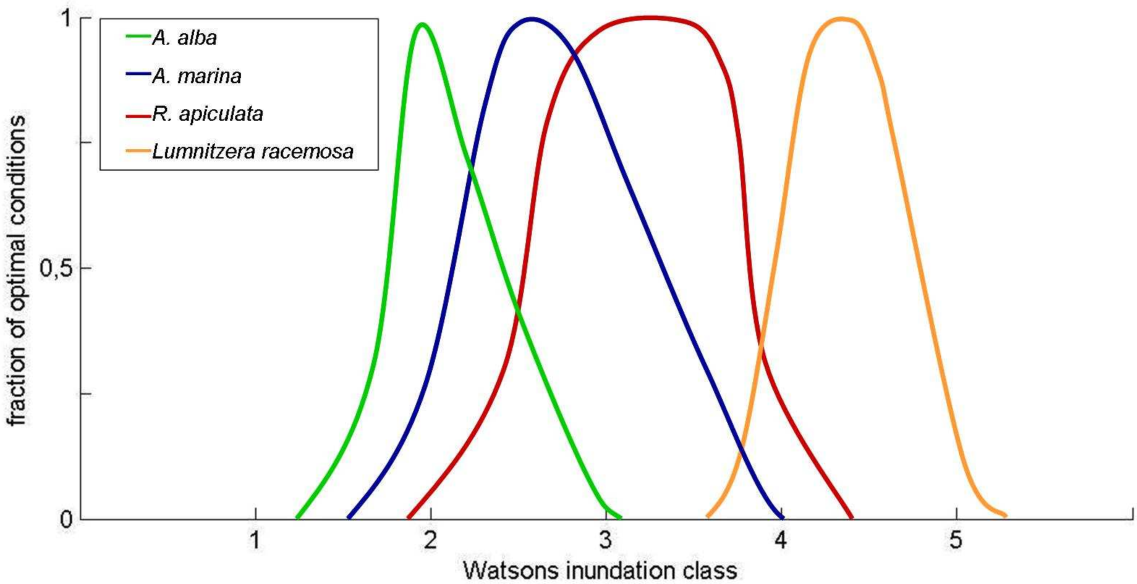


Figure 5 Relation between inundation class and growing conditions for four mangrove species (Te Brake and Van Huijgevoort, 2008)

Table 3 Hydrological classification 2008 (Te Brake and Van Huijgevoort, 2008)

| **Inundation class** | **Tidal regime** *flooded by* | **Elevation** *cm+MSL* | **Duration of inundation** *min per day* | **Duration of inundation** *min per inundation* | **Vegetation** *species* |
|---|---|---|---|---|---|
| 1 | all high tides | < 0 | > 800 | > 600 | none |
| 2 | lower medium high tides | 0 – 50 | 400 – 800 | 450 – 600 | *Avicennia spp., Sonneratia* |
| 2* | higher medium high tides | 50 - 100 | 250 - 400 | 200 - 450 | *Avicennia spp., Rhizophora spp., Bruguiera* |
| 3 | normal high tides | 100 - 150 | 150 – 250 | 100 – 200 | *Rhizophora spp., Ceriops, Bruguiera* |
| 4 | spring high tides | 150 – 210 | 10 – 150 | 50 – 100 | *Lumnizera, Bruguiera, Acrosticum aureum* |
| 5 | equinoctial tides | > 210 | < 10 | < 50 | *Ceriops spp., Phoenix paludosa* |

The Hydrological Classification 2008 was tested in the remaining mangroves in the Mahakam Delta, Kalimantan, Indonesia. Figure 6 shows some measured water levels in the Mahakam Delta. The characteristics are similar to the measured water level fluctuations in Can Gio and Ca Mau, Vietnam (see Figure 4). From these water level measurements, for all plot 'Duration of inundation' was calculated. The average inundation time per day was calculated as average, as median and as geometric mean. Since erroneous measurements - where just one measurement indicates an inundation - can have a major effect on the average inundation time, the effect of a threshold was also tested. All inundations of just one measurement (5 minutes interval) were not considered as inundation.
On all measuring plots the mangrove species were determined. The observed species of all plots (A to F and A'to F') are shown in Table 4. *Rhizophora Stylosa* is related to Class 2* and 3 and *Bruguiera Parviflora* to 2*, 3 and 4. This is visualized by two and three rows in Table 4, respectively (expected according to vegetation). Also, for every plot the inundation class was determined as:

- Average inundation time per day
- Average inundation time per inundation (no threshold)
- Average inundation time per inundation (threshold 5 min)
- Median of inundation time per inundation (no threshold)
- Median of inundation time per inundation (threshold 5 min)
- Geometric mean of inundation time per inundation (no threshold)
- Geometric mean of inundation time per inundation (threshold 5 min)

When the calculated class is in full agreement with the expected class according to the mangrove species found on the plot, then the class is indicated in green. When the calculated and expected class are just one off, then the class is indicated in orange, no agreement is indicated in red. The class 2* is represented by 2,5.

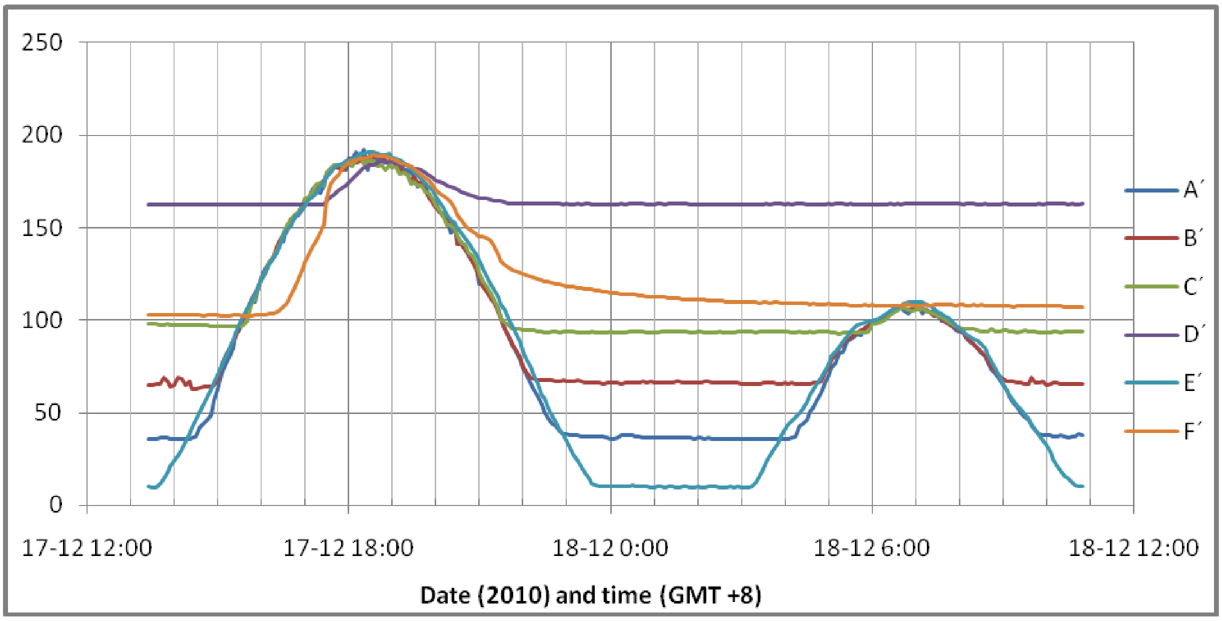


Figure 6 Measured water levels in Mahakam Delta (Indonesia), December 2009

Table 4 Verification of the new hydrological classification in Mahakam Delta, Indonesia

| classification | thres-hold | A | | B | | | C | D | | | F | | | A′ | B′ | | C′ | | | D′ | F′ | agreement | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Avicennia Officinalis | Rizophora Stylosa | Bruguiera Parviflora | Avicennia Officinalis | Rizophora Stylosa | Rizophora Apiculata | Bruguiera Parviflora | Avicennia Officinalis | Rizophora Stylosa | Rizophora Stylosa | Avicennia Officinalis | Sonneratia Caseolaris | Sonneratia Alba | Sonneratia Alba | Avicennia Officinalis | Avicennia Officinalis | Bruguiera Gymnorhiza | Sonneratia Alba | Acrostichum Aureum | Ceriops Decandra | Full agreement | Agreement in one next clas | Full + within one next class | no close agreement |
| Average inundation time per day (I) | | 4 | 4 | 4 | 4 | 4 | 2,5 | 3 | 3 | 3 | 2,5 | 2,5 | 2,5 | 1 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 5 | 4 | | | | |
| Expected according to vegetation | | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 3 | 2,5 | 4 | 3 | 55% | 35% | 90% | 10% |
| | | | 3 | 3 | | 3 | 3 | 3 | | 3 | 3 | | | | | | | 4 | | | 5 | | | | |
| | | | | 4 | | | | 4 | | | | | | | | | | | | | | | | | |
| Average of inundation time per inundation (II) | 0 min | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2,5 | 2,5 | 2,5 | 2,5 | 3 | 3 | 3 | 3 | 3 | 5 | 2,5 | | | | |
| Expected according to vegetation | | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 3 | 2,5 | 4 | 3 | 55% | 45% | 100% | 0% |
| | | | 3 | 3 | | 3 | 3 | 3 | | 3 | 3 | | | | | | | 4 | | | 5 | | | | |
| | | | | 4 | | | | 4 | | | | | | | | | | | | | | | | | |
| Average of inundation time per inundation (III) | 5 min | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 3 | 3 | 3 | 4 | 2,5 | | | | |
| Expected according to vegetation | | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 3 | 2,5 | 4 | 3 | 70% | 30% | 100% | 0% |
| | | | 3 | 3 | | 3 | 3 | 3 | | 3 | 3 | | | | | | | 4 | | | 5 | | | | |
| | | | | 4 | | | | 4 | | | | | | | | | | | | | | | | | |
| Median of inundation time per inundation (IV) | 0 min | 3 | 3 | 3 | 3 | 3 | 2,5 | 3 | 3 | 3 | 2,5 | 2,5 | 2,5 | 2,5 | 5 | 5 | 4 | 4 | 4 | 5 | 2,5 | | | | |
| Expected according to vegetation | | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 3 | 2,5 | 4 | 3 | 55% | 25% | 80% | 0% |
| | | | 3 | 3 | | 3 | 3 | 3 | | 3 | 3 | | | | | | | 4 | | | 5 | | | | |
| | | | | 4 | | | | 4 | | | | | | | | | | | | | | | | | |
| Median of inundation time per inundation (V) | 5 min | 3 | 3 | 3 | 3 | 3 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 3 | 3 | 3 | 4 | 2,5 | | | | |
| Expected according to vegetation | | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 3 | 2,5 | 4 | 3 | 75% | 25% | 100% | 0% |
| | | | 3 | 3 | | 3 | 3 | 3 | | 3 | 3 | | | | | | | 4 | | | 5 | | | | |
| | | | | 4 | | | | 4 | | | | | | | | | | | | | | | | | |
| Geometric mean of inundation time per inundation (VI) | 0 min | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 2,5 | 2,5 | 2,5 | 2,5 | 5 | 5 | 4 | 4 | 4 | 5 | 3 | | | | |
| Expected according to vegetation | | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 3 | 2,5 | 4 | 3 | 55% | 20% | 75% | 25% |
| | | | 3 | 3 | | 3 | 3 | 3 | | 3 | 3 | | | | | | | 4 | | | 5 | | | | |
| | | | | 4 | | | | 4 | | | | | | | | | | | | | | | | | |
| Geometric mean of inundation time per inundation (VII) | 5 min | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2,5 | 2,5 | 2,5 | 2,5 | 3 | 3 | 3 | 3 | 3 | 4 | 2,5 | | | | |
| Expected according to vegetation | | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 3 | 2,5 | 4 | 3 | 60% | 40% | 100% | 0% |
| | | | 3 | 3 | | 3 | 3 | 3 | | 3 | 3 | | | | | | | 4 | | | 5 | | | | |
| | | | | 4 | | | | 4 | | | | | | | | | | | | | | | | | |

From the comparison between the observed species on the various plots and the expected classification, as shown in Table 4, it can be concluded that ‘Average inundation in minutes per day’ shows full agreement in 55% of the plots, and 35% is just one class off. In total 90% of the species has a (rather) good agreement. The results of ‘Inundation time in minutes per inundation’ seem to correlate better than the results of ‘Inundation time in minutes per day’. The ‘Average inundation time' with a threshold of 5 min, and also the 'Median inundation time' with a 5 min threshold, result in an agreement of 70 and 75% respectively and even 100% agreement within one class next to the expected class. According to these results the Hydrological Classification was improved once more. The result of this improvement is shown in Table 5.

Table 5 Hydrological classification 2010 (Oostewaal, 2010)

| **Inundation class** | **Tidal regime** *flooded by* | **Elevation** *cm+MSL* | **Duration of inundation** *min per inundation* | **Vegetation** *species* |
|---|---|---|---|---|
| 1 | all high tides | < 0 | > 600 | none |
| 2 | lower medium high tides | 0 – 50 | 450 – 600 | *Avicennia spp., Sonneratia* |
| 2* | higher medium high tides | 50 - 100 | 200 - 450 | *Avicennia spp., Rhizophora spp., Bruguiera parviflora* |
| 3 | normal high tides | 100 - 150 | 100 – 200 | *Avicennia officinalis, Rhizophora spp., Ceriops, Bruguiera* |
| 4 | spring high tides | 150 – 210 | 50 – 100 | *Lumnizera, Bruguiera, Acrosticum aureum* |
| 5 | equinoctial tides | > 210 | < 50 | *Ceriops spp., Phoenix paludosa* |

The Hydrological Classification that Watson developed (1928) evaluated in the course of this research to the Hydrological Classification 2010 (Oostewaal, 2010). The classification provides a good agreement between expected species form the 'Duration of inundation in min per inundation' and the observed species. This means that the Hydrological Classification 2010 can be used for selecting favorable locations for mangrove rehabilitation. In order to make the use of the classification as simple and straight forward as possible, an implementation tool was developed. In order to get a good indication on the rehabilitation possibilities of an deteriorated mangrove forest, a set of water level measurements can be imported in the tool. The tool immediately indicates to which inundation class the forest belongs and therefore which species can be expected or planted.

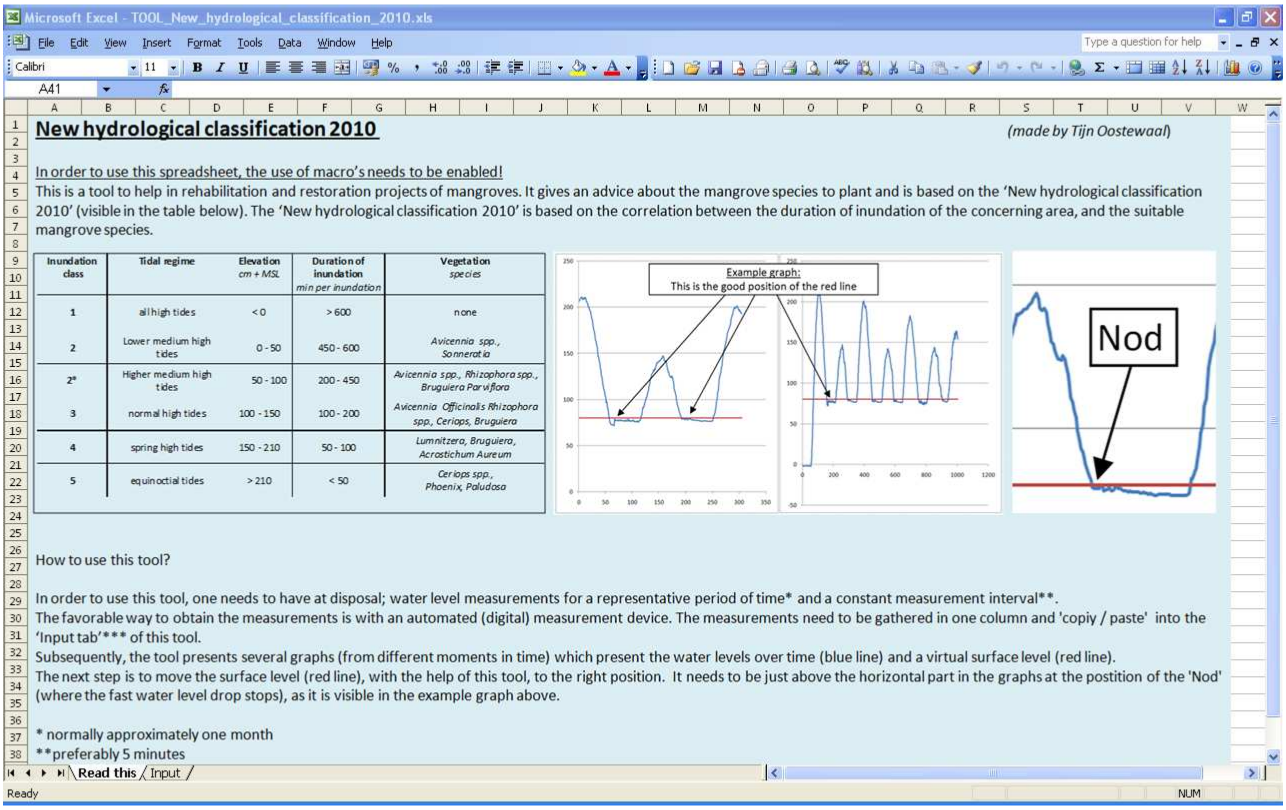


Figure 7 Tool for identifying rehabilitation possibilities of mangrove forests (Oostewaal, 2011)

## 5. Conclusions

Extensive field research showed a strong correlation between species expected from 'Duration of inundation in minutes per inundation' and the observed species. From that the Hydrological Classification, as developed by Watson (1928) was adapted and simplified. A simple tool was developed to provide useful information for mangrove rehabilitation projects.


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