# Improving Hydrological Models of The Netherlands using ALOS PALSAR

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# IMPROVING HYDROLOGICAL MODELS OF THE NETHERLANDS USING ALOS PALSAR

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## ABSTRACT

In this paper the improvement of the hydrological model metaSWAP of The Netherlands, with respect to soil moisture, is studied using remote sensing data. Therefore we investigate the value of ALOS PALSAR data of 2007 in combination with the method of Dubois et al. [1] for measuring volumetric moisture content. Study area is the eastern part of the water board Hoogheemraadschap De Stichtse Rijnlanden, southeast of the city of Utrecht in The Netherlands. Comparing the results of Dubois' empirical model with the metaSWAP calculations resulted in a Root Mean Square Error (RMSE) of 12 % (24 March 2007) and 17 % (9 May 2007). In both cases ALOS PALSAR underestimates metaSWAP. The second RMSE is higher than the first due to rainfall during acquisition.

## 1. INTRODUCTION

Remote sensing is an interesting method to calibrate and improve spatial hydrological models that estimate the spatial distribution of volumetric moisture content. Unlike groundwater levels it is possible to gather spatially distributed patterns of soil moisture from space. Although the temporal resolution of the remote sensing data is often low, the spatial coverage makes it a promising additional dataset for model improvements.

In The Netherlands metaSWAP is a widely-used spatial hydrological model. It is a coupled groundwater and unsaturated zone model. The groundwater model is based on the MODFLOW code [2]. The unsaturated zone model is a quasi steady-state model that uses a sequence of steady state water content profiles for dynamic simulation [3]. Input of this model is precipitation, reference evapotranspiration, soil type, and land use. Output is soil moisture, groundwater level and run-off. The improvement of metaSWAP with remote sensing data has been studied by Schuurmans [4] using ASTER and MODIS. In this paper we study the value of ALOS PALSAR polarimetric data in combination with the method of Dubois et al. [1], by comparing its results with metaSWAP calculations.

ALOS PALSAR [5] is a synthetic aperture radar (SAR) system, and at this moment the only SAR that operates at a wavelength of 24 cm (L-band). Other satellites operate at wavelengths of 5.3 cm (C-band) and 3.1 cm (X-band). The advantage of a longer wavelength is that it deeper penetrates volumes, and therefore reduces the impact of vegetation on soil moisture measurements. The penetration depth of soils is in the order of several wavelengths, but is dependent on the moisture content [6].

Study area for comparing ALOS PALSAR and metaSWAP is the eastern part of the water board Hoogheemraadschap De Stichtse Rijnlanden, southeast of the city of Utrecht in The Netherlands, see Fig. 1. It is referred to as the Langbroekerwetering area.

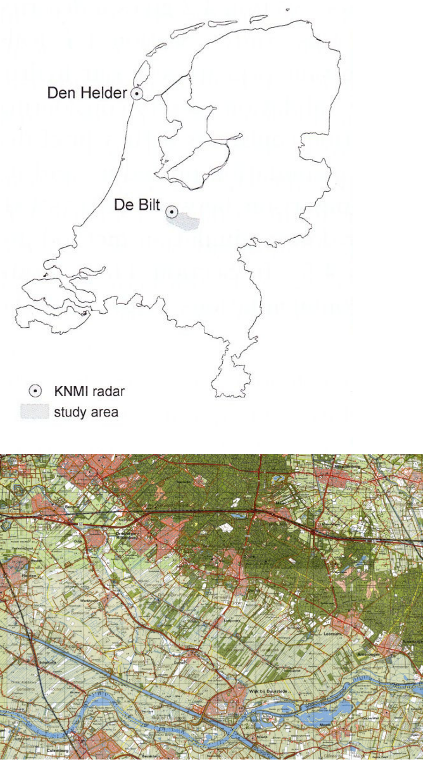


*Figure 1. Location of the Langbroekerwetering area within The Netherlands and map.*

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## 2. METHOD

The method of Dubois et al. [1] that is studied, is based on the empirical relation between volumetric moisture content (in $m^3/m^3$), the electromagnetic surface roughness (in m), and the HH and VV radar backscatter ($\sigma^0$). HH stands for horizontal transmit and receive polarisations, VV for vertical transmit and receive polarisations. The relation is described by Eq. 1 and 2:

$$\begin{aligned}\sigma^0_{HH} &= 10^{-2.75}\frac{\cos^{1.5}\theta}{\sin^5\theta}10^{0.028\varepsilon\tan\theta}(kh\sin\theta)^{1.4}\lambda^{0.7}\\ \sigma^0_{VV} &= 10^{-2.35}\frac{\cos^{3}\theta}{\sin^3\theta}10^{0.046\varepsilon\tan\theta}(kh\sin\theta)^{1.1}\lambda^{0.7}\end{aligned} \quad (1)$$

$$\varepsilon = (a_0 + a_1 S + a_2 C) + (b_0 + b_1 S + b_2 C)m_v + (c_0 + c_1 S + c_2 C)m_v{}^2 \quad (2)$$

Here $\theta$ is the incidence angle on the ground, $\varepsilon$ is the dielectric constant of the soil, $\lambda$ is the radar wavelength, $h$ is the electromagnetic surface roughness, $k = 2\pi/\lambda$ is the wave number, $S$ and $C$ stand for the sand and clay fractions of the soil particles (range between 0 and 1), and $m_v$ is the volumetric moisture content. The latter is relative to the volume of the soil "sample holder", that is: relative to the sum of the volume of the soil particles and the pores [7]. The maximum volumetric moisture content is therefore limited by the pore volume. Tab. 1 shows some typical pore volume values.

*Table 1. Typical values for pore volume of some basic soil types* [8].

| **Soil type** | **Pore volume (%)** |
|---|---|
| Peat | 60-80 |
| Silt | 35-60 |
| Clay | 35-55 |
| Sand | 30-45 |
| Loam | 25-45 |

The coefficients $a$, $b$, and $c$ in Eq. 2 are described by Hallikainen et al. [7]. For L-band Eq. 2 becomes:

$$\begin{aligned}\varepsilon = {} & (2.862 - 0.012S + 0.001C) + (3.803 + 0.462S - 0.341C)m_v + \\ & (119.006 - 0.500S + 0.633C)m_v{}^2\end{aligned} \quad (3)$$

This shows that the dielectric constant is dominated by the volumetric moisture content, and not by the soil composition.

Inverting the relation of Eq. 1 and 2 yields the soil moisture from the radar backscatter. The boundary conditions of this relation is shown in Tab. 2, that also shows the parameters of ALOS PALSAR. Note that these parameters are just outside the boundary of the empirical model. Comparison of ALOS PALSAR and the metaSWAP soil moisture calculations will be done by means of a parcel-based regression analysis.

*Table 2. Boundary conditions of the empirical model of Dubois et al.* [1], *and ALOS PALSAR parameters.*

| **Parameter** | **Dubois et al. (1995)** | **ALOS PALSAR** |
|---|---|---|
| Frequency | 1.5…11 GHz | 1.27 GHz |
| Wavelength | 2.7…20 cm | 24 cm |
| Incidence angle | ≥ 30º | 22º…26º |
| Volumetric moisture content | ≤ 35 % | |
| Surface roughness | ≤ 0.4 λ | |
| NDVI | ≤ 0.4 | |
| RMSE | 4.2 % (1.5 GHz) | |

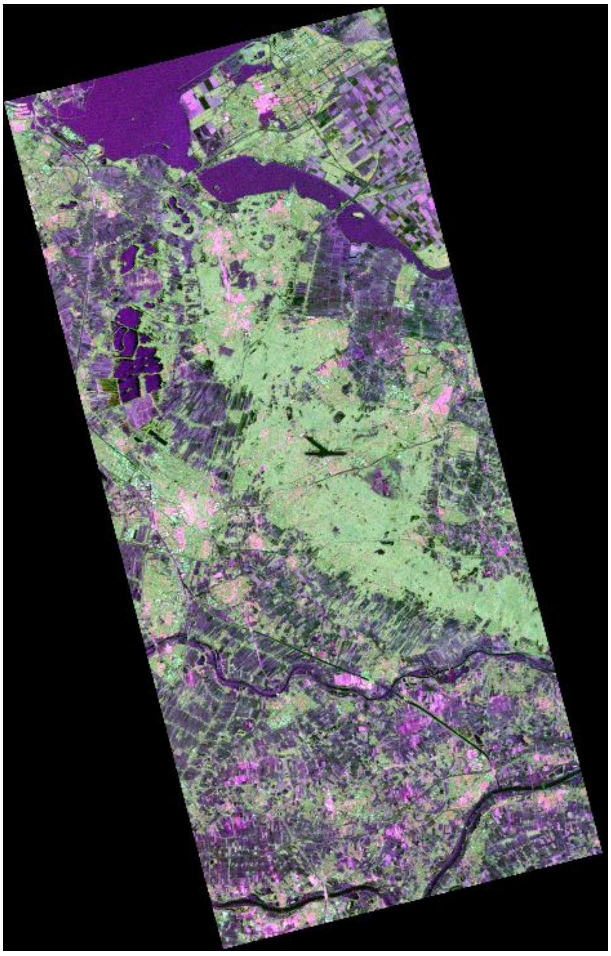

*Figure 2. ALOS PALSAR image of the Langbroekerwetering area of 24 March 2007. Channel order is Red = HH, Green = HV, and Blue = VV.*

## 3. DATA AND PRE-PROCESSING

### 3.1. ALOS PALSAR

ALOS PALSAR polarimetric data is acquired in two slots, one from 7 March - 7 June 2007, and one from 12 March - 12 June 2009 [5]. During the first slot two images containing the Langbroekerwetering area were acquired (24 March 2007 and 9 May 2007). The first image is shown in Fig. 2. The fact that there are only two slots of polarimetric acquisitions means that it is not possible to study longer time series.

The ALOS PALSAR images were processed by ERSDAC to level 4.1, which means that the data are polarimetric calibrated. The images were geocoded to the WGS84 ellipsoid using cubic-convolution resampling. Projection is UTM Zone 31. Because all other data is in Rijksdriehoekstelsel (RD), the national grid of The Netherlands, the ALOS PALSAR images were transformed to RD using nearest-neighbour resampling. Resolution of the images is 30 m, pixel spacing is 25 m.

SAR images in general contain speckle noise. To reduce this noise a moving average filter with a kernel of 3×3 pixels (75×75 m) was applied. Side effect is that the resolution is reduced accordingly. The images are provided in Beta-nought units (radar brightness), and were converted to Sigma-nought ($\sigma^0$) by multiplying with the sine of the incidence angle:

$$\sigma^0 = \beta^0 \sin\theta \qquad (4)$$

The incidence angle for each pixel was derived from the metadata.

### 3.2. Soil map

To determine the sand and clay fractions of the upper soil layer, a soil map of the Geological Survey of The Netherlands was used, see Fig. 3. The resolution of the soil map varies from 25 m (inner area) to 100 m (outer area). The soil map is classified into 21 soil types (excluding water and built-up) that are a composition of 18 topsoil components ("bovengronden"), and 18 subsoil components ("ondergronden") [9]. With the help of the soil texture triangle of The Netherlands [10], the composed soil types were translated into sand and clay fractions of the upper 1 m of soil (about four times the radar wavelength). This layer corresponds roughly with the root zone of the metaSWAP numerical model (between 10 and 70 cm). Topsoil and subsoil compositions of the Langbroekerwetering area correspond rather well for the first 1 m. Tab. 3 shows the resulting soil fractions.

### 3.3. Land use

Land use is obtained from the Netherlands national land-use database LGN4 [11] to analyse and exclude the volumetric moisture content of certain classes. ALOS PALSAR can not measure soil moisture from sealed surfaces (urban, paved roads) and forest canopies (L-band is to short to penetrate forest volumes, therefore longer wavelengths are required: P-band and longer). The LGN4 from the Langbroekerwetering area dates from 1999. The main land uses, forest and grassland, have hardly changed in this area in the period between 1999 and 2007. The exact crop type of the agricultural fields (i.e. maize, beet, grain) is uncertain as farmers change this often. LGN4 land use is obtained from Landsat 7 ETM+ and has a resolution of 25 m.

### 3.4. Meteorological data

To check the utility of ALOS PALSAR for soil moisture measurements, and to have a rough indication of the volumetric moisture content, meteorological data was taken into account as well. Fig. 4 shows the per-day precipitation of De Bilt (see Fig. 1) between 8.00 and 8.00 UTC. The graph shows an almost dry period of more than 40 days between the acquisitions of the ALOS PALSAR images (24 March 2007 and 9 May 2007, day-of-year 83 respectively 129). The graph also indicates that on day 83 no precipitation was measured, and that on day 127 until 129 heavy rain occurred (> 10 mm per day).

To check if it was raining during the acquisition of the ALOS PALSAR images (both 21:43 UTC), historical rainfall images were retrieved from the KNMI (Royal Netherlands Meteorological Institute) radar in De Bilt (see Fig. 1 ). These images show that it has been raining at least 4 hours previous to 21:43 UTC on 9 May 2007.

### 3.5. Normalised Difference Vegetation Index

The Normalised Difference Vegetation Index (NDVI) is determined to have an indication of how much vegetation exists in the different fields. It is used to satisfy the model boundary conditions in Tab. 2. Input for the index is Landsat 7 ETM+ band 3 (red) and 4 (near infrared):

$$NDVI = \frac{Band\,4 - Band\,3}{Band\,4 + Band\,3} \qquad (5)$$

Range of the index is -1 to 1. The higher the index, the higher the contribution of vegetation. Closest cloudless Landsat 7 ETM+ images of the Langbroekerwetering area are from 15 April 2007 and 1 May 2007. Fig. 5 shows the vegetation index extracted from 15 April 2007. Range is -0.58 to 0.67. The image shows that a considerable number of agricultural fields has a vegetation index larger than 0.4. The vegetation index of forest is still rather low, but forest is excluded from the analysis (see Section 3.3). The diagonal stripes in the right part of the image are due to a defect in the Scan-Line Corrector (SLC). The SLC of Landsat 7 ETM+ started to fail on 31 May 2003, and is permanently turned off since 6 June 2007 [12].

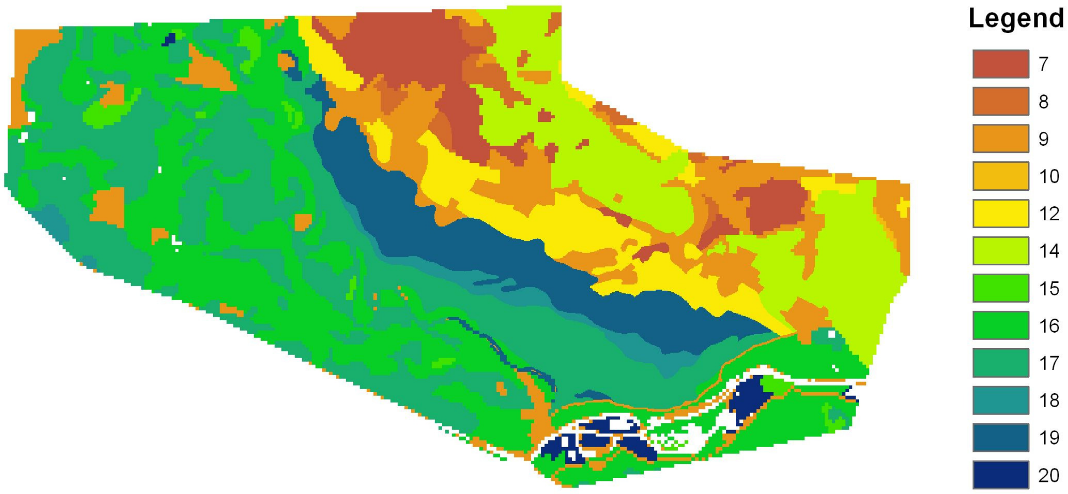


*Figure 3. Soil map of the Langbroekerwetering area (source: Alterra Wageningen UR, The Netherlands).*

*Table 3. Sand, silt, and clay fractions (%) of the soil types present in the Langbroekerwetering area.*

| Soil type | Designator (in Dutch) | Sand | Silt | Clay | Sum |
|---|---|---|---|---|---|
| 7 | Drift sand | 95 | 5 | 0 | 100 |
| 8 | Podzol in loam poor fine sand | 95 | 5 | 0 | 100 |
| 9 | Podzol in loamy fine sand | 85 | 15 | 0 | 100 |
| 10 | Podzol in loamy fine sand on coarse sand | 85 | 15 | 0 | 100 |
| 12 | Enkeerd in loamy fine sand | 85 | 15 | 0 | 100 |
| 14 | Podzol in coarse fine sand | 95 | 5 | 0 | 100 |
| 15 | Sandy clay | 50 | 35 | 15 | 100 |
| 16 | Light clay | 30 | 45 | 25 | 100 |
| 17 | Clay with heavy layers | 0 | 25 | 75 | 100 |
| 18 | Clay on peat | 0 | 25 | 75 | 100 |
| 19 | Clay on sand | 50 | 35 | 15 | 100 |
| 20 | Clay on coarse sand | 50 | 35 | 15 | 100 |

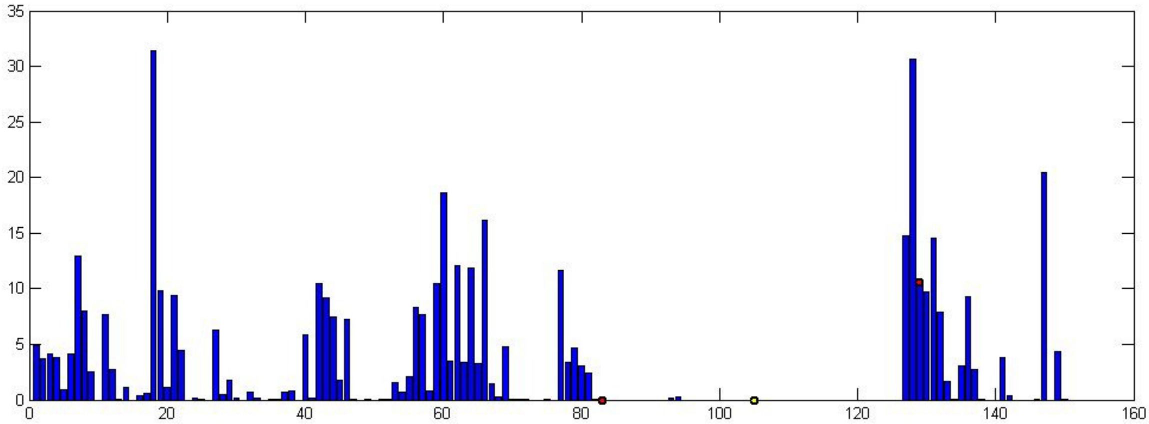


*Figure 4. Precipitation in mm per day measured at De Bilt weather station (see Fig. 1) in 2007 (source: KNMI). Horizontal = day-of-year, vertical = precipitation between 8:00 and 8:00 UTC. The red dots represent the ALOS PALSAR acquisitions, the yellow dot represents the Landsat 7 ETM+ acquisition at 15 April 2007.*

## 4. RESULTS AND DISCUSSION

The volumetric moisture content was determined from the filtered ALOS PALSAR images using the method described in Section 2. The incidence angle that was used to convert from radar brightness to Sigma-nought (see Section 3.1) was also used in Eq. 1. Sand and clay fractions were obtained from the soil map as described in Section 3.2. The result of 24 March 2007 is shown in Fig. 6. The no-data values are due to the fact that there is no soil data (see Fig. 3), and to the fact that Eq. 1 and 2 could not be inverted for a part of the Sigma-nought pairs (HH and VV). The latter occurs more often in urban and forested areas, giving evidence to the fact that it is harder to measure soil moisture in these areas with an L-band system (see also Section 3.3).

The result of 24 March 2007 shows a higher volumetric moisture content than that of 9 May 2007, in particular for the agricultural fields. The second image is also more affected by random noise. Reason for these observations might be rainfall during acquisition on 9 May 2007 (see Section 3.4). Due to rainfall the surfaces are too wet for the radar waves to penetrate vegetation and soil.

The metaSWAP calculation of the volumetric moisture content of 24 march 2007 is shown in Fig. 7. The image clearly reflects the input soil map, that is equal to the map used to determine soil moisture with ALOS PALSAR, see Fig. 3. For the land cover map this is unknown. The edges in Fig. 7, that correspond with the transition of one soil type to another, are not realistic. It seems that metaSWAP overestimates the effect of soil composition.

Comparing the ALOS PALSAR and metaSWAP results, a field approach was followed, taking into account the boundary conditions of Dubois' method (see Tab. 2). Fields were obtained from the LGN4 land-use map of 1999 (see Section 3.3). Selected were those fields that contained grass, maize, beet and grain. Other agricultural fields were excluded because they were less numerous (e.g. potatoes). For reasons previously mentioned, forest, water, urban, infrastructure, and built-up (including greenhouses) were excluded too. Nature areas might have been used, but were less numerous, or contained significant vegetation (forest, heather, reed).

The per-field average volumetric moisture content of grass, maize, beet and grain were computed excluding all no-data pixels (no soil moisture, no soil type, no land use, and no NDVI due to Landsat 7 ETM+ SLC failure), and excluding all pixels with a NDVI larger than 0.4. The remaining fields with less than 20 pixels (1.25 ha) were excluded too, even as the remaining fields larger than 200 pixels (12.5 ha). Reason for that is that small fields do not contain enough samples to compute a reliable average, and that large fields possibly contain to much variation in soil moisture and vegetation.

The numbers of fields that came out of this selection were 263 for 24 march 2007 and 267 for 9 May 2007. For these fields the average ALOS PALSAR volumetric moisture content and the average metaSWAP volumetric moisture content were computed. The results are visualised in two scatter plots, see Fig. 8, together with their regression lines. Regression parameters, including correlation coefficient and RMSE, are shown in Tab. 4. Before analysing the results it must be noted that outliers were excluded from the scatter plots. For the data of 24 March 2007 these were an ALOS PALSAR volumetric moisture content value of 64.5 %, and a metaSWAP volumetric moisture content value of 1.2 %. For the data of 9 May 2007 this was only a metaSWAP volumetric moisture content value of 1.2 %. The remaining total numbers of fields were 261 respectively 266.

The results show low correlation values, in which the values of 9 May 2007 are an order of magnitude lower than of 24 March 2007. The result of 9 May 2007 supports the theory that due to rainfall the surfaces are too wet for the radar waves to penetrate vegetation and soil, and to measure the volumetric moisture content in a proper way. Most likely this effect dominates the effect that the NDVI is from 24 days earlier (15 April 2007) instead of 8 days earlier (1 May 2007).

Focussing on the measurements of 24 March 2007, an additional field constraint was applied in an attempt to improve the result. Because the boundary of Dubois' method on the volumetric moisture content is 35 % (see Tab. 2), all fields with a lower average metaSWAP volumetric moisture content were excluded. However, this slightly worsened the regression. Splitting up the analysis per crop type (grass, maize, beet and grain) lead to the results shown in Tab. 5. Splitting up the analysis per soil type showed no correlation either. For comparison, the regression parameters of the series of Dubois et al. [1] are shown in Tab. 6.

Schuurmans [4] compared metaSWAP with in-situ measurements using ECH2O EC-20 probes in the same area. The measurements were done in duplex (two probes at a horizontal distance of 1 m) in 2006. Tab. 7 shows its regression analysis at a depth of 30 cm (about the wavelength of ALOS PALSAR). Characteristics of the locations are shown in Tab. 8. Results show the error of metaSWAP, but with a strong variation. Unfortunately ALOS PALSAR and the in-situ measurements are not correlated, so the contributions of ALOS PALSAR and metaSWAP to the errors in Tab. 4 and 5, can not be quantified.

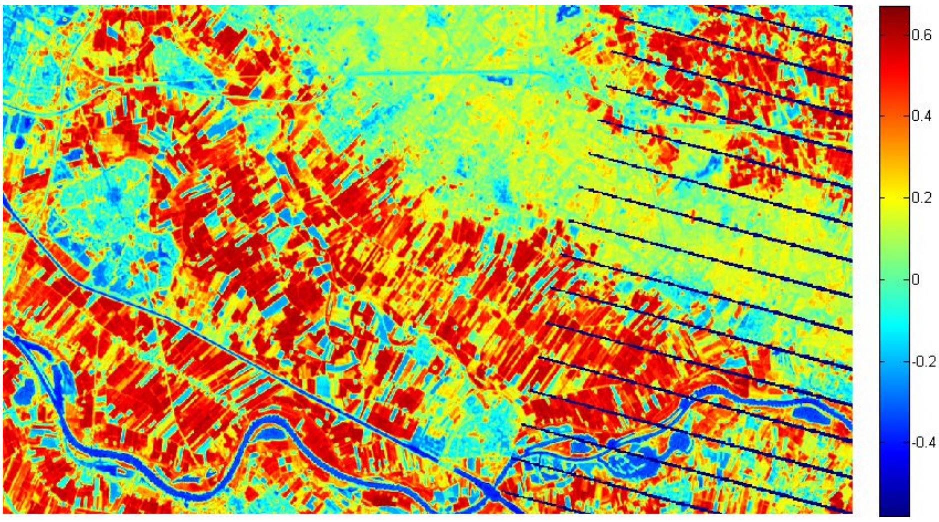


*Figure 5. NDVI of the Langbroekerwetering area of 15 April 2007. Range is between 0.67 and -0.58.*

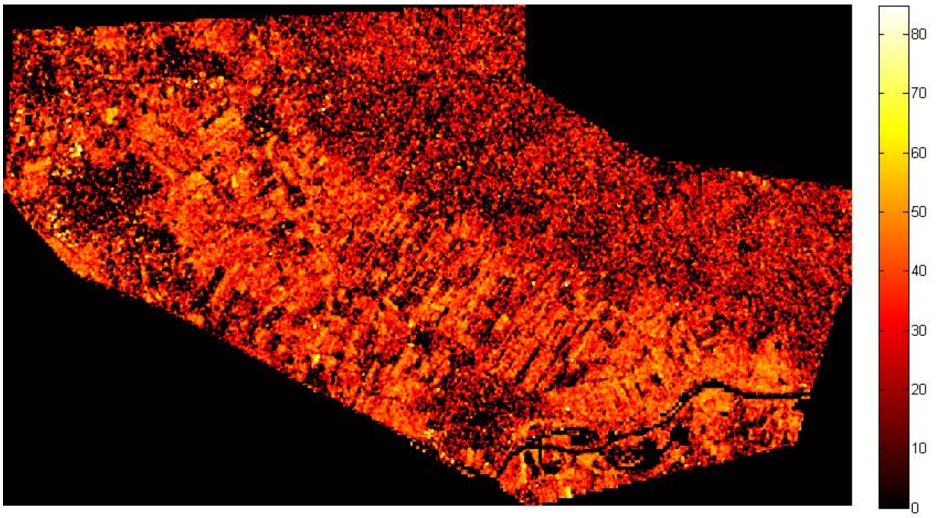


Figure 6. ALOS PALSAR volumetric moisture content on 24 March 2007.

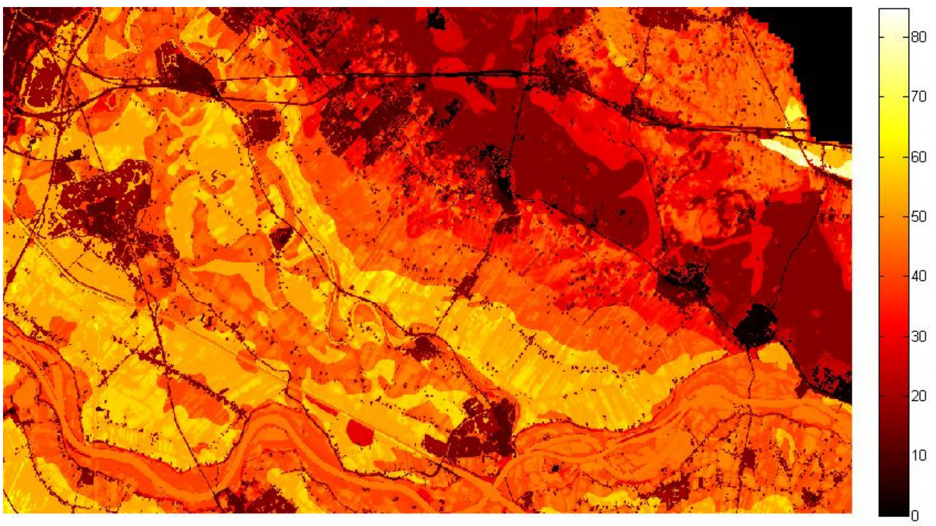


Figure 7. metaSWAP volumetric moisture content on 24 March 2007.

To say more on the reliability of ALOS PALSAR and metaSWAP, and about the value of ALOS PALSAR for metaSWAP, it is recommended to repeat the experiment and synchronise both with in-situ measurements. Another possibility to improve metaSWAP is to study longer time-series (e.g. [13]) in combination with in-situ measurements, however for ALOS PALSAR this means you have to switch to another method. ALOS PALSAR only acquires longer time-series in Scansar HH single-polarisation mode.

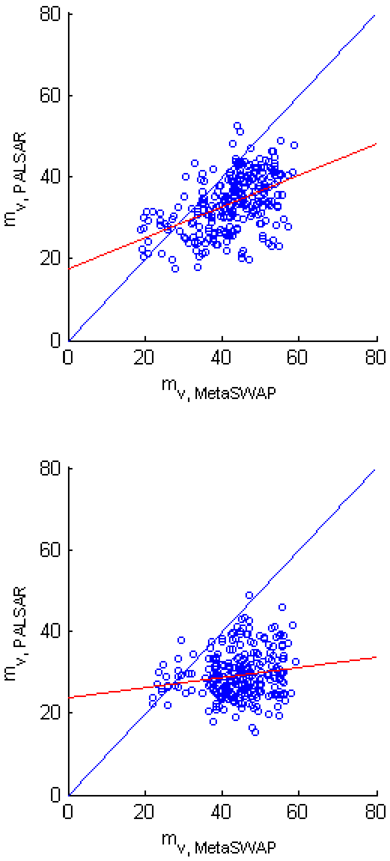


*Figure 8. Scatter plots of the volumetric moisture content of ALOS PALSAR and metaSWAP of selected fields on 24 March 2007 (top) and 9 May 2007 (bottom).*

*Table 4. Regression parameters of the volumetric moisture content of ALOS PALSAR and metaSWAP of selected fields.*

| **Date** | **Nr of fields** | **a** | **b** | **$r^2$** | **RMSE** |
|---|---|---|---|---|---|
| 24/03/07 | 261 | 0.3823 | 17.35 | 0.2258 | 12.05 |
| 09/05/07 | 266 | 0.1262 | 23.82 | 0.0303 | 17.32 |

$m_{v,PALSAR} = a * m_{v,metaSWAP} + b$

*Table 5. Regression parameters of the volumetric moisture content of ALOS PALSAR and metaSWAP of 24 March 2007 of selected fields, per field type*

| **Field type** | **Nr of fields** | **a** | **b** | **$r^2$** | **RMSE** |
|---|---|---|---|---|---|
| All | 261 | 0.3823 | 17.35 | 0.2258 | 12.05 |
| Grass | 105 | 0.2622 | 20.30 | 0.1501 | 12.75 |
| Maize | 135 | 0.3933 | 18.35 | 0.2067 | 11.56 |
| Beet | 9 | 0.8640 | -3.71 | 0.5598 | 11.20 |
| Grain | 12 | 0.3482 | 18.19 | 0.3869 | 11.71 |

$m_{v,PALSAR} = a * m_{v,metaSWAP} + b$

*Table 6. Regression parameters of the volumetric moisture content of the method for imaging radars, and in-situ measurements, by Dubois et al.* [1].

| **Field type** | **Nr of fields** | **a** | **b** | **$r^2$** | **RMSE** |
|---|---|---|---|---|---|
| Various | 19 | 0.8624 | 4.59 | 0.7416 | 4.22 |

$m_{v,SAR} = a * m_{v,in\text{-}situ\ measurements} + b$

*Table 7. Regression parameters of the volumetric moisture content of ECH20 probes at a depth of 30 cm, and metaSWAP of selected fields.*

| **Location** | **Nr of meas. in time** | **a** | **b** | **$r^2$** | **RMSE** |
|---|---|---|---|---|---|
| SK1 | 213 | 1.9485 | -56.02 | 0.5258 | 10.09 |
| SK2 | 213 | 1.3257 | -21.60 | 0.6164 | 6.15 |
| SZ1 | 214 | 0.6316 | 4.44 | 0.5156 | 12.17 |
| SZ2 | 136 | 0.4455 | 16.73 | 0.4952 | 8.00 |
| GD1 | 150 | 1.6089 | -21.07 | 0.5850 | 6.74 |
| GD2 | 150 | 0.8344 | -4.22 | 0.7494 | 9.94 |
| WL1 | 122 | 0.4743 | -2.83 | 0.7221 | 17.16 |
| WL2 | 50 | 0.5203 | -3.09 | 0.6334 | 17.33 |
| LB1 | 245 | 0.6880 | 3.95 | 0.6034 | 2.99 |
| LB2 | 245 | 0.6922 | 4.23 | 0.5404 | 3.40 |

$m_{v,ECH2O} = a * m_{v,metaSWAP} + b$

*Table 8. Characteristics of probe locations.*

| **Location** | **Field type** | **Soil type** | **Sand [%]** | **Silt [%]** | **Clay [%]** |
|---|---|---|---|---|---|
| SK | Grass | 18 | 0 | 25 | 75 |
| SZ | Grass | 19 | 50 | 35 | 15 |
| GD | Grass | 9 | 85 | 15 | 0 |
| WL | Grass | 12 | 85 | 15 | 0 |
| LB | Forest | 7 | 95 | 5 | 0 |

## 5. CONCLUSIONS

Analysing the ALOS PALSAR volumetric moisture content, obtained using Dubois' empirical model, and the metaSWAP volumetric moisture content of the Langbroekerwetering study area, resulted in a correlation ($r^2$) of 0.23 based on 261 agricultural fields on 24 March 2007, and a correlation of 0.03 based on 266 fields on 9 May 2007. The number of fields was limited to those with a NDVI $\leq$ 0.4. The RMSE is respectively 12 % and 17 %. The results of 9 May 2007 are worse due to rainfall during acquisition. Excluding all fields with a metaSWAP volumetric moisture content larger than 35 % (i.e. the boundary of Dubois' empirical model) did not improve the results. There is no optimum correlation for a specific crop type or soil type. The study of Dubois et al. [1] resulted in a correlation of 0.74, and a RMSE of 4.2% based on in-situ measurements of 19 fields.

Comparing metaSWAP with in-situ measurements of 2006 showed the error of metaSWAP, that varies for the different measurement locations. Unfortunately ALOS PALSAR and the in-situ measurements are not correlated, so the contributions of ALOS PALSAR and metaSWAP to the observed errors, can not be quantified.

To say more on the reliability of ALOS PALSAR and metaSWAP, and about the value of ALOS PALSAR for metaSWAP, it is recommended to repeat the experiment and synchronise both with in-situ measurements. Another possibility to improve metaSWAP is to study longer time-series in combination with in-situ measurements.

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