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Data and Information Needs in Inland and Coastal Water Quantity Management

In view of Earth Observation developments

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Summary
The objective of this study is on summarizing the current data and information needs in inland and coastal water management with a focus on water quantity. In order to structure user demands a framework of Essential Water and Coastal Variables has been applied. Current demands regarding information on these variables for water and coastal management has been mapped on current and near future capabilities in earth observation in order to assess current gaps in observational capabilities and technical user demands. Secondly, an assessment has been made of societal, scientific and economic demands for better information regarding the variables treated in this study.

Quantitative estimates regarding evapotranspiration, root zone soil moisture, water extent and sea surface temperature already can be retrieved from earth observation with spatial and temporal resolutions and accuracies which come a long way in meeting requirements for water management.

A significant gap between the capabilities offered by earth observation and the information needed for water and coastal management still exists for adequate information on change in groundwater storage, Snow Water Equivalent (SWE), (sea) water level, topography and coastal bathymetry.

Flood protection is seen to be an area of inland and coastal water management where earth observation has potentially the largest socio-economic benefit. Improved observations regarding precipitation, (sea) water level, elevation and bathymetry will contribute most to improved flood mitigation and flood response.

Drought warning and food security is seen as a second area where earth observation has potentially large socio-economic benefit, especially by improving the skill of water resources and crop forecasting models. For those applications observations regarding changes in groundwater storage, soil moisture and evapotranspiration are of particular benefit.

Globally, water resources are becoming increasingly stressed due to global increase in population, increased economic affluency and climate change. Though the effects will vary locally, depleting groundwater resources and decreasing storages of fresh water in snow and glaciers are particularly relevant in this respect as well as observations regarding changes in groundwater storage and snow water equivalence.

Earth observation regarding inland and coastal water management has currently most commercial relevance for crop and energy production. Reservoir management for energy production is another commercial application which benefits from earth observation data on snow mapping, estimations on snow water equivalence and water level. The increased development of wind at sea is a growing field of applications which needs long term records of water level and significant wave height.

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Earth observations of all components of the coastal and hydrological system will play an important role for future research objectives. Most relevance might be expected for its opportunity to cover the whole globe and thereby contributing to an understanding of coastal lowland systems under varying conditions. In terms of understanding the mechanisms of climate change, particular interest is paid to observations of land –atmosphere interaction and the coupling of the energy and water balances, such as precipitation, evapotranspiration and soil moisture.

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Contents

1 Introduction

Knowledge of the state of inland and coastal water systems is of prime importance to societal, ecological and economic development. No society can thrive without having a keen eye on existing water resources and future developments, be it developments leading to scarcity or to flooding. This asks for a good understanding of water dynamics through time and space which can only be the result of good monitoring of the processes contributing to it. An enormously varied palette of instruments and methodologies has been developed in the past 100 years to monitor inland water resources, coastal waters and their dynamics. Of the various trends which can be discerned, satellite observations enabling synoptic measurements over large areas of the globe almost instantaneously, certainly is one of them. Started in the 1960’s with the advent of meteorological satellites, these platforms now carry instruments capable of measuring aspects of Earth’s system at a scale and precision never thought of. This has improved our understanding of the Earth’s system to a large extent, not the least our understanding of the dynamics of water systems.

Netherlands Space Office (NSO), the space agency of the Dutch government, has as its task to advise upon and realize Dutch space policy. It is therefore, that NSO seeks to inform itself on the status and needs regarding space infrastructure. With that in mind, NSO has commissioned a study to Deltares to explore the current needs for data and observations regarding inland and coastal water quantity management, both in-situ and space borne, and compare these to current and near future developments in earth observation taking into account societal, scientific and economic benefits. The goal is to have a clear, demand driven development of space and instrument technology.

1.1 Scope and set-up

The focus of this study is on information needs for inland and coastal water quantity management in relation to possible opportunities derived from future satellite instruments. The study therefore addresses the following:

- Technical user needs: type of observation, resolution and accuracy
- Societal, scientific and economic value added when user needs are fulfilled

We do not take water quality into account since water quality is part of another study and will not be treated any further here. It is noted here that in practice however, many issues of quantitative water management and water quality are intertwined. Examples are e.g. assessing new water resources due to deteriorated water quality and increased amounts of suspended and dissolved materials in rivers, water bodies and wetlands due to increased runoff and subsequent erosion.

This study is the result of a desk study and subsequent interviews with experts from the fields of hydrology and coastal engineering. In total seven interviews have been conducted with representatives from universities, government and industry. The results of those interviews have been integrated in this report.

The set-up of this report is as follows:
- Scope of inland and coastal water management and their relevant variables is described in chapter 2
- In chapter 3 we describe the use and specification of in-situ measurements and earth observation in inland water management.

- In chapter 4 we describe the use and specification of in-situ measurements and earth observation in coastal water quantity management
- Chapter 5 summarizes the societal, commercial and scientific benefits of earth observation for inland and coastal water quantity management
- Chapter 6 summarizes the results in conclusions and recommendations

2 Relevant Variables for Inland and Coastal Water Management

The availability of freshwater, its spatial and temporal variability in the hydrological cycle, and water quality continue to be major issues for the development of nations, the maintenance of human well-being globally, and the sustenance or rehabilitation of healthy environments. At the same time, shoreline change and coastal flooding are critical concerns for many coasts worldwide and they are expected to be strongly aggravated by sea-level rise. In order for society to protect itself against shortages or over-abundance of water and to distribute it in a proper way to various users, the planning, design and operations of water resources and coastal infrastructure needs a variety of data on various spatial and temporal scales. This chapter gives a summary of the relevance of data and information for inland and coastal water quantity management. It does so by introducing the main hydrological and coastal variables which play a role in monitoring and forecasting. Next, we will discuss main challenges and trends driving the need for information in inland and coastal water management.

Though inland and coastal water management are taken here together, in most cases the management of coastal waters and inland water systems are separately organised and have different approaches. Firstly, inland water quantity management is understood as the activities of planning, developing, distributing and managing the optimum use of fresh water resources. It comprises activities meant to manage flows, currents and reservoirs on a daily basis and to prevent shortage of water as well as the prevention of pluvial and fluvial flooding. Coastal water management can be thought of as part of Integrated Coastal Zone Management (ICZM) and contributes to protection of coastal ecosystems, flood protection and safe shipping. In most coastal areas, inland and coastal water systems are interconnected. Floods occur when the water cannot be sufficiently absorbed or discharged, for example when local downpours, and high water in the rivers are accompanied by high water at the coast. Such conditions can occur in the Netherlands during storm surges and in other parts of the world during hurricanes. Salt intrusion in rivers and salinization of (ground) water bodies can be another example of close intertwining of inland water and coastal management.

2.1 Variables for inland water quantity management

The essential variables for inland water quantity management are derived from the global water cycle (Figure 2.1). The global water cycle describes the distribution of water over, above and below the Earth’s surface. It follows from considerations of mass conservation that the fluxes and storages of water over a basin should comply with the water balance:

$$P - ET = Q + \Delta S$$

Where P is precipitation, ET is evapotranspiration, Q is runoff and S is a storage component made up of a number of terms of which the most prominent are (1) snow and glaciers, (2) surface water (lakes, wetlands, reservoirs and rivers), (3) soil moisture and (4) groundwater. The terms describing the water balance can each directly be influenced to a large degree by human water extraction and spillage or discharge, or can indirectly be affected by land use change and climate change. The various terms in the land surface water balance therefore each play an important role in water management.

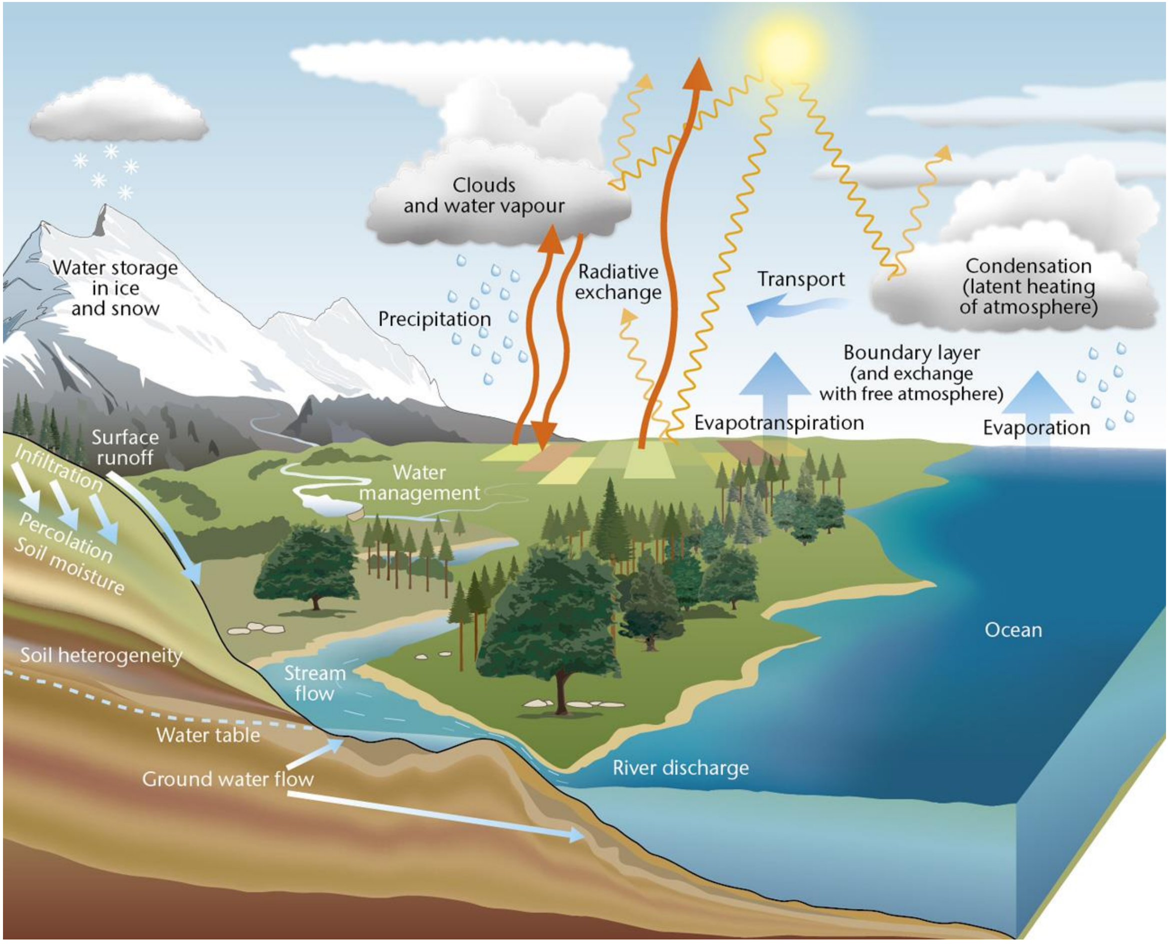

Figure 2.1 Hydrological cycle and its various flows and reservoirs (source: UK MetOffice)

The various components of the water balance are also the basis for the Essential Water Variables as presented in 'The GEOSS Water Strategy' (GEO, 2014). Therefore we take this concept of Essential Water Variables as an organising framework for this study. The following table lists the Essential Water Variables for inland water quantity management.

Essential Water Variable	Description
Precipitation	Any product of the condensation of atmospheric water vapour that falls under gravity
Evapotranspiration	Process by which water is transferred from land to the atmosphere by evaporation and by transpiration from plants
Soil Moisture	The quantity of water contained in the soil above the groundwater table
Snow and glaciers	Ice crystals that precipitate from the atmosphere; fallen snow that, over many years, is compressed into thickened ice masses
Rivers and runoff	River levels, extent and runoff/discharge
Groundwater	Water present beneath the land surface below the upper soil layers when it has completely filled the pore space.

Lakes and reservoirs	Levels and extent (incl. wetlands)
Water demand & usage	Water extracted from the natural water cycle, diverted and/or transported and used for domestic, agricultural or industrial processes.

Table 2.1 - Essential Water Variables considered in this study

Though the Essential Water Variables fully describe the hydrological cycle and are the input for a water balance approach, many factors do influence the terms. Important factors are land use and vegetation characteristics (in relation to Evapotranspiration, Soil Moisture and Water Demand & Use), elevation and topography (precipitation and runoff), soil profile and geology (Ground water). These supplemental Essential Water Variables are measured with multiple purposes and though these are important for water management, they have a much broader relevance than only water management. Therefore, for this study, these supplemental Essential Water Variables, with the exception of ground level elevation or topography, will only be touched upon and have been left largely out of scope. Ground level elevation is considered to be of prime importance for flood management.

2.2 Variables for coastal water quantity management

The coastal zone is a relatively small area of Earth's surface. It comprises a highly dynamic system of sea-land interaction and has a great economic as well as ecological value. The coast is the transition zone between land and ocean. Changes at the coast are driven by upstream processes, human activities from the landward side and at the coast, as well as meteorological and oceanographic drivers from the ocean side (Figure 2.2). Water plays a key role in safety once its mass and energy is released as it rushes onshore, and as a means of sediment transport.

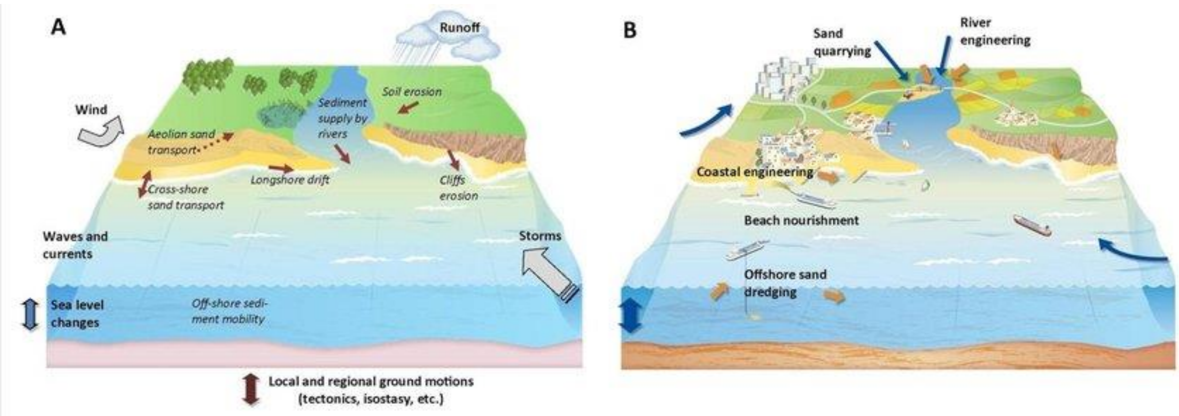

Figure 2.2 Natural and anthropogenic processes affecting shoreline changes (source: Cazenave and Le Cozannet, 2014)

Partly based on the Essential Ocean Variables developed by the Global Ocean Observing System (GOOS), a programme executed by the Intergovernmental Oceanographic Commission (IOC) of the UNESCO, the following set of measurable variables is applied in this study to assess observation gaps.

Essential Coastal Variable	Description
Sea Level (and Wave Height/ Sea State)	The level of the sea's surface, or sum of sea surface height anomaly, surge height and significant wave height (the difference between the elevations of a crest and a neighbouring trough, the degree of turbulence at sea, according to average wave height.
Salinity	Salinity is the saltiness or amount of salt dissolved in a body of water
Temperature	A measure of heat present in a substance
Coastline (shoreline)	The boundary line between land and seawater, or the outline of a coast
Morphology (topography)	The shape, form, elevation (here taken as subaerial)
Bathymetry	The subaqueous shape, form, elevation

Table 2.2 Essential Coastal Variables considered in this study

In this report we focus on two main variables that are indicative for the flood and erosion hazard: sea level and coastline. They are supported by the other main oceanographic descriptors salinity and temperature, and the main coastal descriptors morphology and bathymetry. Although winds are the main driver for storm related flooding, information on wind fields has a much broader application related to meteorological forecasting and has therefore been considered out of scope for this study.

2.3 Relevance of essential variables

Hydrological and coastal information is, next to regular water and coastal management, relevant for various other sectors and activities. Main sectors to be considered are: agriculture, energy, transport, industry, financials & insurance and urban development & construction and the way information is used depends amongst others on the scale of operation (see table 2.3). Information of the amount and spatial distribution of **precipitation** is key for many water resources activities as it is the main input of terrestrial hydrological systems. It determines water provision (direct supply to agriculture as well as water provisioning through runoff and streamflow) as well as of flood generation, potentially with snowmelt contributions. Moreover, precipitation, together with evapotranspiration, determines the amount available for recharging groundwater aquifers and the level in reservoirs.

Evaporation and **evapotranspiration**, the combined effect of evaporation and transpiration of water from vegetation, determines the net amount of precipitation available for runoff and groundwater recharge. Evapotranspiration (ET) estimates therefore are important for water budgets in basins that inform water resources management, policy and planning. On a global scale and over an annual cycle, evapotranspiration equals 65% of the total precipitation, which is comparable with the estimated yearly evapotranspiration rate in the Netherlands, equalling about 60%, though these figures may vary significantly from time-to-time and place-to-place. The remainder of the precipitation being available for fluvial discharge and groundwater recharge. Evapotranspiration is also an important climate variable and input for climate models. It is one of the Essential Climate Variables. Estimates of evapotranspiration are important for irrigation design and operations, for crop yield management and for ecosystem management (Garcia et al., 2016). ET estimates can also be relevant for water supply activities and hydropower in arid areas, especially in the context of climate and land use change in arid areas. It is therefore an important factor to know, though it is one of the variables most difficult to measure directly.

<table>
<tr><th>Geographic unit/Scale</th><th>Coastal and Water Management</th><th>Agriculture</th><th>Energy</th><th>Transport</th><th>Industry</th><th>Urban Development & Construction</th><th>Financials & Insurance</th></tr>
<tr><td>Continental - Global</td><td>International Level Policies and Directives:
- Flood Control & Disaster management
- Ecosystems
- Transboundary Water Management</td><td rowspan="2">Portfolio & Risk management, Corporate Social responsibility (CSR)</td><td rowspan="2">Portfolio & Risk management, CSR</td><td>Optimisation of routing and coastal navigation</td><td rowspan="2">Portfolio & Risk management, CSR</td><td rowspan="2"></td><td rowspan="4">Portfolio & Risk management (floods and agriculture)</td></tr>
<tr><td>Basin/Coast - Continental</td><td>National Level Policies:
- Flood Control (e.e. EU Flood Directive)
- Water allocation & supply (e.g. EU Water Accounts)
- Ecosystems (e.g. EU Water Framework Directive, EU Marine strategy framework directive)</td><td rowspan="3">Coastal and Inland navigation</td></tr>
<tr><td>Basin/Coast</td><td>River Basin and Coastal Policies and Operations (Smart Water Management)</td><td rowspan="2">Production:
- Precision agriculture
- crop monitoring
- irrigation</td><td rowspan="2">Siting, planning, operate:
- Hydropower
- Wind at sea
- Offshore production
- Powerplants (cooling)</td><td rowspan="2">Intake of:
- Production water
- Cooling water</td><td rowspan="2">Design, develop and operate:
- Water supply & sanitation
- Wastewater & sewerage
- Coastal engineering
- Ports infrastructure</td></tr>
<tr><td>Catchment – Basin/Coastal stretch</td><td>(Smart) Water management operations, Coastal engineering and Spatial planning</td></tr>
</table>

Table 2.3 Overview of sectors using hydrological and coastal information for their operations, policies and management.

Streamflow is the primary variable of interest for many water management plans, engineering designs for dams, reservoirs and related infrastructure, flood protection designs and early warning systems, irrigation design and scheduling, navigation, ecosystem management and transboundary surface water allocation schemes (Garcia et al., 2016). Records of extreme values are of importance for estimating return periods for designing flood control as well as low flows during dry seasons. In general this requires long time series of preferably 50 years or longer. Monitoring low flows in real time may allow the scheduling of reservoir releases for environmental health and water allocation purposes. High flow monitoring is essential for flood forecasting and emergency planning. Without streamflow records, it is very difficult to calibrate and validate hydrologic models and forecasts.

Soil moisture is an important variable as plant growth depends on soil water availability. Soil moisture estimates can be used for supplementing irrigation water to cover crop water requirements. It is also important for watershed management and for ecosystem and drought monitoring. It is also a relevant key variable for flood forecasting and operational water management as it reflects the antecedent conditions in watersheds and influences the partitioning of precipitation in runoff and groundwater recharge and thus the severity of floods (Garcia et al., 2016). In the climate science community, soil moisture is a key variable, as it provides a boundary condition of available water fluxes to the atmosphere (over land, as oceans do too) and controls the partitioning of incoming radiation into mostly latent heat (through evapotranspiration) and sensible heat fluxes (through air heating).

Knowledge of temporal and spatial variations of **surface water levels and extent** in rivers, lakes, reservoirs, floodplains and wetlands is of direct relevance to water resource management, flood control operations, navigation, drinking water supply, hydropower, industry and ecosystem management. Surface water levels, and thus areas of water bodies, also are directly relevant for mitigating floods through the monitoring of flood extents and deployment of emergency measures as well as for health issues.

For many river basins the combination of **snow cover and Snow Water Equivalent (SWE)**, the amount of water stored in the snow pack and available upon melt, yields important information about how much water is stored in the basin and might be mobilized during the warmer periods. Knowledge therefore of these variables is important for overall water resources management, hydropower operations, flood control, navigability of inland waterways and environmental management. It is also an important factor for climate science as its albedo and low thermal conductivity have an influence on the local energy budget.
The predictions of flood forecasting and reservoir decision support systems highly depend on the accuracy of input data and state variables of the model. Especially for hydropower reservoirs the snow stored in the upstream part of the river basin is an important quantity as it can be a major part of the river flow during the warm season and thus determine the amount of electricity that can be generated. These are quantities of water stored in the river catchment that will become available for runoff with a delay and will thus influence flood volumes and reservoir volumes (Nester et al., 2012). Additionally, many of the large river basins find their source in mountainous, snow covered areas. Their base flow component is largely determined by the volume of melt water which becomes available during warmer periods. The Rhine is an important example, having its base flow primarily determined in its source area in the Alps. Knowledge of the meltwater component therefore greatly contributes to forecasting high and low stands of this river.

For many activities in large parts of the world, **groundwater** is the primary source for irrigation and potable water. Changes in groundwater level and ground water recharge have an impact on water resources management, transboundary water issues, irrigation, supply of drinking water and supply of water to industry (especially food and beverage), wastewater, environment, energy other than hydropower and urban design and planning (WMO, 2008).

Because of the capture process, pumping will diminish flows to nearby rivers and other surface and groundwater bodies and recharge from river reaches may increase with lower aquifer levels. Lower aquifer levels may negatively affect wetlands and ecosystems along rivers. Lower groundwater levels are synonymous with higher pumping costs, reduced reserves, and less water availability. In addition, water quality may deteriorate rapidly with decreasing aquifer levels, due to the upconing of deeper saline water layers as well as contaminants.

Elevation data are necessary for land use planning, water resources planning, and all water resources design activities, ranging from water supply and sanitation systems, irrigation, hydropower, environment, and flood control, to disaster management. As subsidence is the change in elevation, it can be measured with the same techniques and sensors and can be relevant to the same activities.

Sea Level and Sea State are key variables for coastal flood protection, design and management of coastal protection from erosion, marine safety, marine transport and coastal or marine structures (e.g. wind power). Sea Surface Height is one of the primary indicators of global climate change. On the regional scales, changes in sea level can be far larger than the globally averaged value and result from several factors, including changes in temperature, salinity and circulation. Sea state is the characterization of wave and swell, typically in terms of height, wavelength, period, and directional wave energy flux. Wave characteristics are modified by bathymetry when the depth of the water is comparable to the wavelength, and by surface currents. Sea state is also a substantial modifier of air-sea exchanges of momentum, moisture and CO2.

Sea Surface salinity observations contribute to monitoring the global water cycle (evaporation, precipitation and glacier and river runoff). On large scales, surface salinity can be used to infer long-term changes of the global hydrological cycle. Surface salinity, together with surface temperature, is indicative of the surface expression of ocean frontal features and eddies. Although several studies have already demonstrated the usefulness of satellite SSS measurements, the data is not widely used by the ocean modelling communities mainly due to technical challenges in assimilating SSS data and assessing its impact.

Sea-surface temperature (SST) is a vital component of the climate system as it exerts a major influence on the exchanges of energy, momentum and gases between the ocean and atmosphere. SST largely controls the atmospheric response to the ocean at both weather and climate time scales. The spatial patterns of SST reveal the structure of the underlying ocean dynamics, such as, ocean fronts, eddies, coastal upwelling and exchanges between the coastal shelf and open ocean.

Bathymetry, topography and **coastline** together define the state of the coastal zone and therefore are of primary interest in monitoring coastal erosion and aggradation processes, navigability of coastal seas, and suitability of locations for structures and ecosystems management. Coastal bathymetry strongly influences sea currents and sea state and therefore is highly relevant for modelling coastal processes.

3 In-situ measurements and Earth Observation for inland water quantity management

3.1 Introduction

Here we provide an overview of in-situ measurements and main Earth Observation retrieval algorithms, relevant at the regional or global scale, which are used to measure the Essential Water Variables for inland water quantity management. The available satellite instruments are listed per variable in Appendix A. The overview addresses the achievable spatial, temporal resolution, spatial coverage and the accuracy.

3.2 Precipitation

3.2.1 In-situ measurement

The necessity to know and continuously follow the amount of precipitation in space and time has led to quite some approaches in measurement devices and network design. Traditionally and up to this date predominantly, precipitation is measured by a pluviometer, collecting precipitation over a standardised surface and subsequently measures its volume or weight over specified time intervals, at least daily.

The spatial variability of precipitation is influenced by topographic and climatological conditions. Mountainous areas therefore need a much denser network than coastal areas to capture precipitation patterns with the right resolution. WMO (2008) recommends a density of one station per 250 km^2 in mountainous areas down to one station per 900 km^2 in coastal areas as a minimum requirement. These densities are considered the bare minimum in order to avoid serious deficiencies in developing and managing water resources on a scale commensurate with the overall level of economic development and environmental needs of the country (WMO, 2008). As an example, Netherlands, Germany and Switzerland all maintain precipitation measurement networks with very comparable densities, about one station per 100 km^2. For most water management applications the total amount of precipitation on an hourly to daily basis will suffice with accuracies ranging between 3 – 7% (WMO, 2008). For managing extreme events a measurement frequency of 5 minutes is necessary.

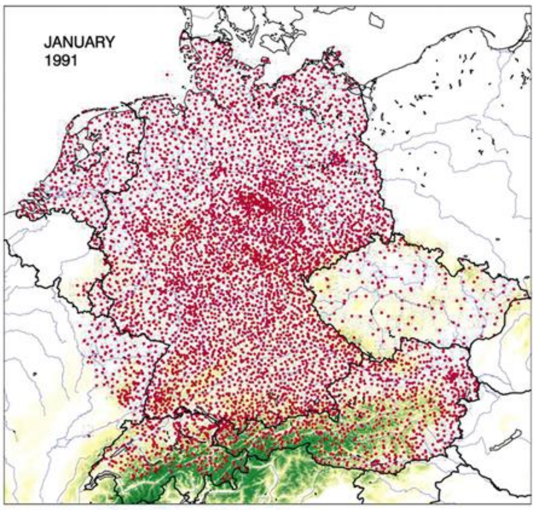

Figure 3.1 Distribution of pluviometers of the national meteorological networks of Germany and Netherlands (after Rauther et al., 2013)

Since the mid-twentieth century, precipitation measurement is further supported by the use of precipitation radar. Its major benefit being its capability to semi-continuously measure the intensity of rain fields over large areas. One station is capable of covering about 180 km radius and most western-European countries nowadays have a network capable of covering its total surface area. Netherlands has two radar stations, one in Den Helder and one in Herwijnen. Radar is an indirect measurement, which makes use of the relation between the intensity of the backscattered radar pulse and the intensity of precipitation. Light rain, drizzle and light snow are difficult to observe however, as well as when lighter rain is shielded off by heavy rain in front of the radar.

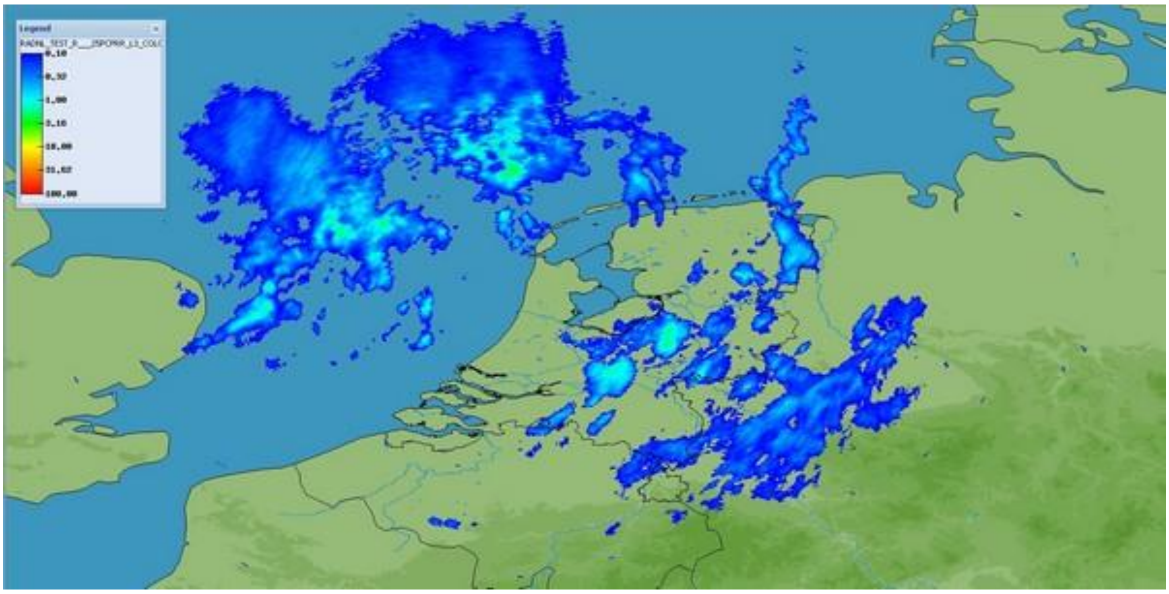

Figure 3.2 Visualization of the KNMI precipitation radar, above the Netherlands. Image obtained with the ADAGUC WMS service of the KNMI precipitation radar (Source: http://adaguc.knmi.nl)

Transboundary or cross-country datasets of in-situ measured precipitation exist as for example for the E-OBS dataset that includes many European countries and has a grid resolution of 0.25[1] degrees and daily time-step (Haylock et al. 2008) and the HYRAS dataset that covers a number of German transboundary river basins including the Rhine (Rauthe et al., 2013) and contains more than 4000 time series of precipitation measurements dating back 30 years. Globally the main databases are the database of the Global Precipitation Climatology Centre that holds monthly data at a 2.5 degrees resolution grid from 1979 to present and daily gridded data at a 1º-grid from 1996 to near-present, based on 64.000 measurement stations. In addition, hourly station observations are available for on average 6500 stations from all over the world. The earliest records start in 1929 and data is provided on a daily time-step and released with a delay of approximately 2 days from real-time.

[1] *Currently also 0.1-degree*

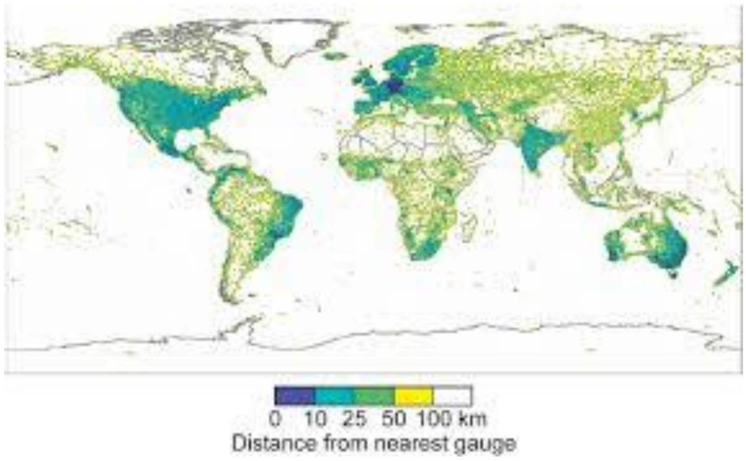

Figure 3.3 Map showing the distance to nearest GPCC gauge, typical of all regular and reliable gauge measurements; blank areas in the figure are beyond 100 km from the nearest gauge (after Kidd et al. (2017)).

3.2.2 Earth observation based products

Next to in-situ observations, precipitation rates are directly sensed by satellites. The main sensors are listed in the overview table. Yet to improve their accuracy the datasets are most of the times bias-corrected or processed. A combination of Thermal Infrared, Passive Microwave and Precipitation Radar can help to improve rainfall detection. Thermal Infrared and Passive Microwave observations are used in most Satellite Precipitation Products. Thermal Infrared observations of top of cloud top temperatures work best for convective precipitation which is mostly found at low latitudes and in summer (Lettenmaier et al., 2015). However, the relationship used for TIR-based estimates of precipitation is weak and not fully understood, in contrast to the scattering mechanism and emission of microwave radiation by ice particles and rain droplets. Rainfall products based on passive microwave measurements make use of various channels measuring brightness temperatures above 37 GHz up to about 200 GHz (Garcia et al. (2016); Lettenmaier et al. (2015)). Many retrieval algorithms exist and below we summarise a number of frequently used algorithms. The first 6 algorithms provide a near global coverage with a relatively coarse resolution, whereas the last algorithm is an example of what can be derived at a very high resolution using SAR-systems.

3.2.2.1 Overview of most important datasets / algorithms

The purpose of the TMPA-3b42RT-algorithm is to produce Tropical Rainfall Measuring Mission (TRMM) merged high quality (HQ)/infrared (IR) precipitation and root-mean-square (RMS) precipitation-error estimates. These gridded estimates are on a 3-hour temporal resolution and a 0.25-degree by 0.25-degree spatial resolution in a global belt extending from 50 degrees south- to 50 degrees north-latitude. The 3B42 estimates are produced in four stages; (1) the microwave precipitation estimates are calibrated and combined, (2) infrared precipitation estimates are created using the calibrated microwave precipitation, (3) the microwave and IR estimates are combined, and (4) rescaling to monthly data is applied (Huffman et al. 2007). On board TRMM a space borne precipitation radar was installed as well. Radars perform superior to passive systems especially in sensing through clouds but the swath widths are relatively narrow meaning that a single location is only observed every 2.5 – 5 days (Lettenmaier et al., 2015).

The Integrated Multi-satellite Retrievals for GPM (*IMERG*) (https://disasters.nasa.gov/instruments/imerg) intercalibrates, merges and interpolates satellite passive microwave precipitation estimates, together with microwave-calibrated infrared (IR) satellite estimates, monthly precipitation gauge analyses, and potentially other precipitation estimators at fine time and space scales. Nine international satellite are considered: GPM, GCOM-W1, NOAA-18, NOAA-19, DMSP F-16, DMSP F-17, DMSP F-18, Metop-A, and Metop-B. The spatial resolution is 0.1 degrees and the spatial coverage is 60ºN-60ºS. The temporal resolution is 30-minutes and the data is available 6 hours after real time. Data is available for the period 2014 to present.

The Global Satellite Mapping of Precipitation (*GSMaP*; JAXA Earth Observation Research Center) provides a global hourly rain rate with a 0.1 x 0.1 degree spatial resolution. GSMaP is a product of the GPM. Values are estimated using multi-band passive microwave and infrared radiometers from the GPM Core Observatory satellite and with the assistance of a constellation of other satellites. The gauge-adjusted rate is calculated based on the optimization of the 24h accumulation of GSMaP hourly rain rate to daily precipitation by NOAA/CPC gauge measurement. Data is available for the period 2000 – present.

The Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (*PERSIANN*) uses neural network classification procedures to estimate of rainfall rate (Sorooshian et al., 2000). The data has a resolution of 0.25°. The PERSIANN system was based on geostationary infrared imagery and later extended to include the use of both infrared and daytime visible imagery. The PERSIANN algorithm to generate global rainfall is based on the geostationary longwave infrared imagery to generate global rainfall. The coverage is 50°S to 50°N globally. The following geosynchronous satellites are considered: GOES-8, GOES-10, GMS-5, Metsat-6, and Metsat-7 and the following low-orbital satellites: TRMM, NOAA-15, -16, -17, DMSP F13, F14, F15.

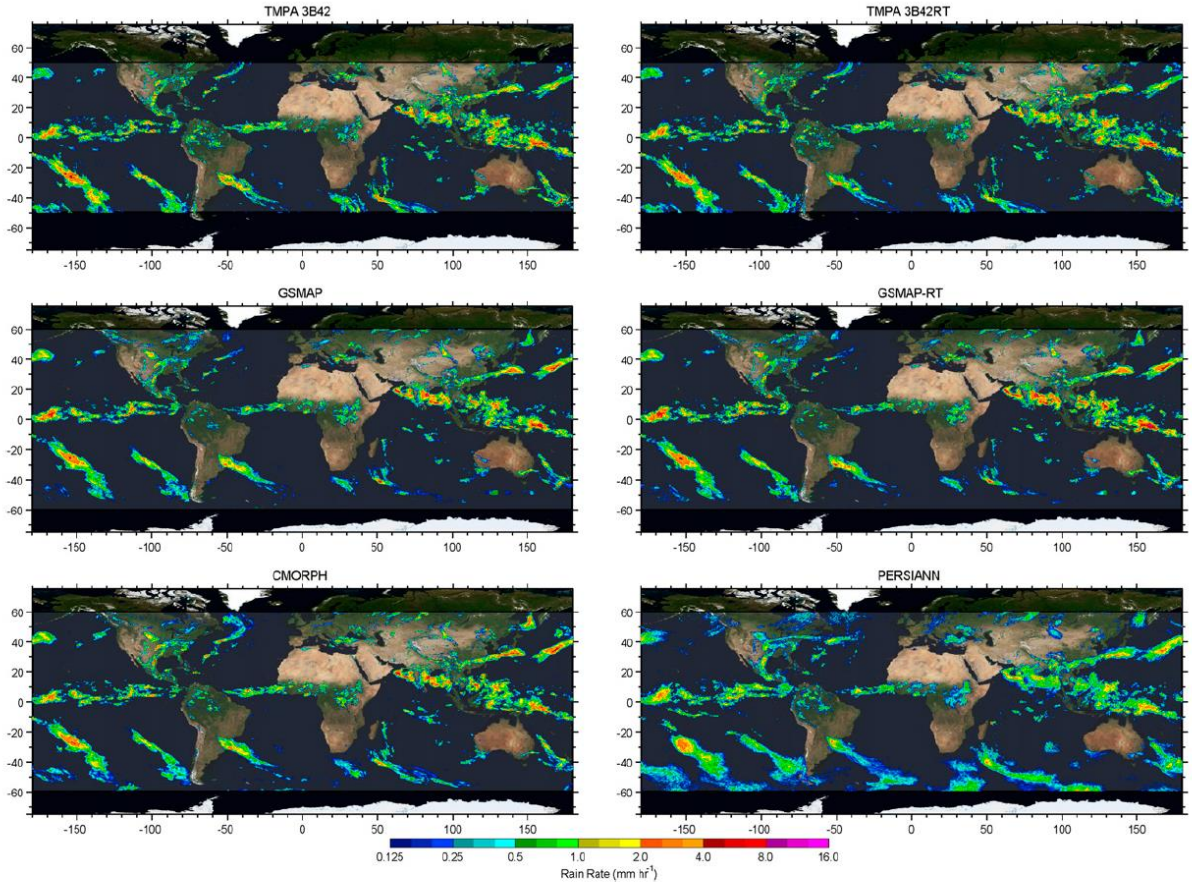

Figure 3.4 Maps of daily average precipitation of each Satellite Precipitation Product at their native spatial resolutions on 18 June 2015 (after Maggioni et al., 2016)

The Climate Prediction Centre (CPC) MORPHing technique (Joyce et al., 2004), *CMORPH*, produces global precipitation analyses at very high spatial and temporal resolution. This technique uses precipitation estimates that have been derived from low orbiter satellite microwave observations exclusively: DMSP 13, 14 & 15 (SSM/I), the NOAA-15, 16, 17 & 18 (AMSU-B), and AMSR-E and TMI aboard NASA's Aqua and TRMM spacecraft. The technique is not a precipitation estimation algorithm, but a means by which estimates from existing microwave rainfall algorithms can be combined. Precipitation estimates from any microwave satellite source can be incorporated. The spatial resolution is approximately 8km. The temporal resolution is 30 minutes and the data is available for the period 2002 – present.

The Climate Hazards Group InfraRed Precipitation with Station data (Funk et al., 2015), *CHIRPS*, incorporates 0.05° resolution satellite imagery with in-situ station data to create gridded rainfall time series for trend analysis and seasonal drought monitoring. Next to precipitation rates the dataset integrates infrared Cold Cloud Duration (CCD) observations. The following satellite (derived) datasets are considered: Tropical Rainfall Measuring Mission 2B31 microwave precipitation estimates, *CMORPH* microwave-plus-infrared based precipitation estimates, monthly mean geostationary infrared brightness temperatures, and land surface temperature estimates. Within the algorithm the satellite datasets are primarily used to interpolate gauge observations and are therefore especially important in data sparse regions. The CHIRPS dataset has a global coverage of 50°S-50°N. The data is available for the period 1981 to near-present.

PREC_X-SAR is a retrieval algorithm which uses synthetic aperture radar (SAR) observations from the TerraSAR-X (TSX) and COSMOSkyMed (CSK) sensors (Marzano et al., 2010) and data from LEO/GEO sensors. Data is available for the period 2009-2015 for amongst others the Mediterranean region, but the algorithm can be adapted to other regions up to 200 x 200 km. With this algorithm Marzano et al. (2010) have demonstrated the capability of X-band SAR (X-SAR) sensors to detect rainfall over both sea and land, which can also be exploited to correct SAR imagery for rainfall attenuation effects. The data has a resolution of 250 – 500 metres.

3.2.3 Conclusions current status

The accuracy of the unprocessed microwave precipitation products is relatively low, due to disturbance by especially clouds and ice-induced back-scattering signal. Karimi and Bastiaanssen et al. (2015) estimated a mean absolute percentage error of satellite precipitation from observed precipitation for approximately 68 data points of 18.5%.

Overall satellite rainfall products tend to overestimate low rainfall amounts. Performance is reasonable with average rainfall amounts but decreases again for extreme rainfall events. These errors influence hydrological performance for flood and water resources assessment. For the first the severity of the events can only be determined when extreme rainfall amounts are well detected, whereas for water resources or drought modelling it is extremely important to capture all light rain events well to ensure correct model states. Maggioni et al. (2018) state that in regions with only a few ground-based rain gauges the hydrological simulations are equal or inferior to gauge-based simulations.

Performance also strongly varies regionally. In the tropics the presence of clouds disturbs the rainfall detection signal. In semi-arid areas rainfall detected in the air may have evaporated before reaching the ground. In mountainous regions the topography and large weather and climate variability hamper satellite observations, whereas the data is extremely relevant here because of the absence of ground observations. For remote sensing of snow, there is a problem with the discrimination between the ice crystals in the atmosphere and the ice on the land surface.

Global products have resolutions of 0.1 to 0.5 degrees (about 125 – 3000 km^2 at the equator and 60 – 1500 km^2 at 60º latitude). With this resolution it is not possible to capture the high spatial variation in rainfall patterns in especially mountainous / coastal regions and local convective rainfall events. Coverage for most of the products reaches not further than 50 or 60 degrees north / south.

When low resolution microwave and infrared products are combined with radar data both the accuracy and the resolution of the data products can highly be enhanced. The influence of clouds can be reduced. The algorithm we presented here using SAR data for precipitation estimation (Marzano et al., 2010) is just one of the many algorithms that have been developed to produce high resolution precipitation estimates (~100x100 m) for specific regions. However, due to the revisit time of SAR-satellites, temporal resolution remains an issue. Yet, the required SAR data is not always free for use.

3.3 Evaporation/evapotranspiration

3.3.1 In-situ measurement

Evapotranspiration is determined by meteorological variables as radiation, wind speed, temperature and relative humidity and by type and status of the vegetation and soil cover. Evapotranspiration is measured either using direct methods, like lysimeters, by micro-meteorological methods, like eddy covariance measurements or indirectly by measuring various meteorological variables which are then used to estimate evapotranspiration based on energy balance equations.

Figure 3.5 Eddy covariance flux tower (courtesy ITC)

Since evapotranspiration varies with the aspect of the slope and vegetation cover and is strongly influenced by built-up area, these factors have to be counted in when considering sufficient spatial resolution and applicability for water management purposes. KNMI in the Netherlands has 20 measurement locations, about 1 per 1500 km^2, to determine the actual evapotranspiration. However, considering its relevance and importance for agriculture to wilting of crops and optimize irrigation, data on a plot-scale become desirable with a daily update frequency (STOWA, 2016). WMO (2008) recommends to measure evaporation with an accuracy of 2 – 5% or 0,5 mm.

Global in-situ observations of variables required to estimate actual evapotranspiration are available from FLUXNET towers. The FLUXNET towers form a network of meteorological sensors measuring atmospheric state variables, like temperature, humidity, wind speed, rainfall, and atmospheric carbon dioxide, on a continuous basis. The global coverage is very heterogeneous with high tower densities in parts of Northern America, Europe and South-East Asia. At other continents the density is still rather low and they cannot provide a good coverage.

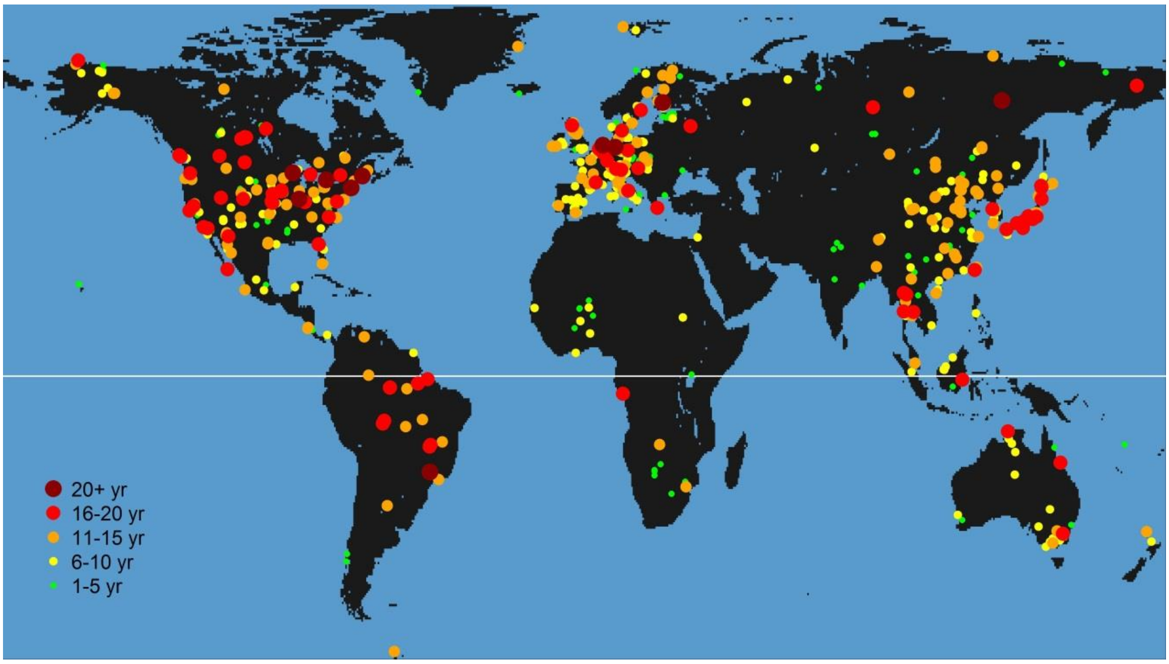

Figure 3.6 Distribution of Fluxnet locations

Alternatively reference potential evaporation can be calculated using a variety of equations such as Makkink, Penman-Monteith, Priestley-Taylor, Hargreaves etc (Sperna Weiland et al., 2014), and De Bruin (2016). The calculated reference potential evaporation is often used as input for hydrological models that simulate actual evapotranspiration themselves and thus do not need actual evapotranspiration. The equations all need a number of meteorological variables as input. The simplest equations only require temperature whereas the fully physically based Penman-Monteith requires wind, radiation, air pressure, humidity and temperature. These variables are measured at most WMO weather stations.

3.3.2 Earth observation based products

Broadly speaking, satellite evapotranspiration (ET) products fall into four categories (Lettenmaier et al., 2015; Garcia et al., 2016). On a fundamental level, ET can be estimated using either surface energy balance models which model the turbulent heat transport from the surface to the atmosphere or Penman-Monteith based methods which model the process of evapotranspiration by taking the surface (or canopy) conductance into account. A third approach, unlike algorithms based on surface turbulent heat fluxes and transport, is based on a water balance approach and makes use of passive microwave sensing data with potential ET estimated using the Priestly-Taylor method, a simplification to the Penman-Monteith method. As a fourth approach, empirical methods, make use of some fitted relation between surface temperature, vegetation indices (NDVI or LAI) and ET.

The above methods differ in complexity and in their demand for (satellite) observations. Input variables that can be obtained from satellite data are:

- Land Surface Temperature
- Soil Moisture
- Radiation fluxes
- LAI / NDVI

- Surface roughness

Most algorithms contain a model component that solves either an energy balance or water balance to assess the net energy or water availability. Input variables for those balances are obtained from remote sensing data, meteorological models and in-situ observations.

Below some examples of ET retrieval algorithms are described. Karimi and Bastiaanssen (2015) give an extended overview of the different methods to derive evapotranspiration from satellite data. The overview paper gives a list of ~ 20 algorithms. Here we only mention four examples that have been developed or used by Dutch research groups: three high and one low resolution algorithm that are developed or frequently used within the Netherlands for national and international applications. An overview of the most relevant satellites measuring land surface temperature, soil moisture and latent heat are provided in the instrument overview table. Most algorithms require land surface properties like NDVI and LAI that can be observed with satellites, yet the description of these relevant datasets is beyond the scope of the current assessment.

3.3.2.1 Overview of most important datasets / algorithms

The Surface Energy Balance Algorithm for Land (Bastiaanssen et al., 1998a), *SEBAL*, is based on the surface energy balance and provides data at a weekly time-step. Its spatial resolution varies but can be as high as 30 x 30 metres. The SEBAL algorithm can be used for monitoring up to field scale. It makes use of TIR to estimate land surface temperature and of VIS to estimate surface roughness (i.e. vegetation height and density). Over the Sahel Bastiaanssen et al. found relatively large deviations which they attribute to the rapid soil moisture depletion in barren sands (Bastiaanssen et al., 1998b). In addition, estimations in complex terrain are hampered by the spatial variation being much higher than can be captured by the grid and observations of input variables can be disturbed by clouds. In general errors tend to average out when a large number of cells is aggregated and the accuracy at 30 x 30 metres can be much lower. The high-resolution data requires additional data to distinguish the signal in the individual cells.

As *SEBAL*, the Surface Energy Balance System (Su, 2002), *SEBS*, is an algorithm making use of the energy balance model. It estimates atmospheric turbulent fluxes and evaporative fraction using satellite earth observation data (TIR for LST and VIS for NDVI and LAI), in combination with meteorological information at various scales. It uses spectral reflectance and radiance measurements; a model for the determination of the roughness length for heat transfer; and a new formulation for the determination of the evaporative fraction on the basis of energy balance. The uncertainties in the estimated heat fluxes are comparable to in-situ measurement uncertainties.

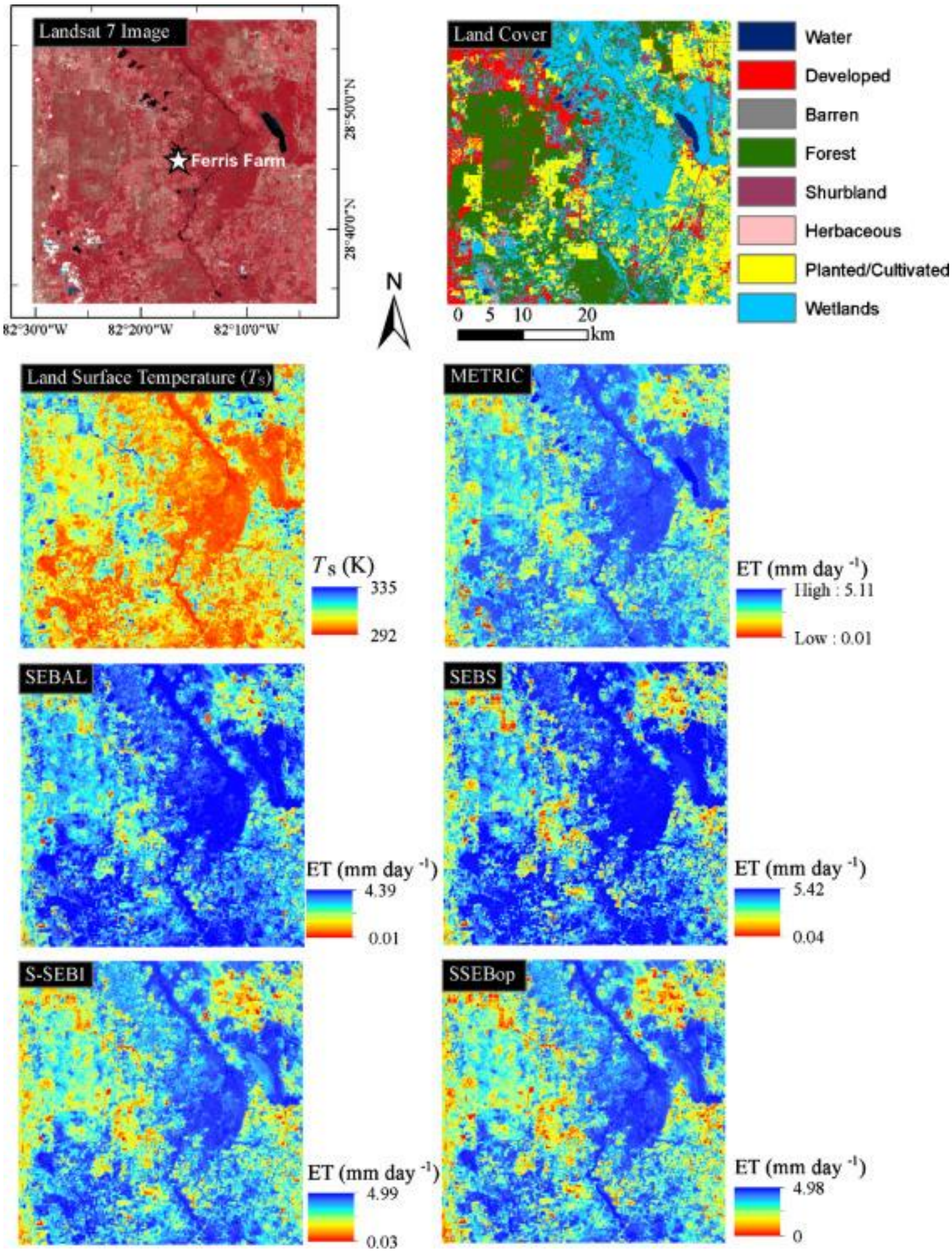

Figure 3.7 Daily ET maps covering the Ferris Farm site derived from five single-source SEB models applied to a subset of a Landsat 7 image (shown as false colour composite into row, left) acquired on October 3, 2001. Also included for reference are a land cover (top row, right) and a land surface temperature map (Ts; second row, left). (After Bhattarai et al., 2016)

The MODIS global evapotranspiration project (Mu et al., 2011) MOD16, derives global terrestrial evapotranspiration from earth land surface by using satellite remote sensing data. The ET algorithm is based on the Penman-Monteith equation. The data is available at a resolution of 1 km for the global land surface and is all derived from the MODIS satellite. Data is available for the period 2000 – 2010 at a time-step of 8 days.

The Global Land Evaporation Amsterdam Model (Martens et al., 2017) is based on water balance modelling and uses passive microwave remote sensing data to solve the Priestly-Taylor Equation. Surface stress is based on soil moisture estimated from low frequency (10

GHz) retrieved soil moisture and surface temperature retrieved from a 37 GHz microwave algorithm (Lettenmaier et al., 2015). The coverage of the dataset is global for the period 1980-2015. The datasets contain individual evapotranspiration components as well as soil moisture (0 -10 cm depth). The spatial resolution is 0.25 degrees. The GLEAM dataset is relevant for large scale hydrological modelling as well as for global land surface modelling.

3.3.3 Conclusions current status

Karimi and Bastiaanssen (2015) are relatively confident on the accuracy of evapotranspiration data derived from remote sensing, they estimate, based on a meta-analysis of reported validations for various algorithms, an overall accuracy of 95% (SD 5%) based on a literature review. Bhattarai et al. (2016) compared the results of 5 products using surface energy balance models with ground based control measurements and found these models to have a R^2 of 0,71 – 0,81 when compared to measured ET and an RMSE of 0,71 – 1,67 mm/day. Spatial resolution strongly depends on the accuracy with which the surface roughness and wind profile can be estimated. MODIS16-products are delivered at a spatial resolution of 500m which can be considered as the generally applicable resolution. With the existing algorithms satellite observations and in-situ datasets can be merged to produce datasets with resolutions of even ~30x30 metres, yet the accuracy of the high resolution product is lower than aggregated versions. In addition, these resolutions cannot be generally retrieved under all circumstances and come with additional inaccuracies. Unfortunately, since cloud cover disturbs the signal sensed by satellite instruments, dedicated retrieval algorithms and the use of multiple satellite sources remain required to derive a reliable estimate of evapotranspiration at the earth surface.

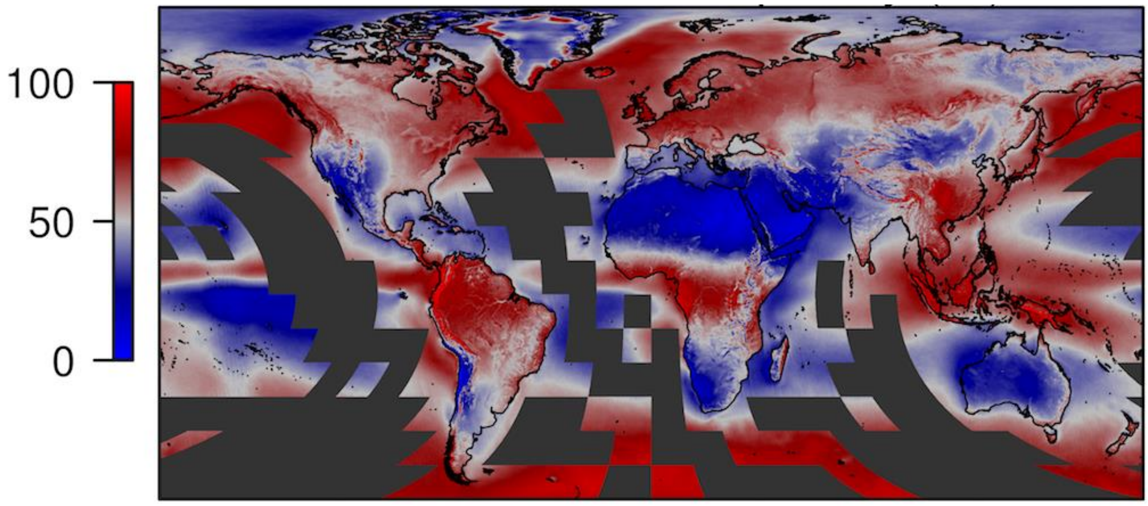

Figure 3.8 Mean annual cloud frequency(%) over 2000 – 2014 (after Wilson and Jetz (2016))

Another issue is that the resultant values represent an “instantaneous” flux, which requires scaling to actual ET integrated over a longer time period (daily) (Garcia et al., 2016). The algorithm disALEXI therefore makes use of geostationary data to observe surface temperature in a 15 minute interval. The spatial resolution of geostationary acquired land surface temperature is in the order of 2000 m at best and therefore these algorithms are best suited for regional to global applications. As an example, Eumetsat’s LSA-SAF-facility delivers daily and sub-daily ET-products based on Seviri and consists of two outputs: the instantaneous ET product (MET) with a time interval of 30 minutes (in mm/h) and the daily evapotranspiration product (DMET) obtained by integrating instantaneous values over the whole day (in mm/d). Both products are generated over the full MSG disc domain, covering Europe, Africa and most of South America at SEVIRI spatial resolution (3 km at sub satellite point). The methodology adopted for the ET product combines the advantages of satellite remote sensing (high repetition rate, wide area coverage, high spatial resolution) with the ability of Soil Vegetation Atmosphere Transfer (SVAT) models to describe physical and physiological process occurring in vegetation canopy. In this approach, radiative data derived from Meteosat Second Generation (MSG) geostationary satellites together with recent land-cover information (from ECOCLIMAP land cover database + LSA-SAF VEGA products) and ancillary meteorological data (from ECMWF forecasts) are used to drive a physical model of energy exchange between the soil-vegetation-atmosphere systems.

In addition more frequent, high resolution Land Surface Temperature information could help to improve ET estimates (Lettenmaier et al., 2015). The newly proposed TRISHNA-mission by CNES has requirements which at least partly cover this gap and will carry an instrument with 4 thermal channels, covering the globe with a 3 day-revisit time and <100 m spatial resolution. Accurate canopy measurements are part of the ICESat-2 data products and might help to accurately resolve surface roughness.

3.4 Snow and Ice Cover

3.4.1 In-situ measurement

Snow depth and SWE are variables which are difficult to assess. The areal extent can be measured using satellite or airborne imagery. In-situ observations of snow fall and snow depth can be complex. Often the terrain is hard to access as for example Arctic regions and high mountains. As a result the available in-situ observations are usually based at lower elevations and thus not fully representative for the surrounding area. In addition, there is usually under-catch in the in-situ snow fall observations due to wind and vegetation cover. Both lead to underestimations of the actual fallen snow. It is suggested that one course for 2 000 to 3 000 km2 is a reasonably good density for less homogeneous regions, and one course for 5 000 km2 in homogeneous and plain areas (WMO, 2008). However, each case must be considered on its own merits, and these generalities must not be applied indiscriminately. Recommended accuracy for measuring snow depth is 1 cm below 20 cm or 10% above 20 cm. As for SWE the recommended accuracy is 2.5 – 10% (WMO, 2008).

In-situ observations of glacier length, area, volume and mass can be obtained from the World Glacier Monitoring Service (WGMS) that contains data from approximately 2500 glaciers worldwide. Data go back up to 125 years. Again the local coverage is variable and depends on measurements conducted. Next to the WGMS there is the World Glacier Inventory (WGI) which contains data for over 130,000 glaciers. This database is mainly based on aerial photography. The database contains maps with for many glaciers only one data entry. Next to the global databases there are many national or regional datasets available. The National Snow and Ice Data Centre (NSIDC) and WMO's "Global Cryosphere Watch" are two portals giving access to various open data sets on snow variables (depth, extent, SWE) covering important regions, mainly of the Northern Hemisphere. As with snow and ice data, the National Snow and Ice Data Centre (NSIDC) and WMO's "Global Cryosphere Watch" give also access to various open data sets on glaciers and ice sheets.

3.4.2 Earth observation based products

Relevant sensors and satellites for snow and glacier observations are listed in the overview table. There is overlap in sensors relevant for snow and glaciers, although SAR is mainly valuable for observing glaciers by providing the background DEM information since the radar penetrates snow and can therefore not correctly quantify the snow cover.

3.4.2.1 Overview of most important datasets / algorithms

For glaciers the most relevant parameters are: glacier motion, mass balance and delineation / retreat. For snow these are snowpack, snow depth, snow water equivalent (SWE) and snow grain size. There is a large number of snow datasets of which two of the most relevant are described below.

Snow Cover

The *MODIS* snow product suite is composed of products covering a range of spatial and temporal resolutions, from 500 m to 0.25°, and from swath to daily, to 8-day to monthly. All products provide fractional snow cover, and snow albedo is provided in the 500-m resolution products. The MODIS snow product suite is composed of products covering a range of spatial and temporal resolutions, from 500 m to 0.25°, and from swath to daily, to 8-day to monthly. All products provide fractional snow cover, and snow albedo is provided in the 500-m resolution products

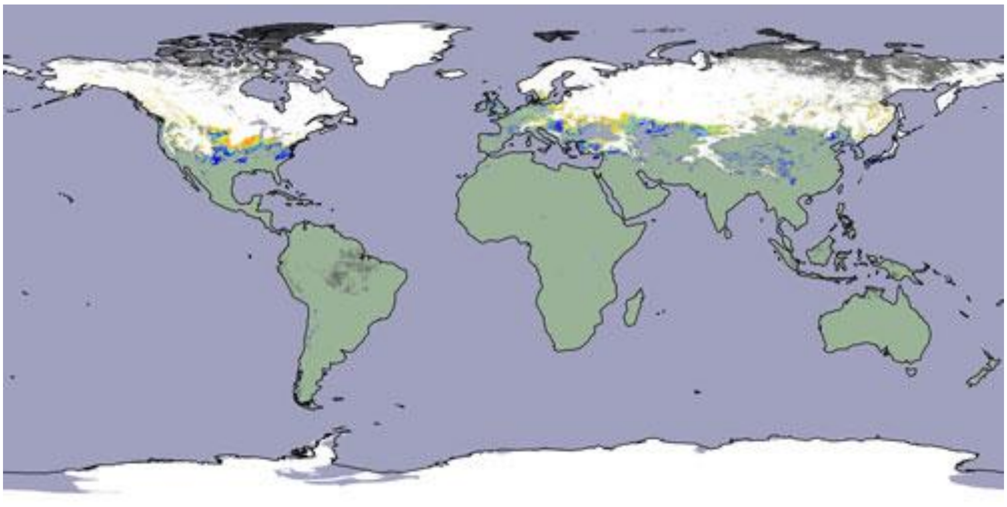

Figure 3.9 MOD10CM MODIS monthly snow-cover product February 2004 (source: NASA)

Snow Cover and Snow Water Equivalent

The *GlobSnow* snow datasets contain satellite-retrieved information on snow extent (SE featuring Fractional Snow Cover, FSC) and snow water equivalent (SWE) extending as far to the past as feasible using the selected sensor-families (source: www.globsnow.info). The current SE dataset is based on optical data from Envisat AATSR and ERS-2 ATSR-2 sensors covering the Northern Hemisphere for the period 1995 to 2012. The SWE record is based on the time series of measurements by two different space-borne passive microwave sensors (SMMR and SSM/I) spanning 1979 to 2012. The SWE product combines satellite-based passive microwave measurements with ground based weather station data in a data assimilation scheme. Both products are provided on a daily time-step. In addition to the long term series of SE and SWE, an operational near-real time (NRT) snow information service is maintained since 2010.

Glaciers
The Randolph Glacier Inventory (RGI) is a globally complete collection of digital outlines of glaciers. The dataset includes ~198 000 glaciers in its latest. Satellite imagery from 1999–2010 provided most of the outlines and include data from Landsat missions, ASTER and TRMM. The uncertainty is about ±5%. The main contributors to uncertainty are misinterpretation of seasonal snow cover and debris cover. These errors appear not to be normally distributed, and quantifying them reliably is an unsolved problem.

3.4.3 Conclusions current status

For the Netherlands snow and glacier monitoring is of minor relevance although the discharge of the river Rhine is influenced by snow and glacier melt and these tend to contribute to maintaining reasonable low flows during late summer. Worldwide a multitude of snow and glacier products exist. Monitoring is most challenging at high latitudes where polar darkness and cloud cover reduce the optical data availability. In addition snow cover in forests is hard to observe.

Records of combined EO data provide time-series of up to 40 years. Using MODIS satellite data resolutions can already be as high as 500 m. SAR data can further increase spatial resolution for glaciers, up to 10 or 20 metres. Yet, for snow the penetration of SAR data is too large. Hu et al. (2017) state that for glaciers high resolution spatial data is most relevant because we are interested in their delineation and decline thereof. Consequently the temporal resolution of glacier datasets is often lower than of snow datasets where using lower resolution spatial data allows for a higher temporal resolution.

SWE in mountainous areas remains hard to sense because of the highly varying topography, while it contains an important source of runoff influencing the severity of flood events and low flow volumes during summer.

For the near future snow and glacier products could be further improved by developing and improving on multi-sensor EO algorithms. Furthermore, both Sentinel-1 and Sentinel-2 provide data that can help to improve glacier and snow datasets with their high temporal and spatial resolution.

3.5 Soil moisture

3.5.1 In-situ measurement

Soil moisture content of a soil varies strongly over depth and reaches 100% saturation at groundwater level. The actual water content profile depends on the soil profile, depth of groundwater table and the antecedent precipitation conditions (see Figure 3.10).

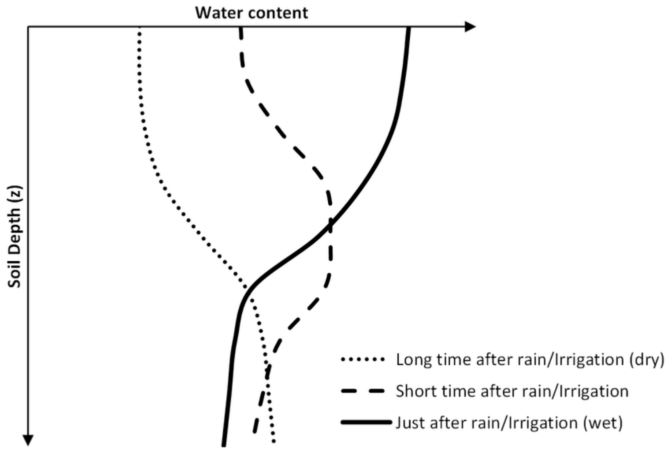

Figure 3.10 Various water content profiles over soil depth for various moments after rain/irrigation (after: Mishra et al., 2015)

In agriculture, root zone water content is most relevant. For water resources management the entire soil moisture profile needs to be known as it governs the storage capacity of the soil and therefore the response of the groundwater system. It is an important variable in climate models and a prime indicator for drought risks. For operational water management and agriculture or irrigation purposes, a resolution of 250 x 250 m (plot scale) and a daily update frequency is desirable (STOWA, 2016). When considering its use in flood forecasting models, the desired resolution and update frequency varies with the physiographic environment and response characteristics of the watershed or relevant tributaries of the river. A higher resolution and update frequency generally being desirable in fast responding systems.

The main global in-situ soil moisture database is the International Soil Moisture Network (ISMN: https://ismn.geo.tuwien.ac.at/data-access/). Data collecting networks share their soil moisture datasets with the ISMN on a voluntary and no-cost basis (Dorigo et al., 2011). Incoming soil moisture data are automatically transformed into common volumetric soil moisture units and checked for outliers and implausible values. The ISMN contains data of 19 networks and more than 500 stations located in North America, Europe, Asia, and Australia. The time period spanned by the entire database runs from 1952 until the present, although most datasets have originated during the last decade. The database is rapidly expanding, which means that both the number of stations and the time period covered by the existing stations are still growing. Yet, the global coverage is very heterogeneous and highly depends on countries willingness to share their data and thus satellite data can provide an important supplement to the in-situ data.

3.5.2 Earth observation based products

Satellite derived soil moisture products make use from the fact that changes in surface soil moisture lead to changes in the surface microwave emissivity and backscattering properties of the land surface. Therefore two types of sensors are used to derive soil moisture: passive microwave sensors can detect soil moisture variations by measuring the brightness temperature of the emitting surface and active sensors (radars) can detect soil moisture variations by measuring the backscatter radar signal returned to a satellite sensor (Lettenmaier et al., 2015). Since both signals are influenced by vegetation cover and backscatter also by soil roughness, various algorithms have been developed to retrieve soil moisture. An important factor relates to the fact that satellite derived soil moisture products only represent the moisture status in the upper few centimetres of the soil, with L-band microwave capable of penetrating maximum 5 cm. The complex relationship of soil moisture distribution with depth prohibits therefore the use of satellite derived soil moisture products in accurate estimation of the total moisture content of the unsaturated zone above the groundwater level. Nevertheless, satellite derived soil moisture products find useful application in agriculture and irrigation, especially for drought management, and are a valuable input into Land Surface Models and Climate Models.

3.5.2.1 Overview of most important datasets / algorithms

There are many soil moisture retrieval algorithms and data sets. An important division is made by those based on brightness temperature and those based on backscatter coefficient. Brightness temperature is measured using *passive microwave sensors*, whereas backscatter coefficient is measured using radar sensors. Various factors influence the brightness temperatures measured by the satellite sensors and have an effect on the soil moisture retrieved. Most notable of these are the Vegetation Optical Depth and atmospheric attenuation (Karthikeyan et al., 2017). Most algorithms use Radiative Transfer Models to relate brightness temperature and soil dielectric constant and link soil dielectric constant with soil moisture using ‘dielectric mixing’ models. Since all the passive microwave satellite sensors have capabilities of measuring multi-frequency/angular dual polarization brightness temperatures, current algorithms are capable of retrieving simultaneously surface temperature along with soil moisture and Vegetation Optical Depth, thus bypassing the need to use NDVI or LAI-products from optical imagery to estimate Vegetation Water Content. Apart from physical models, soil moisture is also derived from passive microwave measurements using statistical regression techniques. AMSRE-E, SMOS and SMAP are three of the mostly used satellites having passive microwave sensors on board. Spatial resolution of the sensors varies between ~ 13 to 60 km and the overpass frequency of microwave sensors is much higher, on average every 1 to 7 days.

De Jeu and de Nijs (2017) developed an algorithm that uses the high resolution data from AMSR-2 and SMAP. They developed a soil moisture product that is available at a daily time-step with technically spoken a spatial resolution of 100x100 meters, although depending on the availability of raw data the information content or effective spatial resolution may be lower. The algorithm directly uses the Level-1 satellite antenna data. The resolution of the processed data is higher than the satellite footprint which is possible because the algorithm uses all available and thus overlapping images. For the period 2012-2017 De Jeu and Schalie processed AMSR-2 C-band data. C-band penetrates approximately 1-2 cm into the ground. For the period 2015-2017 they also processed SMAP L-band data that penetrates 6-7 cm into the ground. According to their analysis the resulting soil moisture products have a higher resolution and higher accuracy than already existing soil moisture products. Over the Netherlands they showed good performance, the SMAP based product outperforms the AMSR-2 based product. The data can be made available in near-real time with a delay of 6-hours.

Active Microwave Sensors provide data at resolutions as high as 10 metres but their temporal revisit time is lower than that of Passive Microwave sensors. A complete global coverage may take 6 to 60 days for the individual sensors. As is the case with soil moisture measurements based on brightness temperatures, there exist a number of approaches to derive soil moisture from backscatter coefficients. The backscatter coefficient is a function of physical and electrical properties of the soil surface and the radar characteristics (wavelength, polarization and incidence angle). It also depends on the amount reflected from the vegetation as well as the soil layers. Due to the high resolution of active microwave sensors retrieval models have to take into account the effect of soil roughness. Various approaches have been developed to retrieve soil moisture taking into account the effects of vegetation and soil roughness. Most retrieval models use empirical or change detection approaches (Karthikeyan et al., 2017) making use of the various characteristics of the sensor (wavelength, polarization, incidence angle). A successful approach is the change detection algorithm developed by the TU-Wien which makes use of multi-temporal passes to obtain relative changes in soil moisture. As with passive microwave sensors, lower frequency (L-band) signals are less influenced by reflections from the vegetation cover and have a higher penetration depth, making them more suitable for soil moisture retrievals than X-band or C-band.

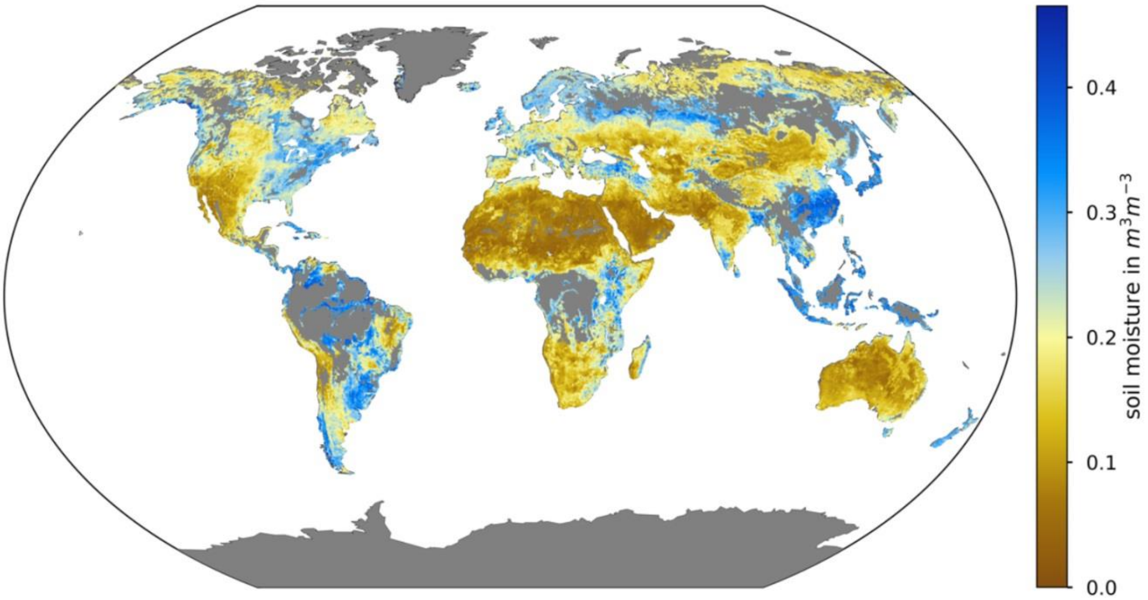

Figure 3.11 Average volumetric soil moisture for May 2018 from the COMBINED product (*https://climate.copernicus.eu/land-hydrology-cryosphere*)

One of Europe's main soil moisture products is ESA-CCI that merges information from passive and active sensors to create time-series of significant length with reasonable resolution. The ESA Climate Change Initiative soil moisture group has developed and evaluated a methodology that takes advantage of the retrieval characteristics of passive and active microwave satellite estimates to produce an improved soil moisture product (Dorigo et al., 2016). Level 2 soil moisture products, produced outside the processing chain by various data providers, are used as input to the ESA CCI SM products. A daily product is generated with a grid spacing of 0.25°. The data availability of ESA CCI SM varies through space and time due to the varying spatial and temporal availability of the single-sensor Level 2 input products. The multi-decadal blended dataset (1979 – 2016) is expected to enhance the basic understanding of soil moisture in the water, energy and carbon cycles.

3.5.3 Conclusions current status

The accuracy of soil moisture data depends on atmospheric and land surface conditions. Vegetation emits and backscatters microwave signals and dense vegetation (e.g., forests) can significantly attenuate or dominate the soil moisture signals, making it hard to retrieve soil moisture information (Lettenmaier et al., 2015). Heavy rain clouds also add noise to the retrieval process, thus retrievals over active raining areas are less reliable. Finally, maximum depth attainable for current sensors (L-band) to estimate soil moisture is about 5 cm. With the launch of SMOS and SMAP standardised soil moisture products with a resolution of up to 10 km are now available, with an accuracy of <0,04 m^3/m^3 and a revisit time of 2 – 3 days. SAR-based products potentially have a much higher spatial resolution but this comes at a cost of accuracy, due to the errors in the backscatter model, and lower revisit time. Opportunities arise for products making use of multiple instruments, signal characteristics (like polarization) or image processing.

3.6 Groundwater

3.6.1 In-situ measurement

Networks for groundwater level monitoring usually cover aquifers of large regional size. They serve to provide data about groundwater system behaviour and overall impacts on the groundwater situation caused by groundwater exploitation and other interventions. They may cover an entire country, as is the case in the Netherlands or only the plains and valley fills. Primary networks have their observation wells in the major aquifers, mainly in the fresh water zones.

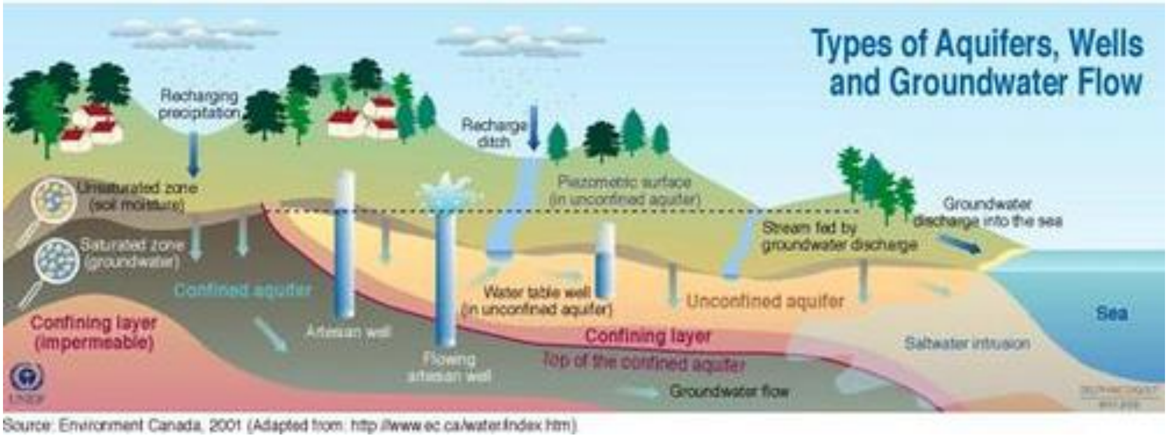

Figure 3.12 Idealised profile showing groundwater flow and types of aquifers (source: Environmental Canada, 2001 - adapted from: www.ec.ca/waterindex.htm)

The selected wells are usually sufficiently spaced to provide an overall picture of the groundwater situation. The cost of installing groundwater level measurement wells is large which prohibits sufficient monitoring networks in most countries, especially in sparsely populated areas. IGRAC (2008) recommends at least one well per 25 – 100 km^2 for studies to estimate aquifer recharge/depletion and one well per 10 – 25 km^2 for studies to estimate groundwater flux. The density of wells in confined aquifers can be much less than those in unconfined aquifers, which are open to meteorological and human influences. For phreatic aquifers in the Netherlands, one groundwater well per 7.5 – 12.5 km^2 is recommended. Actual densities of national groundwater monitoring networks vary considerable, from one well per 35 km^2 in Bayern, Germany to one well per 1500 km^2 to monitor groundwater occurrence in the large aquifers in Texas and Montana. Apart from national monitoring networks, groundwater typically is also measured in proprietary networks and wells for private use. Generally, biweekly sampling of groundwater head is recommended for most groundwater management activities (IGRAC, 2008).

The International Groundwater Resources Assessment Centre established a global database of groundwater observations that includes many monitoring networks.

3.6.2 Earth observation based products

Since groundwater resides below the ground surface there conventional satellite instruments measuring electromagnetic radiation from earth are not capable of measuring it. Satellite gravimetry, capable of measuring tiny changes of the gravity field, however is capable of measuring changes in groundwater storage. Currently there is one set of gravity measurement satellites – the Gravity Recovery and Climate Experiment (GRACE) is a joint mission of NASA and the German Aerospace Center. Twin satellites took detailed measurements of Earth's gravity field anomalies from its launch in March 2002 to the end of its mission in October 2017. By measuring gravity anomalies, GRACE showed how mass is distributed around the planet and how it varies over time and therewith it provides an important source of information on the dynamics of groundwater depletion and storage. One of the main advantages of GRACE over other satellite datasets is that it doesn't require a reference surface. GRACE gathered a global coverage every 30 days and far exceeded its 5-year design lifespan, operating for 15 years up until 2017. Its successor, GRACE-FO, has successfully been launched on 22 May 2018.

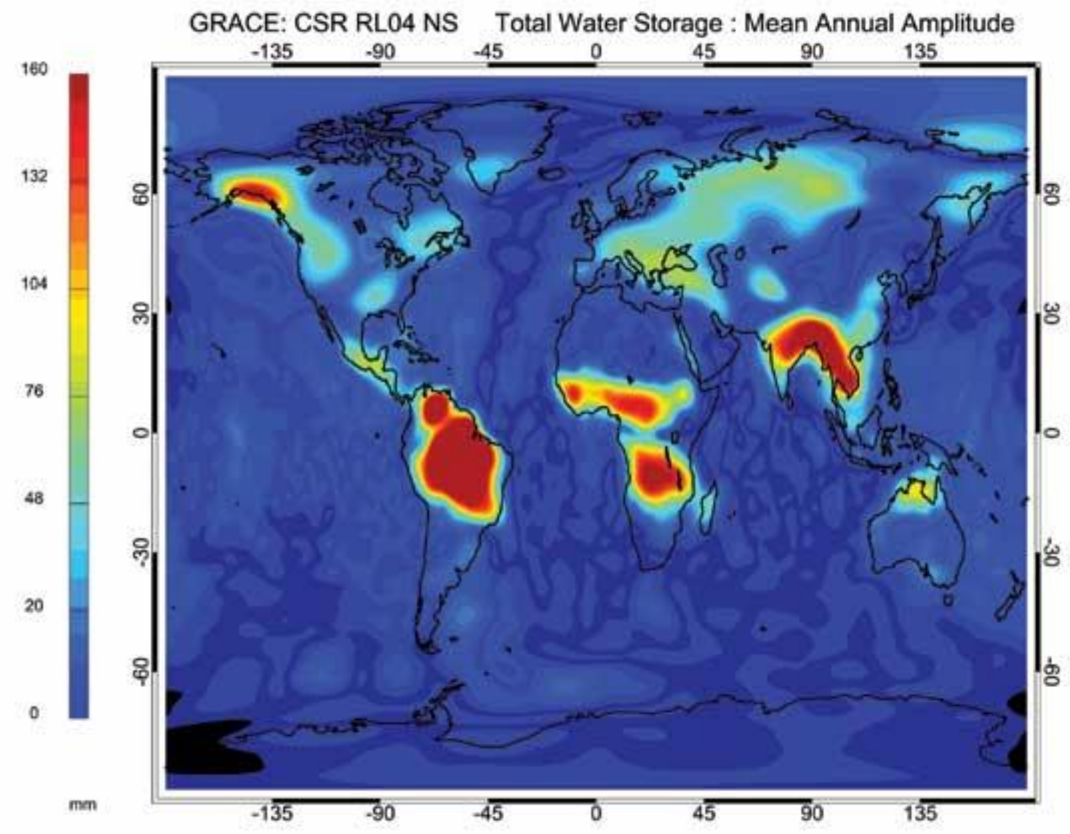

Figure 3.13 Mean annual amplitude of total water storage on Earth in 2007 as measured by GRACE (courtesy NASA).

The experimental laser on board the new mission is expected to be 20 times more accurate. The GRACE dataset has a resolution of approximately 300 – 400 km and a monthly time step. In addition to groundwater GRACE in combination with radar can help with sensing large water bodies, which is especially relevant for extended wetland areas / lakes partly covered by trees and thus hard to sense using microwave.

An alternative to gravity measurements can be found in measuring the effect of changes in groundwater storage by measuring its effect on land movement. Changes in groundwater storage in confined aquifers result in an elastic response of the soil matrix noticeable as either subsidence (groundwater withdrawal) or heave (recharge). This response can be measured by means of interferometric analysis of repeat pass SAR-imagery. Interferometric SAR (InSAR) exploits the phase difference between two complex SAR observations of the same area, taken from slightly different sensor positions, and extracts distance information about the Earth's terrain as the phase correlates well with the land surface topography. Sentinel 1A has a 6 - 12 days repeat cycle and the first of the set of two satellites was launched in 2014. The InSAR data only provides an indirect source of information on groundwater depletion and rather measures land subsidence or deformation. InSAR has proven to be capable of measuring ground movement with mm-precision, making use of X-band, C-band or L-band active microwave sensors.

3.6.2.1 Overview of most important datasets / algorithms

One of the earliest studies to use GRACE-data is Rodell et al. (2009). They use GRACE data to simulate groundwater variations from a data-integrating hydrological system to compute groundwater depletion over the Indian subcontinent. Combinations of land surface models were used to remove the effect of root-zone soil moisture and records of reservoir storage to remove surface water storage effects from the Total Water Storage variability to estimate groundwater storage variability.

Miro and Famiglietti (2018) downscaled GRACE data to higher resolution to analyse groundwater depletion in California and concluded that a higher-resolution GRACE like data product would significantly improve information availability for local-scale decision makers and could offer novel data for regions that do not have adequate in situ monitoring networks. Döll et al. (2014) also mention the low resolution of GRACE as drawback and in addition mention the seasonal disturbance of the signal by variation in soil moisture and snow / ice.

Castellazzi et al. (2014) combined low resolution GRACE data on groundwater depletion with high resolution detection of groundwater depletion areas from RADARSAT-2 to detect important local decreases in Mexico. One of their conclusions was that the signal was disturbed by surface water storage increases included in the GRACE gravity fields.

For example NASA uses Sentinel 1A data to derive the land subsidence resulting from groundwater depletion in California, see the figure below.

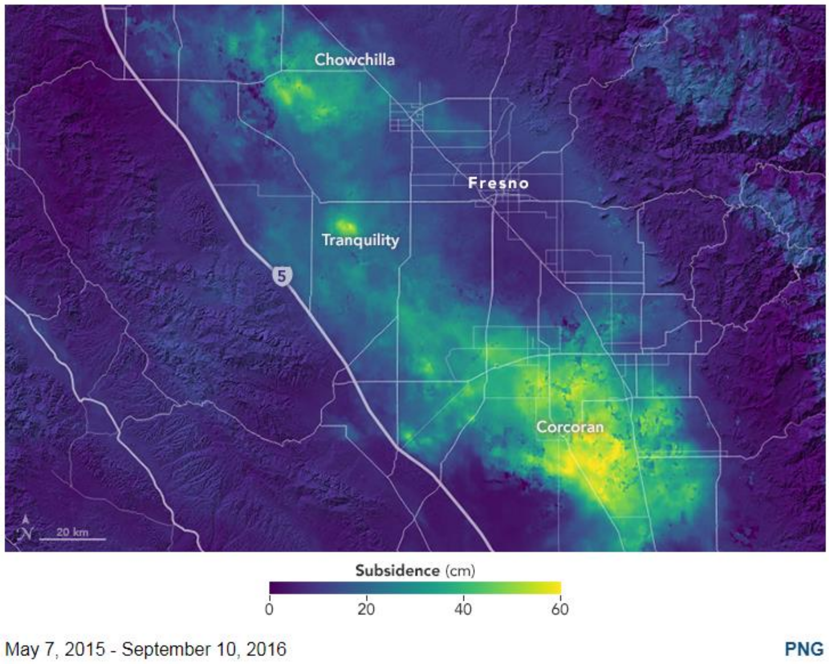

Figure 3.14 Subsidence in part of the San Joaquin Valley between May 2015 and September 2016 as observed by the European Space Agency's Sentinel-1A (Courtesy Tom Farr and Cathleen Jones; NASA-JPL)

Chen et al. (2016) did analyse InSAR data from ALOS PALSAR scenes for a longer period (2007-2011). With the InSAR data estimates of subsidence can be made. Then, using the algorithm of Galloway and Burbey (2011) for confined aquifers the deformation can be translated into groundwater head changes. Using InSAR data they could characterize seasonal and long-term changes in aquifer storage and groundwater levels for agricultural regions at the basin scale. Analysis can be further improved with ALOS-2 and Sentinel-1 that have higher temporal sampling rates. Parker et al. (2017) did already estimate land subsidence in the Perth Basin using both TerraSAR-X and Sentinel-1A InSAR data. They conclude that, although the analysis could only be performed for a period of 0.7 year, because of the only recent data availability of Sentinel-1A InSAR, both datasets were able to capture the in-situ monitored subsidence. The deviation from in-situ data was only 9 mm (Sentinel-1A) and 5 mm (TerraSAR-X).

3.6.3 Conclusions current status

There are a number of (new) satellite instruments that give high resolution information on subsidence and indirectly on groundwater depletion, however the quantification of absolute groundwater volumes is not possible on high resolution. GRACE is the main source for estimating changes in groundwater storage and thus recharge, but its resolution is not high enough to use for large scale land surface / hydrological model initialization or local groundwater monitoring, because the models typically have resolutions of 1 degrees or higher and spatial variation in groundwater storage changes cannot be captured at a 300 km scale InSAR provides higher resolution data with a higher time frequency, but does not provide direct measurements of groundwater occurrence. GRACE does provide information for the total water mass stored including deep groundwater, but can only be used to monitor *changes* in mass. Therefore in-situ observations of groundwater depth and presence remain the most valuable source.

3.7 Streamflow and river discharge

3.7.1 In-situ measurement

Since only for very small streams a direct measurement of discharge is possible, a large number of indirect measurement techniques and devices have been developed, e.g. flumes and weirs, flow velocity times stream cross section, tracer techniques, ultrasound and electromagnetic measurements. However, the most common way to monitor discharge is by measuring water level at gauging stations and using a stage-discharge curve representative for the given location. In general, a sufficient number of streamflow stations should be established along the main stems of large streams to permit interpolation of discharge between the stations. The specific location of these stations should be governed by topographic and climatic considerations (WMO, 2008). To ensure adequate sampling, there should be at least as many gauging stations on small streams as on the main streams and covering different geologic and topographic environments. General indications of the minimum density of measurement locations are hard to give, due to the large variety of hydrological regimes, scale and physiography. WMO (2008a) recommends a minimum of 1 station per 1000 km^2 in mountainous areas up to 1 station per 2750 km^2 in coastal areas. In Europe, the average density of stream gauging stations varies from about one station per 150 km^2 (UK, France) tot about one station per 300 km^2. The USGS maintains 7000 stations (equalling 1 station per 1400 km^2). On the other hand, Alsdorf et al. (2007) note that the gauge density in the Amazon is roughly 4 orders of magnitude less than a typical area in the eastern United States. The WRIS in India manages roughly one station per 3000 km^2 over the Indian part of the Ganga river basin. WMO (2008a) recommends a water level measurement every 10 – 20 min. and accuracy in water depth measurement of 0.1 m or 2% and width of water surface of 0.5%. However, river dynamics actually determines the number of stations which can be better defined in number of stations per river stretch because the density of river networks varies around the globe.

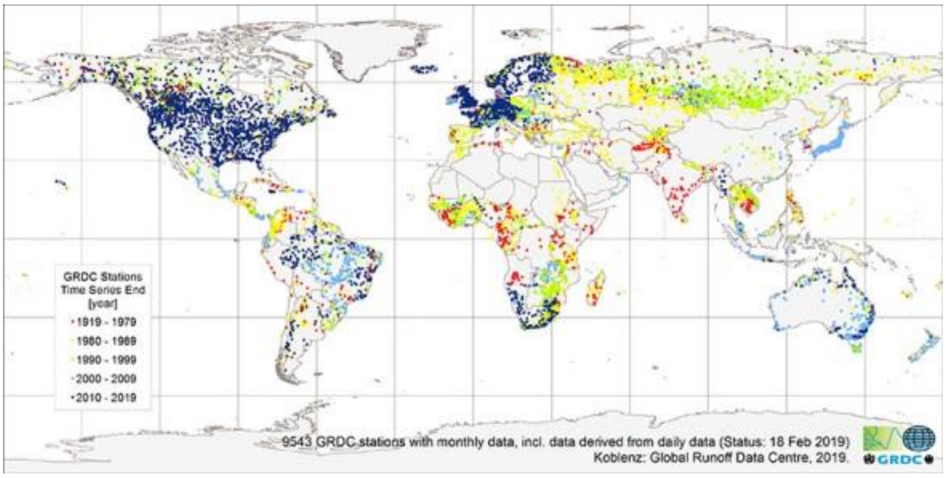

Figure 3.15 Global distribution of GRDC stations with monthly data – status February 2019 (source: GRDC)

Discharge observations for rivers all over the world are systematically saved in the Global Runoff Database (https://www.bafg.de/GRDC/). This database contains time series of daily and monthly river discharge data of currently more than 9,500 stations worldwide. This adds up to around 415,000 station-years with an average record length of 43 years. There is always a delay in the observations becoming available in the GRDC database. End November 2018 only 550 stations, nearly all located in the US, do already have data available for 2018. However, the number of stations in developing countries is often limited and additional observations are required here to estimate amongst others freshwater availability (Alsdorf et al., 2007). In addition, single gauge observations cannot provide reliable discharge observations for wetlands, floodplains and braided rivers.

3.7.2 Earth observation based products

Essentially, spaceborne observations need to measure river stage and cross sectional velocity to be able to infer discharge estimates. However, no current satellite-based method can measure cross-sectional velocity, so most approaches are developed in such a way that this can be side-stepped by using various hydraulic assumptions. Since these methods make use of satellite derived data on river stage, acquired by altimeter data, and water extent, derived by various optical and microwave sensors, examples of both variables will be described.

3.7.2.1 Overview of most important datasets / algorithms

Van Dijk et al. (2016) introduce a method to derive river discharge from satellite data as an extension of existing research. The main improvement is reached by combining Passive Microwave water extents, MODIS8 optical data and river altimetry data and designing a method that is applicable worldwide. The river discharge estimates are based on 'stage-discharge' curves that in their algorithm relate river discharges to inundation extents of upstream areas / cells, hereby enabling the derivation of river discharge when inundation extents are observed. The algorithm was developed on a monthly time-step to ensure sufficient data could be included.

The algorithm performed well in unregulated lowland rivers in boreal and tropical regions with a reasonable intra-annual variability. Yet, performance decreases when rivers become more regulated, or in arid regions where floods last relatively shortly. In general satellite discharge observation for smaller basins would require higher resolution observations in both space and time, the latter because variations in flows and floods are more likely on a daily / weekly time-step than on a monthly time-step.

The above methods are surface area – discharge relations. Satellite altimeters also provide relevant information on the river stage. Altimetric data from TOPEX/Poseidon has been used to derive river stages of larger river basins. The radar observations are based on pulse returns and therefore require overpass over a longer period of time, thus mainly working for larger rivers. Another complication with current ocean altimeters is that revisit times typically exceed ten days and tracks are hundreds of km apart. Hence data generally cannot be obtained at specified river locations, and rather must be used opportunistically where orbit tracks cross rivers (Lettenmaier et al., 2015).

SWOT - The Surface Water and Ocean Topography satellite mission, planned for launch in 2021, will solve the problem of the widely spaced tracks of nadir-pointing altimeters by producing radar-imagery derived water level heights rather than one-dimensional track-returns. Van Dijk et al. (2016), Durand et al. (2016) and Lettenmaier et al. (2015) mention the value of the upcoming SWOT data for estimating river discharges. SWOT could potentially provide information for all rivers of 100 metres and wider. SWOT retrievals will be possible nearly anytime only not during intense precipitation events. The measurements will include river water surface elevation, top width and free-surface slope which can be combined to estimate river discharge by completing for example the Saint-Venant equation or directly using the data as input to hydrological / flood models. It will be possible to extract estimates of surface water slope from the SWOT images to accuracies of 1 cm per 10 km of river stretch. Yet, in-situ discharge measurements will remain the best source of discharge observations because the overpass frequency will only be 21 days.

3.7.3 Conclusions current status

The GRDC datasets provides a good and consistent source of discharge data for rivers worldwide, yet the global coverage is very heterogeneous. Discharge observations from space can supplement the GRDC dataset, especially for larger ungauged basins. With the current satellite data it is possible to derive river discharges with a reasonable performance only for non-regulated river discharges of significant size. The required surface water extent data can now reasonably reliable be obtained on a monthly time-step using a combination of microwave satellite data and radar data that is needed to produce cloud free images. Local training of algorithms is required to correct for local disturbing influences from vegetation. Deriving river discharges remains a highly local process and is at this stage only possible for the larger rivers of the world with lengthy in-situ training records.

The planned SWOT mission provides a promising new source of high spatial resolution information for narrower river branches although derived datasets will likely have a low temporal frequency.

3.8 Water level and extent

3.8.1 In-situ measurement

In-situ gauge measurements have helped to quantify the movement of water (discharge) in river channels but provide comparatively little information about the spatial dynamics of surface water extent, such as flood plain flows and the dynamics of wetlands (Alsdorf et al., 2007). This result is a knowledge gap regarding the volumetric dynamics of water storage for large parts of the globe. It is expected that when storage changes in all of Africa’s lakes, reservoirs, and wetlands are included in the continental water balance, the variability in surface water storage may well approach that of soil moisture (Alsdorf et al., 2007).

In-situ lake and reservoir dimensions and locations have been collected first in the Global Reservoir and Dam database. This dataset has been extended with natural lakes in the HydroLAKES dataset (Messager et al., 2016). HydroLAKES is a database aiming to provide the shoreline polygons of all global lakes with a surface area of at least 10 ha. Additional attributes for each of the 1.4 million lakes include estimates of the shoreline length, average depth, water volume and residence time.

3.8.2 Earth observation based products

The relevant satellite instruments have been listed in Appendix A.

3.8.2.1 Levels

Duan and Bastiaanssen (2013) used 4 satellite based lake level databases : (i) Global Reservoir and Lake Monitoring (GRLM), (ii) River Lake Hydrology (RLH), (iii) Hydroweb and (iv) ICESat-GLAS level 2 Global Land Surface Altimetry data (ICESat-GLAS) to estimate water volume changes in lakes and reservoirs in combination with satellite imagery data, without any in-situ measurements and bathymetry maps. Compared to in-situ water levels, satellite altimetry products provided accurate water level variations for the lakes they considered. The (RMSE) was within 4.6 to 13.1% of the mean volumes of in-situ measurements. All water levels were converted to the Water Level Above the Lowest Level (WLALL), and the series of Landsat TM/ETM+imagery data were selected to extract corresponding surface areas for establishing area–WLALL relationships.

Optical, SAR and altimeter sensors are used in various algorithms for surface level estimation. For the largest reservoirs Gao et al. (2012) estimated reservoir storage variations from MODIS images for reservoir extents and retrievals from TOPEX/Poseidon and other satellite altimeters for reservoir levels. From the satellite observations they were able to derive relations between storage and surface area for 34 large reservoirs.

3.8.2.2 Surface water extents

Pekel et al. (2016) used Landsat satellite images to quantify changes in global surface water over the past 32 years at 30-metre resolution. They recorded the months and years when water was present, where occurrence changed and what form changes took in terms of seasonality and persistence. The maps were created from individual full-resolution images from Landsat 5, 7 and 8 satellites. They acquire multispectral imagery at 30m resolution in six visible, near and shortwave infrared channels. Each satellite is in a near polar orbit, and provides global coverage every 16 days, combined they have an eight-day revisit period. Thermal imagery and the contrasting spectral properties of water and other features in the visible, near and shortwave infrared channels were used to separate pixels acquired over open water from those acquired over other surfaces. The pixels were classified using an expert system (see Pekel et al., 2016).

Donchyts et al. (2016) developed a way of evaluating flood extent and permanent water by combining several remote sensing datasets in Google Earth Engine: Landsat with Shuttle Radar Topography Mission. With this method, flood maps all over the world (with details up to 30 metres) were produced, going back up to 1999. The satellite data was combined with knowledge about the flow of water over the terrain and OpenStreetMap GIS data to optimize the surface water estimates. The water maps Deltares created are available as monthly time series of images. The gains and losses of land and water around the globe have been made available in the Deltares Aqua Monitor (see Figure 3.16). In recent work data from Pekel et al. (2016) and data from other satellites (MODIS and Sentinel) have been included as well to increase the accuracy of the maps and to correct for cloudiness and vegetation. With this approach monthly varying extent time-series for individual reservoirs are now being developed.

As part of the ESA CCI Land Cover Change Initiative a SAR-based approach has been implemented to derive information on inland water bodies. Multi-temporal acquisitions of Envisat ASAR Wide Swath Mode with local gap fillers based on Image Mode and Global Monitoring Mode from the years 2005 to 2010, MERIS data and auxiliary datasets have been used to generate a single epoch map of permanent open water bodies at 300 m resolution (http://maps.elie.ucl.ac.be/CCI/viewer/index.php).

3.8.3 Conclusions current status

The algorithms and data available to estimate the surface water extent of lakes, wetlands and reservoirs have improved a lot over the last decades (Pekel et al., 2016; Donchyts et al., 2016). Especially with the new available Sentinel datasets resolutions of 10 metres and higher can be obtained. Still, local optimization of the datasets for disturbing signals from amongst others vegetation and clouds will remain required. Those satellites that pass over with short repeat intervals have a relatively low resolution and data merging and extrapolation is needed to downscale these data to higher resolution using amongst others radar data. For the static derivation of the outline of lakes SAR can be combined with optical data to correct for the vegetation influence.

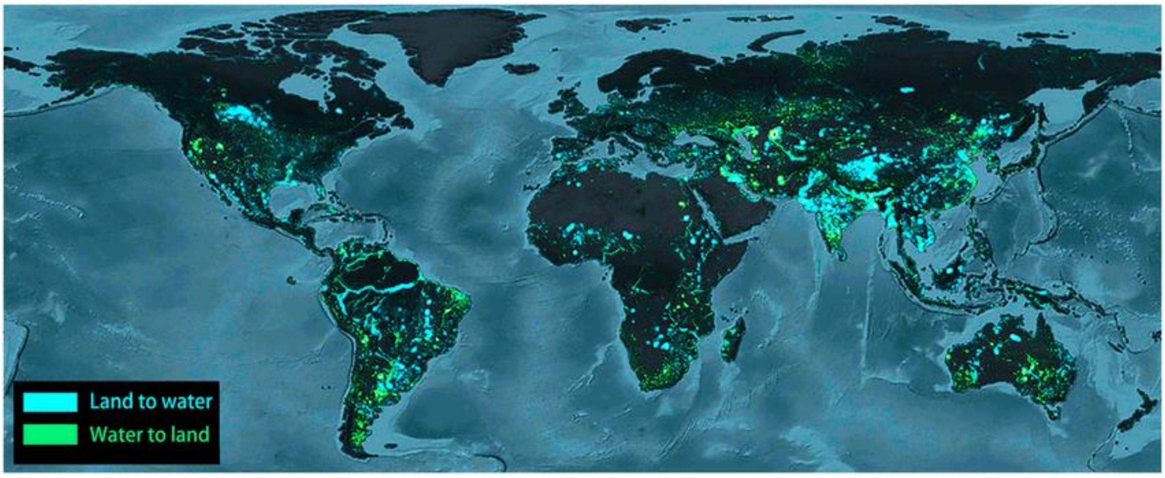

Figure 3.16 Heat map of global surface water and land changes (figure reprinted from Donchyts et al., 2016).

The translation of this information to reservoir and lake volumes, which are good estimators of local fresh water availability and relevant for reservoir management, remains a challenge. Ideally the bathymetry of the reservoir / lake would be known. Hereto data from radar altimeters (Alsdorf et al., 2007), used for measuring elevations of the ocean surface for decades, provide a valuable source. However, altimeters miss too many freshwater bodies to be useful hydrologically as a result of their orbital spacing.

The SWOT mission could provide valuable new information for the derivation of storage relations for lakes and reservoirs. With its high resolution it is able to sense extent variation for lakes as small as 250 m^2. Height accuracy is < 10 cm when averaging over water areas > 1 km2 and < 25 cm when averaging over water areas in the range of 250 m^2 – 1 km^2. It will use two Ka-band receivers for surface water elevation and microwave measuring for surface water extents. Spatial resolution of SWOT will be 6 – 7 m in the azimuth direction and 10 – 60 m in the range direction and the repeat period will be about 21 days. In wetlands surface water observations can be disturbed by the presence of vegetation. Wetlands often host a variety of vegetation species and the possible noise observed by SWOT for these different vegetation types is already under research by amongst others NASA (Siward; Understanding SWOT Measurements in Coastal Wetlands).

3.9 Surface elevation

Surface elevation models are a core spatial dataset for many water resources applications. Netherlands has a multi-annual LIDAR-acquisition programme which enables the construction of a digital elevation model with a 0,5 m raster and height accuracy of <5 cm standard deviation and <5 cm systematic error. Most countries do not have such a programme or do acquire data only over parts of the country. Current global DEM's use satellite radar ranging or stereoscopic multi-pair imagery to estimate elevation differences. Currently most in use are SRTM, ALOS/PALSAR and Tandem-X. Tandem-X DEM can be considered as the most recent and has a spatial resolution of 12 m at the equator and 2 m relative accuracy for areas sloping less than 20º. Especially for relatively flat terrain these errors are too large for appropriate hydrological forecasting. Schumann and bates (2018) mention various studies highlighting the fact that the use of current satellite derived DEM's can result in differences in runoff of 10% and that SRTM DEM has a residual vertical error which is for most river gradients an order of magnitude larger than the flood waves in those rivers. What is more, inaccuracies will have effect on modelled flood extent and inundation area since the residual error in the SRTM DEM is too large compared to most river gradients.

3.10 Water use/demand

Statistics on water use are collected and distributed by national authorities and water production companies in many countries. However, not everywhere the necessary infrastructure is in place and often these statistics are then derived from aggregated country statistics such as population density, GDP and industrial activity. For agricultural water use the FAO database forms one of the major sources combined with datasets as for example the higher resolution global crop dataset of monthly irrigated and rain fed crop areas around the year 2000 (MIRCA2000; Portmann et al., 2010). With a spatial resolution of 5 arc min (about 9.2 km at the equator), MIRCA2000 provides both irrigated and rain fed crop areas of 26 crop classes for each month of the year including multicropping systems. When this data is combined with information on irrigation efficiency and irrigation needs per crop type reasonable estimates of irrigation demand can be obtained.
Water demand (Wada et al., 2014) is often sub-divided in:

- industrial water demand;
- household water demand;
- livestock water demand and
- irrigation water demand.

Industrial:
Gridded annual average industrial water demand data has been collected in a number of studies, see for example WRI (1998). There is limited available data to identify the seasonal trends whereas daily industrial water demand likely fluctuates over the year. Hereto Wada et al. (2014) developed an algorithm that calculates country-specific economic development based on four socioeconomic variables: gross domestic product (GDP), electricity production, energy consumption, technological development per country and household consumption. Valuable satellite information is gathered in:

- NASA's global maps of Earth at night, providing a clear composite view of the patterns of human settlement across our planet.

Household

Household water demand is estimated multiplying the number of persons in a grid cell with the country-specific per capita domestic water withdrawal. The daily course of household water demand can be estimated using daily air temperature as a proxy. The country per capita domestic water withdrawals are available from FAOSTAT. Gridded global population maps can be used to downscale the yearly country population data (FAOSTAT) to produce gridded population maps for each year. Here there are additional satellite based products that can help to downscale to high resolution, first of all the above mentioned Global maps of Earth at night and second:

- Lead by JRC the Global Human Settlement (GHS) framework produces global spatial information about the human presence on the planet over time including built up maps, population density maps and settlement maps. This information is derived from global archives of fine-scale satellite imagery, census data, and volunteered geographic information.

Livestock:
Gridded global livestock densities of cattle, buffalo, sheep, goats, pigs and poultry and their corresponding drinking water requirements can be obtained from FAO. To generate time-series country statistics are available from FAOSTAT.

Irrigation:
Satellite data can provide highly valuable input for estimation of irrigation demand. First of all with the comparison between remote sensing products for actual evapotranspiration and modelled actual evapotranspiration estimates of actual irrigation and irrigation needs can be made (Bastiaanssen et al., 2012). In dry areas where irrigation would increase crop yield the difference between potential evaporation and actual evapotranspiration can be large. If the remotely sensed actual evapotranspiration is higher than the actual evapotranspiration modelled under natural conditions the difference is an indication that irrigation has been applied and an estimate of irrigation water supplied can be made.

In addition irrigation demand models often require information on the crops located in the irrigation areas, there growing cycles and possible changes over longer time-periods. Satellite images can be used to, at least, derive LAI, NDVI but also to distinguish individual crop types.

4 In-situ measurements and Earth Observation for coastal water management

4.1 Introduction

Here we provide an overview of in-situ measurements and main Earth Observation retrieval algorithms, relevant at the regional or global scale, which are used to measure the Essential Water Variables for coastal water quantity management. The available satellite instruments are listed per variable in Appendix A. The overview addresses the achievable spatial, temporal resolution, spatial coverage and the accuracy. A global overview of the different sensor classes is given in Figure 4.1

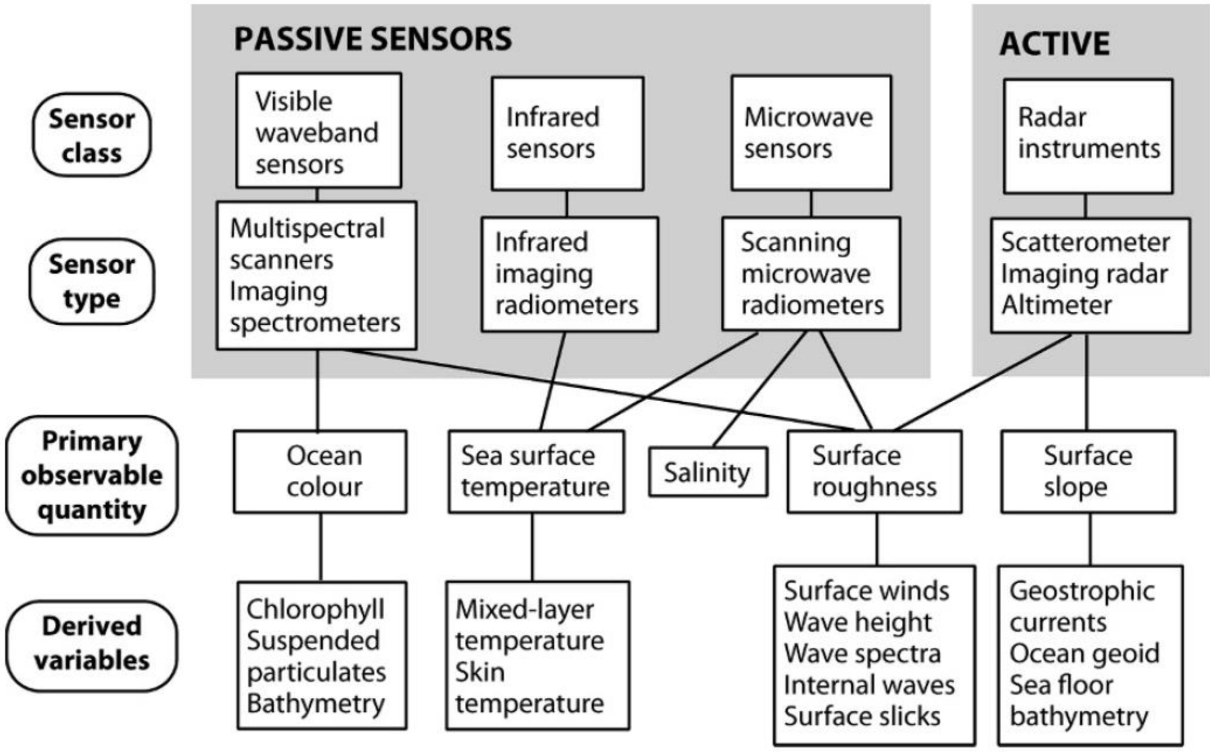

Figure 4.1 The different remote sensing methods and classes of sensors used in satellite oceanography, along with their applications (from Robinson, 2004).

4.2 Sea surface height, salinity and temperature

4.2.1 Sea level and wave height

In situ sea level observations are made using tide gauges which record sea levels as average values over periods varying between 5 and 15 minutes. This sampling is adequate for most operational applications involving the monitoring of tides, storm surges and mean sea level. Integration over shorter time intervals is necessary for monitoring seiches and tsunamis, given that these are fast-travelling waves and short duration processes. An overview of locations comprising the Dutch monitoring network for sea level and waves is given in figure 4.2.

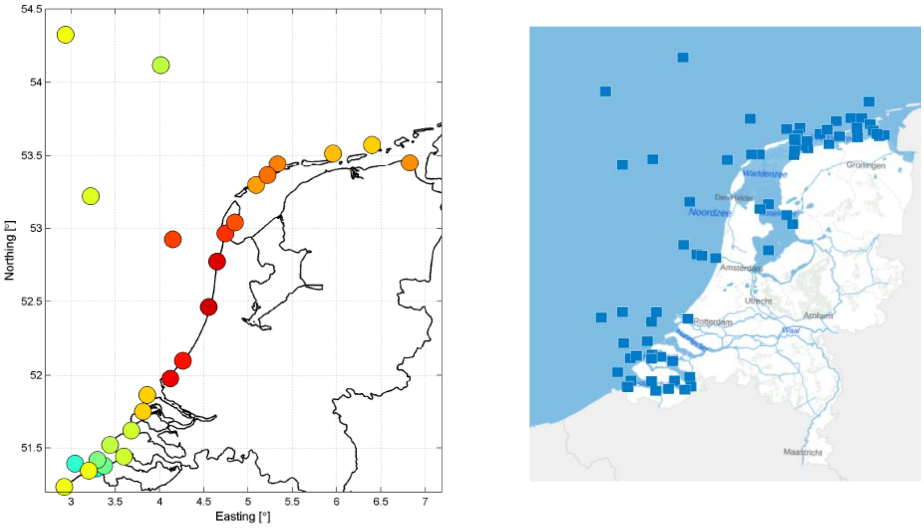

Figure 4.2 (left) Dutch monitoring network for sea level, (right) Dutch monitoring network for waves (source: RWS - Waterinfo).

Global data are collected by the Global Sea Level Observing System. The Global Sea Level Observing System was established in 1985 by the UNESCO Intergovernmental Oceanographic Commission to establish a well-designed, high-quality in situ sea level observing network to support a broad research and operational base. The backbone of the global network is the GLOSS Core Network (GCN), a global set of 300 tide gauge stations that provide optimal sampling of the global ocean.

Figure 4.3 GLOSS Core Network of tidal gauges for sea level measurements

In-situ sampled tide gauge data and wave data provide valuable information for analysis and at the locations where the observations are located but suffer from limitations due to geographical distribution (especially regarding under sampling along long coastal stretches around the world), tide gauges are attached to the land and influenced by local movements of the substratum and there is no common reference frame for the records which creates a problem of stacking them together.

Over the last 25 years satellite altimetry has been a valuable tool in oceanography and global sea-level monitoring. A variety of parameters may be inferred using the information from radar altimeter measurements, such as time-varying sea-surface height (ocean topography), information for mapping sea-surface wind speeds and significant wave heights, the topography of land and ice sheets, and even that of the sea floor. Radar altimeters use the ranging capability of radar to measure the surface topography profile along the satellite track. They provide precise measurements of a satellite's height above the ocean by measuring the time interval between the transmission and reception of very short electromagnetic pulses. By measuring the departure of sea surface height from its long-term mean level at that location, the sea surface height anomaly (SSHA) product obtained from satellite radar altimeters is capable of directly detecting the presence of ocean eddies, fronts, and waves (significant wave height) along a track. A number of altimeter-derived products are available via projects and services like AVISO, PEACHI, PISTACH and RADS, maintained by TU-Delft. Current accuracies are close to 0.3 mm/yr (Cipollini et al., 2017; Ablain et al., 2017), the requirement prescribed by the Global Climate Observing System (GCOS). However, coastal altimeter processing still poses problems and most altimeter products flag observations in a stretch of 10 – 50 km out of the coast. Recent improvements in processing algorithms and instruments give way to coastal altimeter products with root mean square differences as low as 4 cm at many stations, allowing for instance the characterization of the annual cycle of sea level along the UK coasts (see Cipollini et al., 2017). The launch of CryoSat-2, Sentinel-3 and AltiKa with two important technological improvements, i.e. SAR mode altimetry and Ka-band altimetry—offers opportunities for coastal altimetry. The importance of Sentinel-3 is magnified by the fact that it is due to provide systematic oceanographic observations for the next 20 years. Next to that, the wide-swath high-resolution observations expected from the surface water and ocean topography (SWOT) mission, due for launch in 2021 will further contribute to improved coastal altimeter data. However, revisit times are still low with a 10 day to 4 week frequency for most satellites. Higher updates for models and monitoring are possible when combining satellite-tracks in the products, as is mostly done now, but still do not meet an hourly to daily update frequency necessary for storm surge monitoring and modelling.

The retrieval of waves and winds in the coastal zone is also still in development. The scatterometer is a satellite radar-instrument which provides a measure of wind speed and direction near the sea surface derived from sea state. The EUMETSAT METOP ASCAT - Advanced Scatterometer uses radar to measure backscatter to determine speed and direction of winds over the surface of the oceans. ASCAT data feeds numerical weather prediction models, provides useful information on ice, snow and soil moisture, and is used to analyze areas of individual storm activity, Surface winds images are created hourly for ascending and descending 25 km and 50 km data. Daily images are archived for 7 days. A very different approach to the measurement of ocean surface waves is possible if waves can be explicitly imaged by a high-resolution SAR-instrument that obtains a snapshot view of the sea surface, particularly the slope of the waves, which can be clearly detected if illumination conditions are suitable (Robinson, 2010; Ablain et al., 2016).

4.2.1.1 Conclusions current status

Current satellite derived Sea Level and Wave data have reached a high level of accuracy over open ocean. Altimeters have been used successfully to derive global estimates of tides. On deep water estimates, of tides are generally quite accurate (with the possible exception of high-lattitudes) and are by default removed time altimeter data. Effects of winds and pressure are by default also removed using models (DAC aviso). In shallow coastal waters both the tidal estimates and DAC are less accurate and the linear correction approach ignores nonlinear interaction, which is more prominent near the coast. In general altimeter products are aimed at use in deep water and the slower oceanic dynamics. Much can still be improved in coverage, accuracy and processing of altimeter sea level observations near the coast. For that, dedicated studies are required to better understand the variations in the wave field near the coast, including the estimation of coastal sea-state bias. Altimeters collect data along their tracks, and hence there are per definition huge spatial gaps in the data. The launch of the Sentinel-programme (Sentinel-3 and -6) and SWOT will greatly contribute in covering spatial demands. However, revisit times still do not meet the requirements for monitoring and model updates for storm surges. Near the coast there are strong interactions with bathymetry. In this sense, we expect much from SKIM (Ardhuin et al. 2017) for extraction of coastal wave spectra.

4.2.2 Salinity

Measurements of ocean salinity are done for oceanographic and meteorological studies over open ocean or close to the coast as a means to monitor coastal and estuarine processes. Figure 4.4 shows the network along the Dutch coast, which is primarily focussed on the Southwestern intertidal delta. Relevant global and regional networks are the ARGO-network which collects daily data from 3000 floating buoys worldwide and the NOOS (Northwest Shelf Operational Oceanographic System) which collects daily data from 21 moorings and four vessels, Argo, Drifters, starting gliders, 20 tide gauges covering the North Sea and North-western shelf area.

Figure 4.4 Dutch monitoring network for salinity monitoring. (source: RWS WaterInfo)

Retrieval of Sea Surface Salinity from satellite sensors involves: (1) determination of Brightness temperature (Tb) at the sea surface by correcting for ionospheric, atmospheric, and extra-terrestrial radiation; (2) correcting for sea surface roughness and Sea Surface Temperature; and (3) calculation of Sea Surface Salinity from Tb. Radiative transfer models allow correction for up- and down welling emission from the atmosphere, for atmospheric and ionospheric attenuation, and for Faraday rotation of the polarized microwave emissions as the radiation passes through the ionosphere. Down welling galactic emissions are taken into account using maps provided by radio astronomers. With these corrections, and knowledge of the SST and roughness, salinity can be calculated from brightness temperature.

The Advanced Microwave Scanning Radiometer - EOS (AMSR-E) was placed in orbit on the Aqua satellite in 2002 but because of its limited ocean salinity measurement accuracy, it was not suitable for measuring the small salinity gradients of the open ocean. However, AMSR-E data taken over the Amazon River plume was originally used to demonstrate the feasibility of measuring ocean surface salinity with microwave radiometers from space. SMOS, SMAP and Aquarius all use passive L-band microwave technique at f = 1.41 GHz (= 21.4 cm) with spatial resolutions of 40 km or more.

SMOS uses an interferometric antenna system to avoid the need for a very large antenna to measure the small salinity signal. Aquarius uses a large reflector to sense the same low frequency microwave signals as SMOS. The Microwave Imaging Radiometer with Aperture Synthesis on the SMOS satellite measures the passive microwave emission of earth's surface (the brightness temperature, Tb) at a frequency of 1.400–1.427 GHz in the L-band. Radiation down welling from space at ~1.4 GHz and impinges on the ocean surface and is partly absorbed within a ~1-cm thick upper layer and partially reflected toward the upper atmosphere. Both moisture and salinity decrease the microwave radiation emitted from the earth's surface. SMOS collects data at 6 AM and 18 PM (local time) each day and the surface of the earth is fully covered every three days. Aquarius has an active microwave system coupled to the passive system, yielding a sensitivity that is a least an order of magnitude better than SMOS but over a larger spatial footprint and a longer 8-day repeat cycle for full coverage of the earth.

4.2.2.1 Conclusions current status

Sea surface salinity from passive microwave is currently too course to be of benefit for coastal zone models because they require a higher resolution, especially in tidal and estuarine areas, and also for most (river) regions of fresh water influence. Outside these regions salinity is secondary variable for sea currents in the coastal zone and therefore of limited importance.

4.2.3 Temperature

Sea Surface Temperature is available from ARGO and many satellite sensors, such as MODIS-Aqua, MODIS-Terra and Suomi National Polar-orbiting Partnership, or Suomi NPP-VIIRS. They are provided for three periods: as daily, 8-Day and Monthly averages.

Figure 4.5 Dutch monitoring stations for water temperature (°C). (source: RWS – Waterinfo)

The MODIS instruments are similar, but products may vary slightly because of differences in time of overpass. VIIRS is a different instrument, but it is processed similarly, because efforts are made to SST continuity MODIS to VIIRS for the production of a Consistent Data Records (MODIS/VIIRS science team). Temperature can change more rapidly near the coast than in the open ocean, therefore data-gaps by cloud cover are more of an issue near the coast. For example the signature in SST can change significantly in less than a day if the wind direction changes.

For the different sensors, daily, 8-day and monthly SST averages, respectively are very similar, and are known to be reliable. SST measurements from satellite remote sensing can be determined from thermal infrared and passive microwave radiometry. Both methods have their advantages and drawbacks: while thermal infrared data can provide a skin-temperature SST product with higher spatial resolution and accuracy, microwave sub-skin information is less sensitive to clouds and other atmospheric effects. Hence, the result from clever combinations and interpolations, resulting in the MODIS SST4 and VIIRS triple window products are being provided. Comparison between averages shows that daily averages typically show more variability (high values) than averages that have been calculated for longer timescales. Finally, hourly Meteosat Second Generation (MSG) SEVIRI Level 3C Sea surface Temperature data are available through the EUMETSAT Satellite Application Platform OSI-SAF (http://www.osi-saf.org/). These data are compliant with the state-of-the-art Group for High Resolution Sea Surface Temperatures (GHRSST) Data Specification (GDS).

4.2.3.1 Conclusions current status

SST techniques are furthest developed, and can be used close to the coast. A higher temporal coverage would improve the applicability near the coast. Geostationary satellites have the high temporal coverage, but lack the resolution required. Note that the maximum resolution of 500 m (Sentinel-3/SLSTR) is often too course for estuarine and inland waters. As an alternative derivation of water surface temperature from Landsat thermal bands has been attempted.

4.3 Coastline, morphology and bathymetry

Soft-sediment coasts are highly dynamic in time and space, and constitute a substantial part of world's coastline. The morphology and bathymetry of the coast change by sediment transport under the influence of changing sea level and hydro-dynamics (Figure 4.6). As coasts are highly developed and densely populated due to the amenity and aesthetics that they provide, erosion of these coasts over the last few decades is already resulting in coastal squeeze (Pontee, 2013). Inevitably, climate change impacts on sandy coasts will only exacerbate this situation (Nicholls et al., 2007; Ranasinghe, 2016). Thus, reliable assessments of the occurrence of rates of shoreline change are basic necessities for erosion hazard and risk assessment, coastal engineering, nourishment and building with nature projects, and mitigation of climate change impacts along high value coastlines around the world (Luijendijk et al., 2018).

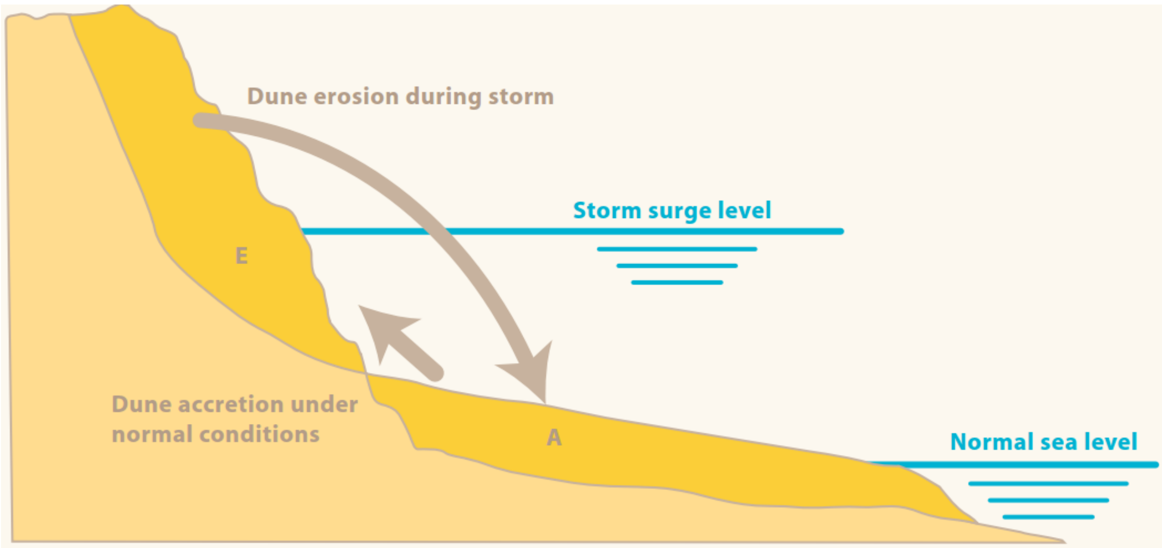

Figure 4.6 Graph illustrating the cross-shore impact of storm surge on dune-beach interactions.

Coastal erosion is a dynamic process, which is often event-driven (a storm) and its consequences may be at least partially reversed during calmer periods. Such events are superimposed on the long term coastal evolution. Coastal behaviour also has a spatial dimension: the longshore currents may permanently remove sediment from the shore, but they also may bring new sediments from elsewhere (Marchant (ed), 2010)

European projects such as Eurosion and Conscience proposed guidelines for monitoring of erosive coasts (Marchant (ed.), 2010; Sutherland, 2010). Different techniques have been developed to measure and model water depth and shoreline changes and provide an accurate baseline for morpho-sedimentary analyses (Table 4.1). At their best, coastal state indicators integrate site-specific knowledge and study results with repeated measured data to provide coastal managers with information that they can act on to manage their beaches in an adaptive manner. The beach monitoring programmes at these locations reflect the needs of the coastal managers through an appropriate choice of coastal state indicator and threshold values. Accuracies are different for different techniques, coverage as well. This is elaborated in the following sections

4.3.1 Coastline

In situ Coastline data is available in Open street map OpenStreetMap (OSM) at mean HW https://wiki.openstreetmap.org/wiki/Coastline), EMODnet Bathymetry http://www.emodnet.eu/bathymetry, and from topographic maps (which are based on aerial photographs and surveying) in the Netherlands by Kadaster Geo-informatie, in the UK Admiralty charts.

Monitoring type	Explanation	Examples
Small scale		
Linear arrays of point sensors	Measurement of the depth of scour under all conditions	Tell Tail scour monitoring system
Underwater acoustic measurements of the seabed	An acoustic backscatter device can be used to detect the level of the seabed and give information about sediment in suspension in situations where the seabed and instrument are fully submerged.	Autonomous Sand Ripple Profiler (ASRP)
Measurements of emerged toe levels	There are a number of techniques that can be used to measure emerged coastal defence structure toe levels at a point every low tide.	Argus video system Counting the number of steps above the beach level at access points
Measurements of mixing depth	The seabed mixing depth is the maximum depth below the seabed where sediment motion occurs	Stack of numbered aluminium disks of known height
Medium scale		
Cross-shore profile surveys and topographic surveys	Beach profiles and topographic surveys are typically collected using a large range of methods	Theodolite Kinematic GPS (e.g. mounted on a quad bike) Laser scanning systems Repeated digital photography (Argus) X-band radar
Large-scale		
Mapping of tidelines or shorelines	The position of the shoreline or tidelines (i.e. location of some representation of high water level and low water level) is commonly marked on maps. Different editions of the same map series, sometimes stretching back more than 100 years, can be used to determine long term changes to the position of the shoreline.	Orthorectified aerial or satellite photos Topographic LIDAR Bathymetric LIDAR Synthetic Aperture Radar (SAR) Bathymetric surveys from ships

Table 4.1 Coastal monitoring methods (Marchant (ed.), 2010)

Google Earth Engine has been used to derive global waterline from a large collection of optical satellite data (Donchyts et al, 2016) with an extension of derived eroding or accreting trends at sandy coasts (Luijendijk et al., 2018). Dutch waterline and trend had been derived by Hagenaars et al. (2017). Intertidal bathymetry and morphology, and coastline determination all benefit from waterline techniques (Wang, 1997; Niedermeier et al., 2000; Foody, 2005; Gens, 2010) to interpolate height (z) from reference gauge or model data. Horizontal accuracy varies from metres to 1-2 pixel size (which can be 25 m).

In the Netherlands, national yearly coastal profile measurements (JARKUS) were formerly collected by surveying, now by airborne LiDAR (laser altimetry) during low water combined with offshore single-beam echo sounding at high water. LiDAR is also at the base of the AHN Measurements and used for the extrapolation of (eroding or accreting) trends. In research projects terrestrial laser scanners (in the Netherlands e.g. Zandmotor, Kustgenese), and ARGUS video monitoring system (currently at Zandmotor) are used. Techniques have been developed to measure and model water depth and shoreline changes and provide an accurate baseline for morpho-sedimentary analyses.

4.3.2 Morphology/topography

Worldwide (coastal) topography has been available since the shuttle radar topography mission (SRTM). Airborne LIDAR (Light Detection and Ranging) has cm to dm accuracy, dGPS and GPS Real-Time Kinematic (RTK) measurements have cm-accuracy.

4.3.3 Bathymetry

Bathymetry is the information that describes the topography of the seabed, as depth from the sea surface to the seafloor. It is an essential component in understanding the dynamics of the marine environment. Safe ocean navigation relies on accurate bathymetry data, which are also essential for planning marine installations and infrastructure such as wind turbines, coastal defences, oil platforms and pipelines.

Underwater multi- and single-beam surveying is such as the Vaklodingen dataset distributed by Rijkswaterstaat consists is processed into gridded tiles of 20 m by 20 m resolution. The frequency of measurements strongly depends on the area of study. For the Wadden Sea, temporal sampling frequency is three years. The vertical accuracy of those measurements can be estimated at 50 cm (2 times the standard deviation) (Wiegmann et al., 2005).

The main global data set of in situ bathymetry is the General Bathymetric Chart of the Oceans (GEBCO) https://www.gebco.net/data_and_products/gridded_bathymetry_data/ GEBCO operates under the auspices of the International Hydrographic Organization (IHO) and the Intergovernmental Oceanographic Commission (IOC) of UNESCO. The gridded data are produced by additional processes i.e. interpolation and satellite gravimetry. Seabed 2030, a collaborative project between the Nippon Foundation and GEBCO aims to bring together all available bathymetric data to produce the definitive map of the world ocean floor by 2030 and make it available to all. EMODnet Bathymetry http://portal.emodnet-bathymetry.eu provides data collected and managed by an increasing number of organisations from government and research for European Seas.

Nationally, in situ bathymetry is measured by the hydrographic offices using multi-beam and single-beam echo sounding (which we consider to be in situ techniques in this report). Finally, some of these datasets are available from RWS Geoservices or through scientific databases (e.g. van Dijk et al., 2011; Damen et al., 2018).

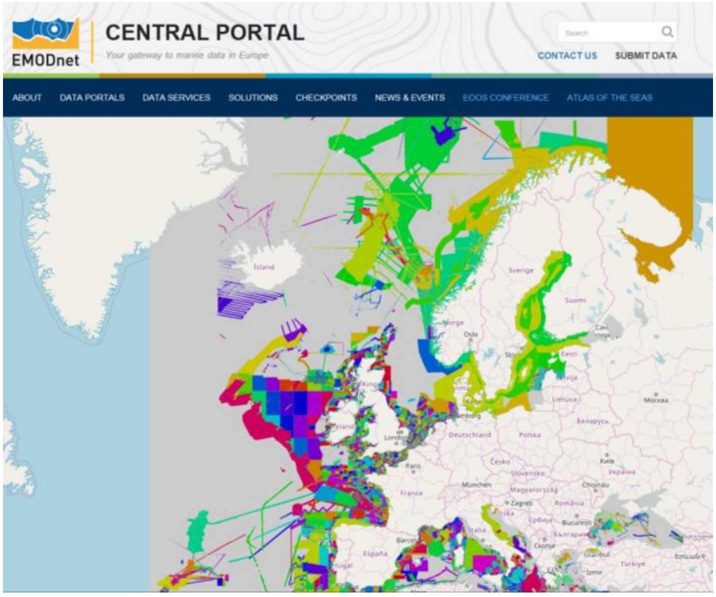

Figure 4.7 Source referenced in-situ bathymetric data as available through the EMODNet-portal. Colours refer to different sources (source: EMODNet).

Overall, different remote sensing techniques are available to provide bathymetry. Repeated bathymetric mapping over large areas is still not well developed owing to the different limitations of the retrievals and computing power.

From sea to land the main techniques comprise:
- Altimetry sounded bathymetry, Deep water bathymetry, 1km resolution,
- Synthetic Aperture Radar(SAR) bathymetry, coastal bathymetry, 100m resolution,
- Optical satellite derived bathymetry, shallow water bathymetry, 1.5m - 15m resolution

SAR and multi-spectral-derived bathymetric maps are the most common used for coastal water at this moment. SAR-derived methods make use of the spectrum of wavelength and wavedirection of the surface waves to derive depth to bottom. Independence of weather conditions and water quality make the approach versatile but this comes at a cost for accuracy and resolution. Multispectral-derived methods make use of differences in water leaving radiance for various spectral bands. In clear water, depth penetration can be as high as 20 m and with current multi-spectral imagery, resolutions as high as 1,5m can be realized. Accuracy is in the order of 20 cm, making these techniques suitable for monitoring trends and spatial phenomena. LIDAR is an alternative approach but currently only available on airborne platforms. LIDAR based bathymetry makes use of two pulses, one in infrared and one in green, and measures the time difference upon reflection as a measure of water depth. The ATLAS-instrument on ICESat-2 might be an alternative to airborne acquistions but current experience is restricted to an airborne experiment using a similar photon-counter as ATLAS. It showed to detect bathymetry up to 8 m deep in the oligotrophic waters of Keweenaw Bay, Lake Superior with a 0.4 m accuracy (Forfinski-Sarkozi and Parrish, 2016). Both LIDAR and multispectrally-derived bathymetry depend on meteorological conditions which restrict its use. However, large databases of multispectral imagery make it feasible to derive bathymetric maps based on a pixel-by-pixel time series, circumventing limitations posed by cloudiness.

4.3.4 Conclusions current status

Optical data are impacted by clouds. This can be overcome by querying huge data collections (as in Google Earth Engine). Note that optical data have a sampling bias for fair weather. All polar orbiting observations are biased and observations of important coastal and ocean processes are now missed. The sun-synchronous acquisition biases the observations, because the sun doesn't only act as a light source but also as a component in the Sun-Earth-Moon gravitational system which forces the tidal components (Eleveld et al., 2014). Consequently, sun-synchronous satellites always sample a certain coupling between tidal constituents. Consecutive observations of one 24-hr.cycle – which is known to affect many physical and biogeochemical processes at the coast and in the ocean – are also inaccessible from these sun-synchronous sensors.

5 User demands and benefits

In this chapter we will discuss the current coverage by earth observation of user demands regarding information on inland and coastal water variables. Following this, the societal, economic and scientific relevance of improved earth observations is discussed. An overview is given in Table 5.1.

5.1 Current coverage of information needs by Earth Observation

Based on the overviews of chapter 3 and 4 we can assess the current level at which information needs for inland and coastal water management are covered by Earth Observation. We do so first by comparing state-of-the-art in-situ-measurement requirements regarding spatial density and temporal frequency with current spatial and temporal resolutions of earth observation products for the various variables. Though it is a comparison of in-situ point sampling densities with spatial resolution it is a first indication of how close current products come to information needs, given the fact that there is currently no standard to compare to. In figures 5.1 and 5.2 of the spatio-temporal scales of in situ monitoring and earth observation capabilities is given against the background of spatio-temporal scales of various hydrological variables and floods and droughts. The figures show a classification of hydrological processes according to typical length and time scales based on Blöschl and Sivapalan (1995) and van Loon (2015). Shaded regions show characteristic time-length combinations of hydrological activity (variability). The ellipses show the most commonly required spatial and temporal frequency for monitoring the respective variables. The dashed quadrants summarize spatio-temporal capabilities of classes of earth observation sensor: spectro- and MW-radiometers, SAR, gravimetric and current precipitation constellation. The lower left-corner of the quadrant coincides with the spatial and temporal resolution of the instrument class. Figure 5.3 shows this for coastal and marine processes.

For none of the variables, earth observation currently completely fulfils the information needs regarding spatial and temporal resolution. For mapping water extent, however, earth observation can be considered to fulfil information demands and satellite based water body maps are increasingly used (e.g. in the framework of monitoring SDG-goals related to water availability and for flood mapping).

The largest gaps are for groundwater, snow cover/snow water equivalence (SWE) and elevation. Currently, global groundwater measurements are only possible with GRACE-FO. A monthly revisit time is considered to be low with respect to water management user needs and ideally would be weekly to bi-weekly. Spatial resolution of 300 km only suffices observations for the largest basins and wetlands at continental scale. Improvements to a spatial resolution of 10 – 50 km are needed to comply with water management user needs. InSAR products can fill the gap but only for confined aquifers and when auxiliary data on compressibility is available. Regarding soil subsidence InSAR actually fulfils many user demands, especially in coastal urban areas and is developing as a necessary tool for flood hazard assessments.

Satellite derived DEM's do not yet meet end user requirements for water management, especially for the derivation of hydrological model river networks and for flood modelling. Tandem-X DEM can be considered as the most recent and has a spatial resolution of 12 m at the equator and 2 m relative accuracy for areas sloping less than 20º. User needs regarding elevation are a dm-height accuracy at a m-scale resolution and are currently not met with the most recent satellite-derived DEM's. Another approach might develop by applying ICESat-2 LIDAR-data (ATLAS) to construct a global datum reference which can be used in tiling local DEMs in a global DEM and thus realizing a high accuracy DEM.

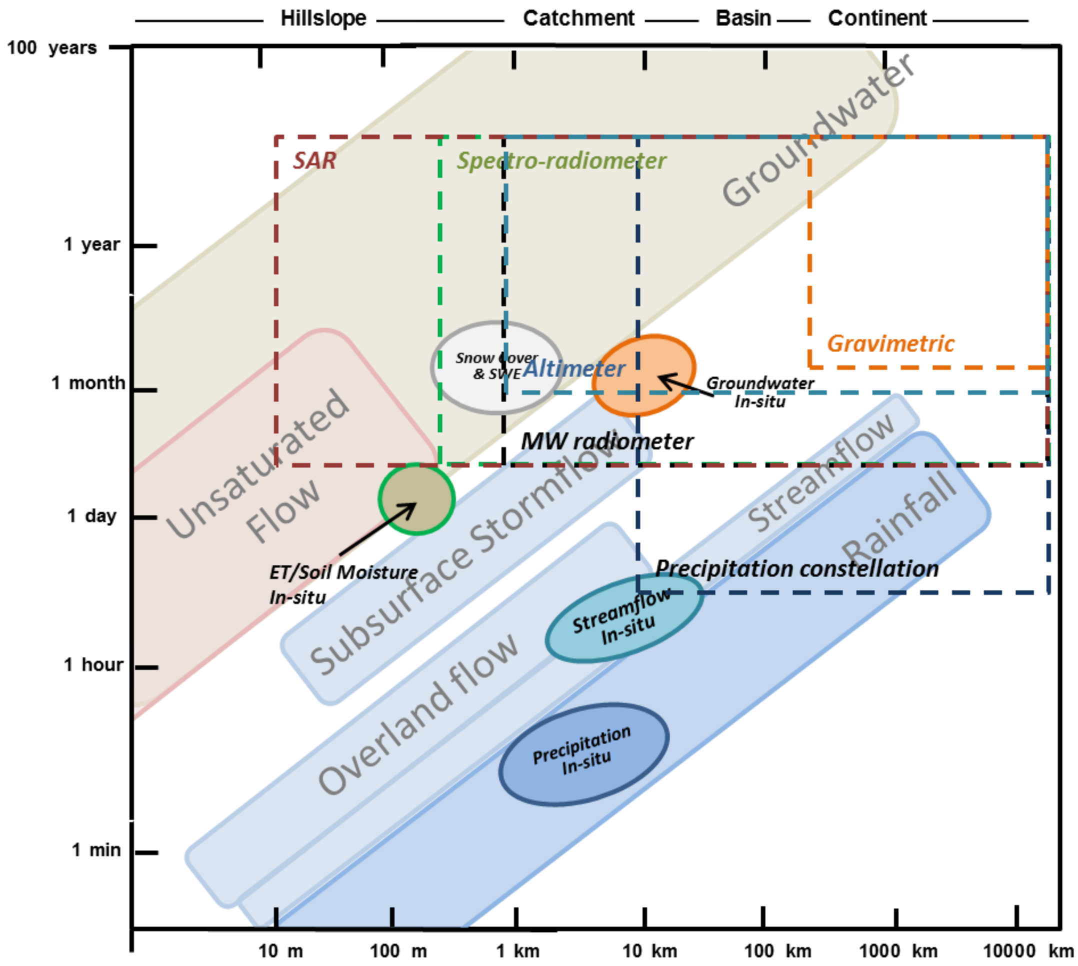

Figure 5.1 Time-Space diagram of hydrological variables, in situ monitoring and earth observation capabilities. Partly based on Blöschl and Sivapalan (1995) and van Loon (2015)

Snow cover-products are currently operational for water management purposes when only considering snow cover mapping. However, for estimations of Snow Water Equivalent currently no adequate products are available, whereas this is extremely relevant for the improvement of forecast skill for dry season water shortage, reservoir re-filling and upcoming floods. The biggest issue here is related to the measurement approach in relation to penetration depth. Passive microwave instruments are capable of estimating SWE of relatively thin, cold snow packs over large, flat areas but fail in heterogeneous, hilly and mountainous areas and for snow packs thicker than 0.5 m. Measuring variations in snow depth using ICESAT-2 might give improved results.

Much is expected from the SWOT-mission regarding water level measurements. Sampling distance will substantially improve with respect to current altimeters, such as Poseidon-3, thanks to Ka-band interferometer (KaRIN). Still, the monthly revisit time is too low to be applicable for many water management purposes, such as fluvial and coastal flood forecasting and operational water schemes on a daily to weekly basis. Secondly, the design of SWOT is such that it will pick up signals for river widths of more than 100 meter which limits its use for modelling streamflow for most upstream source areas and medium-sized river systems, such as in the Netherlands.

For satellite precipitation products there is a gap between spatial and temporal resolution with the requirements for water management. This is especially so for applications in urban areas and mountainous areas and for convective phenomena that require both a higher spatial and

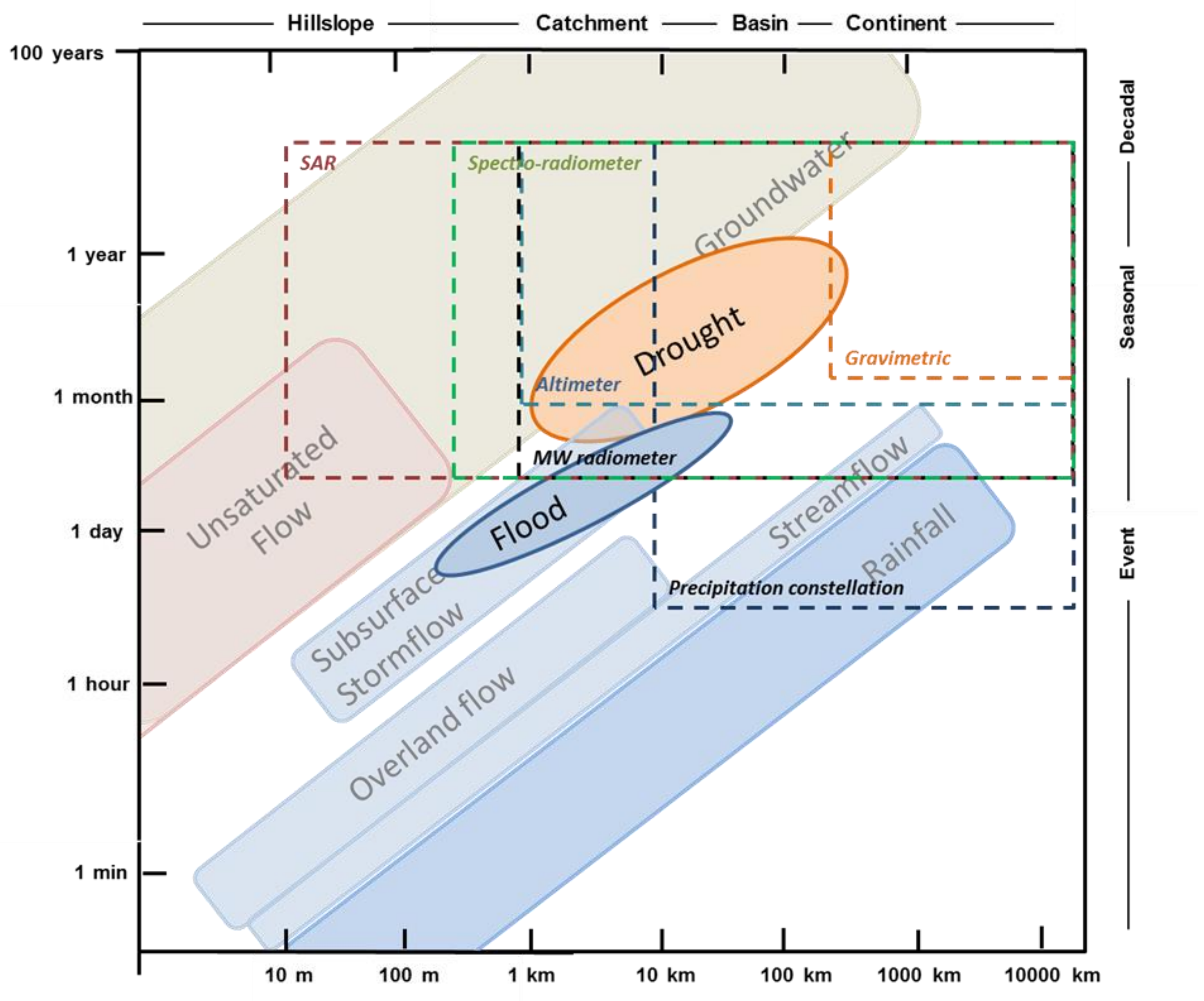

Figure 5.2 See Figure 5.1 – including floods and droughts. Partly based on Blöschl and Sivapalan (1995) and van Loon (2015)

temporal resolution. Products seem to best perform for average rainfall events but have difficulties in measuring extremes and in measuring snow fall amounts.

Current satellite derived products for soil moisture and evapotranspiration do come a long way in meeting user demands for water management. The products give information on a scale which was inconceivable up to recently. Soil moisture products are used as input for hydrological models, flood forecasting and drought warning systems. They are available for farmers to optimise their yield and irrigation requirements and for traders and crop insurers to estimate yields and losses. Improvements are to be expected in spatial resolution of soil moisture products with newly developed retrieval algorithms. However, these products rely on government-funded missions for which no follow-up has been planned. Secondly, using L-band and C-band frequencies, these products give an estimation of soil moisture in the upper soil skin and methods that combine retrievals with models to estimate soil moisture profile are still developing.

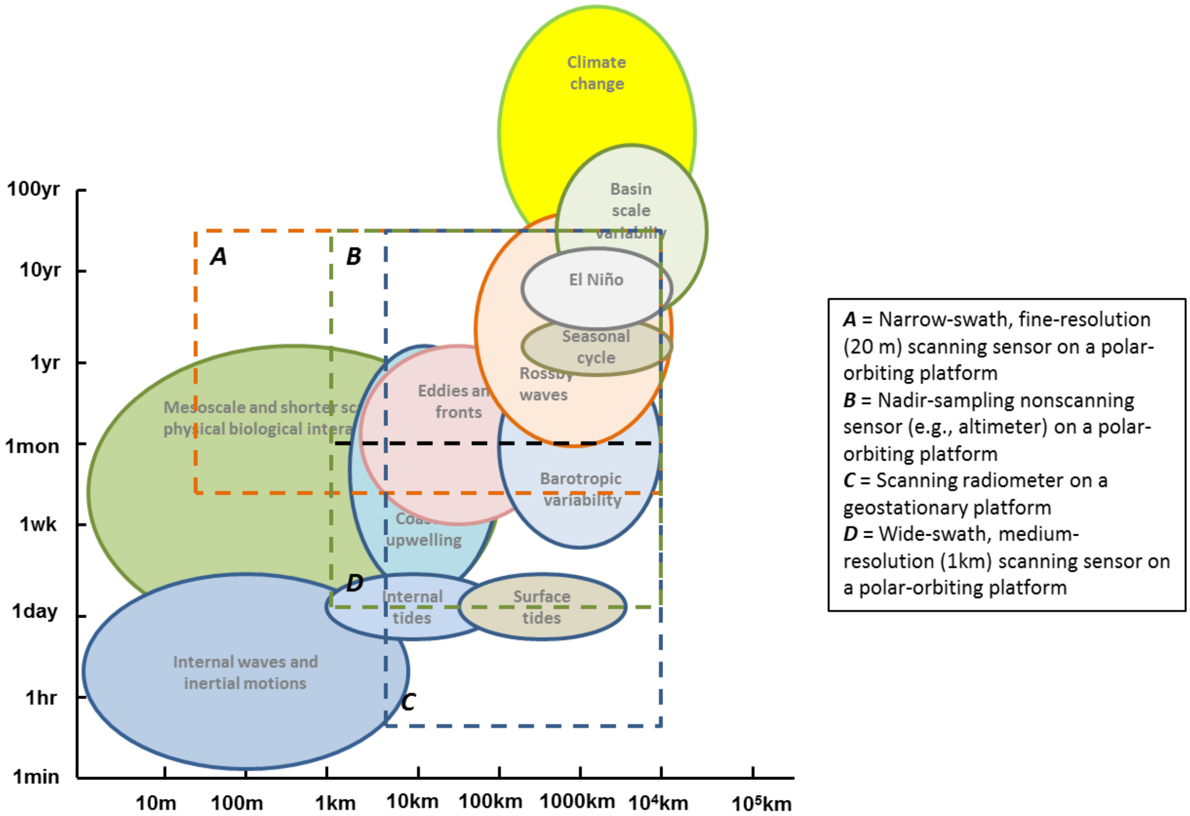

Figure 5.3 Time-Space-diagram of marine and coastal processes and current earth observation capabilities. Partly based on Robinson (2010) and Chelton et al. (2001).

There exist many satellite derived evapotranspiration products taking various approaches towards solving complex energy balance equations. As with soil moisture, the products give information on a scale which was inconceivable up to recently. As an example, Dutch water boards are using satellite-derived ET-products for optimising their water management. Satellite-derived ET-products are currently used for crop and irrigation management. State-of-the-art is that currently various sensors are used and mostly complemented with empirical and/or ground-based measurements which give ET-estimations at a 100 m to 1 km spatial resolution and multiday to biweekly revisit time. Higher revisit times come with lower spatial resolution. The main obstacle in deriving daily, 100 m resolution satellite-only products is the fact that currently high-resolution NIR/TIR-sensors lack as well as high resolution canopy-measurements. The newly proposed TRISHNA-mission has requirements which at least partly cover this gap and will carry an instrument with 4 thermal channels, covering the globe with a 3 day-revisit time and <100 m spatial resolution.

For coastal water management, sea level and wave height as well as bathymetry show the largest gap in user demands and current satellite capabilities. Current and near future altimeter constellations like Sentinel-3 and SWOT, will come a long way in resolving the issues hindering application of altimetry in coastal environments. Further developments regard the wet tropospheric correction and retracking over coastal areas. However, there still remains a significant gap in revisit time when considering the needs for storm surge monitoring and near coastal wave propagation. Ideally, hourly to daily instead of a monthly revisit time as for Saral/Altika and Sentinel-3, would suffice.

A great deal of progress has been made in developing satellite derived bathymetry maps, though accuracy still remains an issue. For EU H2020 project BASE-platform, a vertical accuracy of 0.5 m and 10% depth was estimated. The technique can be used to a max of 1 – 1.2 times Secchi depth (the depth at which a white disk lowered in the water can be seen). Current coastal bathymetric maps derived from multispectral imagery from Landsat or Sentinel-2 have accuracies in the order of 1.5 m in turbid coastal waters where dm-accuracy is needed for instance for ocean current models and design of coastal defences.

Satellite derived sea surface salinity products cannot catch local variations at a scale smaller than 40 km. As for sea surface temperature and shoreline monitoring, current satellite derived products are already close to current user demands in terms of resolution and accuracy.

Concluding the summary above, a large number of satellite instruments is used to derive various water and coastal variables. However, an approach which combines the various retrievals in ways that maximizes their potential is largely missing and only recently subject of research. In Aires (2014) several methodologies have been developed to integrate different satellite derived hydrological datasets based on a water balance budget closure. These approaches provide new optimized datasets at the pixel scale (not only the basin scale). Since no model is applied the resulting datasets are interesting for model calibration and validation.

5.2 Societal, commercial and scientific relevance

Over the past decades, earth observation has contributed significantly to our understanding of the distribution and dynamics of inland water systems and coastal waters. The data and information fill serious observational gaps which continue to exist since many regions in the world miss a proper coverage of in-situ sampling networks. This is the case for both inland water management as for coastal water management. Many of the networks, especially in the tropics and subtropics as well as the northern snow covered regions, suffer from deteriorating maintenance and are actually becoming sparser if existent at all (UNESCO, 2015). On the other end of the spectrum there is a growing appetite for data and information in regions with advanced water management systems. This arises from two trends. Firstly, an autonomous technological trend supported by the ever growing opportunities of ICT and prospects for automating and fine tuning of operational processes in water management. For instance, inland water authorities in the Netherlands are investing continuously in operational systems to fine tune the local water levels and the distribution and allocation of water resources. Complex surface and groundwater models are at the core of this approach, fed with local data on surface water level and groundwater level and forced by meteorology and anthropogenic

	Precipitation	Evapotranspiration	Soil Moisture	Snow and Glaciers
Technical applicability of satellite derived products for inland and coastal water quantity management	Performance is reasonable for average rainfall amounts; spatial and temporal resolution not yet adequate for convective storms and over mountainous catchments and in urban areas. Coverage to max. 50°-60° latitude	Operational products available, opinions on the quality of the high resolution products are mixed.	Operational high resolution products available	Low applicability due to low accuracy
Technical Relevance for inland and coastal water quantity management	Very relevant variable; alternative in-situ measurements exist in many areas but improved satellite observations highly relevant for ungauged areas and snow fall.	Relevant variable for recharge estimations. In-situ measurements on operational scale mostly absent.	Relevant variable for recharge estimations, drought and flood forecasting. In-situ measurements on operational scale mostly absent.	Very relevant for many river basins (mid-latitude and higher; Himalaya) as it is an important factor for base flow estimation and flood forecasting
Required improvements for inland and coastal water quantity management	Possibly multi-instrument mission.	Improvements in TIR/NIR and surface roughness necessary. Planned mission TRISHNA may offer opportunities.	Currently no follow-on L-band radiometer mission planned, necessary to continue services. Extension to P-band would improve estimations of the soil moisture storage component.	Still in development. Possible opportunities for a combined LIDAR/InSAR-product which can go beyond currently feasible snow pack estimation of <0,5 m.
Societal Relevance	Very relevant for water management, flood mitigation, drought forecasts, ecosystem management.	Relevant for drought forecasts and ecosystem management.	Relevant for flood and drought forecasts.	Relevant for flood and drought forecasts, river management (low flows) and water demand.
Economic Relevance	Direct benefits for crop production and reservoir management. Large indirect benefits for various sectors since rainfall impacts operations.	Direct benefits for crop production and reservoir management.	Direct benefits for crop production.	Direct benefits for reservoir management. Indirect benefits for inland water transportation.
Scientific Relevance	Very relevant variable for climate change research - Essential Climate Variable. Very relevant variable for estimating the connection between water and energy balance	Very relevant variable for climate change research - Essential Climate Variable; very relevant variable for estimating the connection between water and energy balance	Very relevant variable for climate change research - Essential Climate Variable; very relevant variable for estimating the connection between water and energy balance	Very relevant variable for climate change research - Essential Climate Variable.
Co-benefits			Soil moisture observations can be used as validator of precipitation or virtual rain gauge	

Table 5.1 Overview of variables for inland and coastal water management: technical applicability of satellite derived products and relevance

Considered to be most relevant

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	Groundwater	Water Level & Stream Flow	Water Extent	Elevation
Technical applicability of satellite derived products for inland and coastal water quantity management	Low applicability for gravimetric measurements due to low spatial resolution, but demonstrable benefits for water resources modelling at continental scale. Medium applicability for InSAR derived groundwater abstraction due to complex indirect measurement and restriction to confined aquifers.	Low applicability for current altimeters and surface water mapping. Opportunities exist for future SWOT-mission carrying KaRIN-instrument.	Operational products available using full archived data. Very high-resolution multi-spectral imagery able to meet requirements of m-scale mapping.	Low applicability of current satellite derived DEM's due to low spatial resolution and accuracy.
Technical Relevance for inland and coastal water quantity management	Highly relevant in many areas because in-situ measurements are sparse in many countries. Important variable for drought forecasting and base flow estimation.	Highly relevant for water management and flood forecasting models for ungauged basins in many parts of the world.	Highly relevant for flood emergency response and relevant for water management.	Highly relevant for many aspects of planning, design and maintenance of water management and coastal management measures. Highly relevant for inland and coastal flood forecasting models.
Required improvements for inland and coastal water quantity management	Improved spatial resolution of current gravimetric missions (GRACE-FO) from 300 km to 10 - 50 km with a biweekly revisit-time is needed.	Ka-band altimeter on SWOT offers future opportunities for dense sampling. Improved temporal sampling from 27 days to daily is needed.	Current satellite derived products are already close to current user demands in terms of resolution and accuracy.	Spatial resolution at m-scale and accuracy at dm-scale based on a multi-annual refreshment rate.
Societal Relevance	Highly relevant for large parts of the world where overexploitation takes place. Groundwater abstraction is expected to increase significantly over large parts of the world. Very relevant for drought forecasting, stream flow forecasting and ecosystem management, possibly for risk on subsidence	Very relevant for (smart) water management and flood mitigation.	Very relevant for flood emergency response. Relevant for water management and ecosystem management.	Relevant for flood emergency response and for planning and design of water management and coastal infrastructure.
Economic Relevance	Large indirect benefits for optimization of water allocation and irrigation schemes.	Direct benefits for reservoir management, operational water management and navigation	Direct benefits possible for reservoir management.	Large indirect benefits for planning and design of water management and coastal infrastructure.
Scientific Relevance	Relevant for answering questions regarding human impact on water system and impact of climate change.	Relevant for answering questions regarding human impact on water system and impact of climate change.	Relevant for answering questions regarding human impact on water system and impact of climate change.	Essential for modelling hydrological processes. Historical trends in elevation are relevant for answering questions regarding geomorphological processes and geo-hazards and the impact of climate change.
Co-benefits	Co-benefits possible for measuring snow mass and changes in snow mass storage.	Co-benefits possible with coastal altimeter as is the case for SWOT.	Similar approaches as for shoreline monitoring.	Also very relevant for coastal applications.

Table 5.2(continued) Overview of variables for inland and coastal water management: technical applicability of satellite derived products and relevance

Considered to be most relevant

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	Sea level & Sea State	Sea Surface Salinity	Sea Surface Temperature	Shoreline	Bathymetry & Topography
Technical applicability of satellite derived products for inland and coastal water quantity management	Low applicability of current altimeters in coastal seas due to difficulties in retracking and wet tropospheric correction. Improvements possible with SARAL/AltiKa, Sentinel-3 and future SWOT-mission.	Low applicability in coastal seas due to low spatial resolution.	Current sea surface temperature products meet spatial and temporal resolution requirements for mapping in coastal seas.	Operational products available using full archived data. Very high-resolution multi-spectral imagery able to meet requirements of m-scale mapping.	Low to medium applicability with accuracies on m-scale. Applicable for regional assessments and trend analysis based on full archive processing.
Technical Relevance for inland and coastal water quantity management	Highly relevant for measuring sea level rise, sea state and storm surge forecasting. Long-term records highly relevant for coastal protection. Relevant for ecosystem management.	Secondary variable; less relevance for sea state and storm surge forecasting, coastal protection. High relevance for coastal water quality, ecosystem management and monitoring fresh/salt-interface at river mouths and in tidal areas.	Secondary variable; less relevance for sea state and storm surge forecasting, mitigating coastal erosion and flood defence planning. Related to oxygen content and relevant for coastal water quality and ecosystem management.	Highly relevant for assessing coastal erosion and for flood defence planning. Relevant for ecosystem management.	Highly relevant for storm surge models, sea current, assessing and mitigating coastal erosion.
Required improvements for inland and coastal water quantity management	Ka-band altimeter on SWOT offers future opportunities for dense sampling. Improved temporal sampling from 27 days to daily is needed.	Required improvements related to coastal water quality.	Current satellite derived products are already close to current user demands in terms of resolution and accuracy.	Current satellite derived products are already close to current user demands in terms of resolution and accuracy.	Spatial resolution at m-scale and vertical accuracy at dm-scale based on an annual refreshment rate. Possible opportunities for combined very-high resolution multi-spectral imagery and LIDAR.
Societal Relevance	Highly relevant for coastal protection and coastal planning. Relevant for ecosystem management.	Relevant for ecosystem management.	Relevant for ecosystem management.	Highly relevant for coastal protection and coastal planning. Relevant for ecosystem management.	Highly relevant for coastal protection and coastal planning. Relevant for ecosystem management.
Economic Relevance	Direct benefits for maintenance of nautical structures and wind parks.	No direct benefits.	No direct benefits.	Large indirect benefits for planning and design of water management and coastal infrastructure.	Direct benefits for nautical transport and fisheries, maintenance of nautical structures and wind parks.
Scientific Relevance	Long term sea level variation is a very relevant variable for climate change research - Essential Climate Variable.	Very relevant variable for climate change research - Essential Climate Variable.	Very relevant variable for climate change research - Essential Climate Variable.	Relevant for answering questions regarding coastal processes and hazards and the impact of climate change.	Essential for modelling coastal processes. Relevant for answering questions regarding coastal processes and hazards and the impact of climate change.
Co-benefits	Co-benefits possible with inland water altimeter as is the case for SWOT.	Co-benefits possible for soil moisture as is the case for SMOS, SMAP.		Similar approaches as for water extent monitoring.	Use of bathymetry in combination with surface water extents will support to estimation of reservoir storage.

Table 5.3(continued) Overview of variables for inland and coastal water management: technical applicability of satellite derived products and relevance

Considered to be most relevant

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interventions. This has prompted an increased effort in new data acquisition methods capable of delivering data at higher frequency and especially in a denser grid. The second trend is the increased awareness that climate change might have a huge impact on water security, functioning of ecosystems and riverine and coastal flood hazards. Advanced understanding and long term monitoring are necessary to understand the impacts and properly plan for adaptation measures. As an example, these two trends might come together in the operational water management of the river Rhine. The decrease in alpine glaciers and even complete disappearance will be partly accompanied by an increase in built reservoirs in order to restore water storing capacity which could potentially help to maintain the end of summer low flows at Lobith which now partly exist of glacier melt waters. Management of these reservoirs and spills will have a large effect downstream. Consequently, cross-border regulations and operations will be further developed, which increases the need for timely and detailed information on the water budgets in the Rhine catchment.

Even though the value of earth observation information in inland and coastal water management in planning, operations and decision making is generally acknowledged to be evidently high, the number of comprehensive assessments of it is limited. Examples include the savings of $ 1 billion over ten years by using Landsat imagery in combination with ground based data in ten states of the US to create water use maps that are accurate at the scale of individual fields (GEO, 2014). A further indication of the value of information for water and coastal management has been summarized in the review of options for the evolution of the Copernicus programme (PWC, 2017). The study focuses on the benefits for the EU thanks to Copernicus services in the EU. Since these services depend, at least partially, on satellite data, the study might give an indication on the scale of economic benefits related to the capability of earth observation for various themes. The benefits have generally been estimated based on existing Copernicus services and take a low estimate and high estimate into account, primarily depending on service uptake.

5.2.1 Inland water systems: water use and water related hazards

Globally, water demand has been steadily rising over the past decades and now equals about 4500 km^3 (Figure 5.1). Though this figure equals only about 5% of precipitation over land, global withdrawals are currently near maximum sustainable levels nowadays (Gleick and Palanappian, 2010). The level of global water withdrawal becomes more relevant when taking into account large challenges at regional scales and the projected increase of 20% - 30% in water demand to between 5500 and 6000 km^3/year by 2050. For instance, changes in surface water resources are expected to be small on a subcontinental scale, ranging from -5 to + 5%, but are expected to be deteriorating strongly in a band of countries from Spain and Morocco to Pakistan (Burek et al., 2016). In many countries, there are areas where groundwater abstraction exceeds recharge, leading to the over exploitation and degradation of important aquifer systems. The largest abstractions are in India, USA, China, Iran and Pakistan. They account for 67% of total groundwater abstraction worldwide. Groundwater is being depleted at a rate faster than it is replenished. For instance, in 2010 25% of total ground water abstraction in India, China and Pakistan exceeded recharge. Projected trends indicate that this might worsen and indicate that in the 2050s, groundwater abstraction will increase by 39% compared to the current situation (Burek et al., 2016).

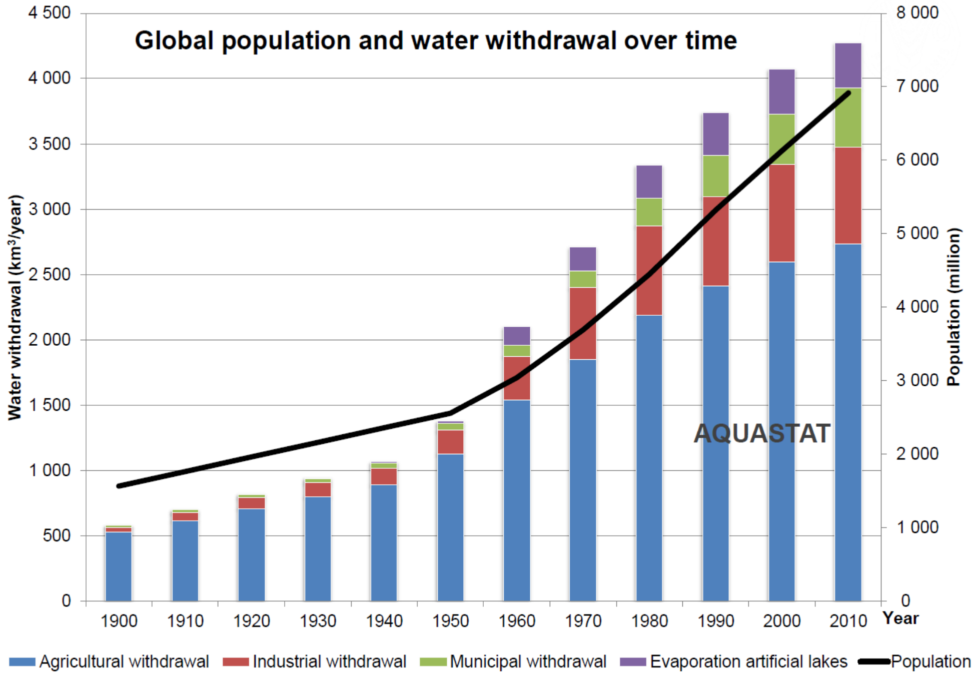

Figure 5.4 Global population and water withdrawal over time (source: Aquastat/FAO)

The trends in water availability are accompanied by projected changes in flood and drought risks. Economic losses due to water-related hazards have risen greatly over the past decades. Since 1992, floods, droughts and storms have affected 4.2 billion people (95% of all people affected by all disasters), causing US$1.3 trillion of damage – 63% of all disaster-related damage worldwide (UNESCAP/UNISDR, 2012). The population currently affected by land degradation/ desertification and drought is estimated at 1.8 billion people, making this the most significant category of 'natural disaster' based on mortality and socio-economic impact relative to GDP per capita (WWAP, 2018). Drought is also a chronic, long-term problem compared to the short-term impacts of flooding, and droughts are arguably the greatest single threat from climate change. Changes in future rainfall patterns will alter drought occurrence, and consequently, soil moisture availability for vegetation in many parts of the world. The predicted longer duration and severity of droughts can be alleviated by more water storage, which requires upscaling of infrastructure investments that can have significant trade-offs for society and the environment. Therefore, water storage in the environment ('green infrastructure') must be part of location-specific solutions. The impacts of droughts will be worsened by the increasing withdrawals in response to the increasing water demand (WWAP, 2018).

A prime objective of inland water management is to sustainably manage water as a finite resource taking into account the dynamics of the hydrological system and variable demands from societal and economic sectors. Of the main uses agriculture accounts for the largest share in global water withdrawals, about 65%, the vast majority of which is used for irrigation. Due to a lack of monitoring and reporting and due to the inherently variable nature of irrigation it is difficult to have reliable estimates in space and time (WWAP, 2018). Estimates on future increases in water consumption for agriculture vary. Burek et al. (2016) have projected increases in global crop irrigation water requirements for 2050 to be somewhere between

23% and 42% above the level in 2010 though figures are uncertain as a result of uncertainty in the impacts of expected improvements in irrigation water efficiency.

Total water use by industry and energy production accounts for roughly 20% of global withdrawals, where energy production has a share of 75% and industry of 25%. Based on their scenario's, Burek et al. (2016) expect the overall water demand from industry to increase across all the regions of the world, with the exception of Northern America and Western and Southern Europe. Industrial demand could increase with up to eight times (in relative terms) in regions such as Western, Middle, Eastern and Southern Africa, where industries currently account for a very small proportion of total water use. Industrial demand should also increase significantly (up to two and a half time) in Southern, Central and Eastern Asia (Burek et al., 2016).

Municipal withdrawal, including domestic water use, roughly accounts for 10% of global water withdrawals and is expected to increase significantly over the period up to 2050 in nearly all regions of the world, with the exception of Western Europe where it remains constant (WWAP, 2018). In relative terms, domestic demand will rise by more than threefold in all African and Asian subregions, and it will more than double in Central and South America (Burek et al., 2016).

Apart from the trends in water demand, which point towards increased water stresses in large areas of the world, there are also economic benefits to be expected when water is secured sustainably and efficiently allocated and distributed. OECD (2018) mentions that the benefits from strategic investments in water security could exceed hundreds of billions of dollars annually. On the other hand, assembled information provides an indication of the scale of global economic losses related to water insecurity (OECD, 2018): USD 260 billion per year from inadequate water supply and sanitation, USD 120 billion per year from urban property flood damages, and USD 94 billion per year of water insecurity to existing irrigators. Further, water-related losses in agriculture, health, income and property could result in a decline by as much as 6% of GDP by 2050 and lead to sustained negative growth in some regions of the world (World Bank, 2016).

Most impacts of climate change on freshwater systems and their management are due mainly to increases in temperature and sea level, altered patterns and magnitudes of precipitation and changes in the variability of these quantities (Jimenez Cisneros et al., 2014). The impact is projected to be felt in the extremes of water availability, resulting in decreases in renewable water resources on the one end and intensifying floods on the other end. For each degree of global warming, approximately 7% of the global population is projected to be exposed to a decrease of renewable water resources of at least 20%. Climate change is projected to reduce renewable surface water and groundwater resources significantly in most dry subtropical regions. This will intensify competition for water among agriculture, ecosystems, settlements, industry, and energy production, affecting regional water, energy, and food security. In contrast, water resources are projected to increase at high latitudes. Proportional changes are typically one to three times greater for runoff than for precipitation. By the end of the 21st century, the number of people exposed annually to the equivalent of a 20th-century 100-year river flood is projected to be three times larger for very high emissions than for very low emissions for the fixed population distribution at the level in the year 2006 (Jimenez Cisneros et al., 2014).

5.2.1.1 *Opportunities for Earth Observation*

Current trends in water use point towards an increased pressure on fresh water resources. Of these, groundwater is one of the most pressed as mentioned earlier. Groundwater resources, once depleted, take long before restored to original levels. Much of the world's food supply comes from irrigation in dry to moderate climates. Consequently, by far most of the water diverted, impounded, or pumped by humans is for irrigated agriculture (Wada et al., 2013; 2014). Accordingly, irrigated agriculture has created massive dislocations in water stores and disruptions in the hydrologic cycle, as documented by GRACE (Richey et al., 2015). PWC (2017) estimated that large benefits might come from improved global food security through improved drought forecasting and irrigation management. Benefits are related to the savings on EU-contribution to global food security thanks to better crop production insurance. Hence, take up of information relevant for crop forecasting will be particularly relevant for farmers and insurance companies, taking into account drought forecasts in their portfolio. Actually, satellite derived soil moisture and evapotranspiration are increasingly used for crop production and irrigation schemes and find their way already in economic products.

Groundwater and snow resources also serve as the base flow component for many rivers, which is relevant for inland water transport, irrigation and hydropower. Adequate information on groundwater and snow pack resources and the dynamics thereof can therefore be considered to become of prime importance nowadays as well as in the future. PWC (2017) finds that benefits in Europe from the Copernicus programme for water management might cover various aspects, of which the increase in hydropower production and saving of groundwater are considered to be the most promising. PWC (2017) could not find adequate figures to assess the benefits of Copernicus for optimization of inland waterway transport. However, benefits might be considerable if transport costs for low water situations are taken into account. For example, in Jonkeren and Rietveld (2009) it is estimated that in the period 1986–2004 there has been an annual average welfare loss of €28 million due to low water levels in the part of the river Rhine market considered. The estimated loss in 2003 was as high as €91 million due to the very dry summer in that year.

Possible reductions in economic loss and economic impact of fatalities and injuries caused by riverine flooding might be considered to be a key driver for future investments in earth observation. Large benefits are to be expected as PWC (2017) has estimated for the Copernicus programme in the EU. The benefits stem both from improved preparedness, prevention and mitigation to be delivered through uptake of flood forecasting-services as well as from improved ground logistics and response through rapid mapping services, delineating flooded areas. Taking the aforementioned gaps in observational capabilities into account, these benefits can be greatly increased through improved Digital Elevation Models and water level measurements, as well as improved precipitation measurements at scales commensurate with the observed phenomena.

5.2.2 Coastal zone

Currently, a little bit more than 10% of the global population lives in the Low Elevation Coastal Zone (LECZ), at maximum 10m above sea level. The importance of coastal zones can be attributed to two key elements: (1) ecosystems goods and services concentrated in coastal marine and estuarine systems and (2) population settlement and the transition of shipped goods to land and vice-versa. In terms of ecosystems goods and services, the coastal zone has a high value. Based on a summary of ecosystems services worldwide, Constanza (1997) estimated its value in natural disturbance regulation (storm protection, flood protection) comprises $270 billion per annum. The global oceans-based economy is estimated at $3 trillion a year, which is around 5 per cent of global GDP (UN, 2017). The production of wind energy at sea is a rapidly increasing activity in coastal water. At the end of 2017, nearly 84% of all offshore installations were located in the waters off the coast of eleven European countries. The remaining 16% is located largely in China, followed by Vietnam, Japan, South Korea, the United States and Taiwan.

On the other hand, coastal systems are particularly sensitive to three key drivers related to climate change: sea level, ocean temperature, and ocean acidity (Wong et al., 2014). Coastal systems and low-lying areas will increasingly experience adverse impacts such as submergence, coastal flooding, and coastal erosion due to relative sea level rise (RSLR). Almost two-thirds of the world's cities with populations of over five million are located in areas at risk of sea level rise. The potential costs associated with damage to harbours and ports due to sea level rise could be as high as $US111.6 billion by 2050 and $US367.2 billion by the end of the century. In the absence of adaptation, beaches, sand dunes, and cliffs currently eroding will continue to do so under increasing sea level. Large spatial variations in the projected sea level rise together with local factors means RSLR at the local scale can vary considerably from projected global mean sea level rise (GMSLR). Changes in storms and associated storm surges may further contribute to changes in sea level extremes but the small number of regional storm surge studies, and uncertainty in changes in tropical and mid-latitude cyclones at the regional scale, means that there is low confidence in projections of storm surge change. Both RSLR and impacts are also influenced by a variety of local processes unrelated to climate (e.g., subsidence, glacial isostatic adjustment, sediment transport, coastal development) (Wong et al., 2014).

5.2.2.1 Opportunities for Earth Observation

Of the main challenges in coastal engineering knowledge of relative sea level rise and the workings of nature-based solutions under varying circumstances are the most important. Adequate measurements of sea level, sea state and bathymetry are evidently of value in coastal areas and necessary to protect this area. As far as coastal themes are considered, currently most benefits from the Copernicus programme are estimated for coastal area monitoring, especially regarding savings on expenditures for coastline protection (PWC, 2017). However, offshore wind energy is considered to be a field of application where considerable benefits are to be expected in the coming years, thanks to both improved sea state information and wind vector data. Benefits in maritime navigation are considered to be relatively small.

5.2.3 Science

Satellite observations have revolutionized advances in hydrologic science, involving the extension of knowledge about processes and state variables from the scale of field experiments to regions, continents, and the entire Earth. Assessment of such variables as patterns of rainfall and its effect on hydrological processes, surface soil moisture, surface energy balance and its relation to climate, temporal variations in groundwater storage have transformed our understanding of water’s role in the planet’s behaviour and have enabled comprehensive linking of hydrologic processes that vary across a wide range of temporal and spatial scales (Lettenmaier et al., 2015). The same counts for coastal processes where satellites and autonomous sensor systems have revealed a dynamic global ocean system on unprecedented temporal and spatial scales observing variations in regional sea level, coastal waves and surges, coastal erosion and aggradation processes and the variability in salinity and temperature (Cazenave et al., 2017). It is safe to assume that Earth observation therefore will play a substantial role in data acquisition for future research objectives.

In the Netherlands, the National Science Agenda includes the ‘Blue Route’ which relates most strongly to needs regarding observations and measurements of water and coastal systems as it focuses on understanding, utilising and protecting oceans, seas, deltas and rivers, as well as saltwater, fresh water and groundwater, in order to improve sustainability, wellbeing and prosperity worldwide. The following lines of approach, which take the issues of living in a highly urbanised coastal lowland as a point of departure, have been defined:

1. Living in the Delta – *How do we develop a Sustainable Urban Delta in which different populations can live, work and eat together safely, healthily and sustainably?*
2. Water as a source – *How can we make sustainable and economically responsible use of the water and the energy, natural resources and food located on, in and under that water?*
3. Water as a blue pathway – *How can we redesign vessels with carbon-neutral and autonomous navigation systems and futureproof our ports and waterways to make shipping sustainable and safe?*
4. Living on water – *What opportunities do floating homes and businesses, aquaculture, and hydropower offer at a time when the sea level is rising, the climate is changing and we are running out of space?*

These questions need an understanding of the downstream consequences of urban growth or changes in the severity, duration, and occurrence of floods and droughts as a result of climate change, and to apply this understanding to making predictions for the future (National research Council, 2012). Next to that, fundamental gaps exist in the understanding of the climatology and the average spatial and temporal characteristics of key hydrologic fluxes, namely, precipitation, evapotranspiration and groundwater fluxes (National research Council, 2012; National Academies of Sciences, Engineering, and Medicine 2018). This will need an understanding of the processes that link components of the water cycle and the energy cycle and requires direct information on the patterns and dynamics of precipitation, evapotranspiration and groundwater fluxes (National Research Council, 2012; National Academies of Sciences, Engineering, and Medicine 2018) which is proposed in the Decadal Strategy for Earth Observation from Space as Highly Important topics. Understanding the mechanisms and rates of change behind global and regional variability on all scales, and projecting future changes in sea level, is an interdisciplinary challenge to oceanographers and of primary relevance to the above agenda (National Research Council, 2015). Significant regional patterns of sea level change result from uneven rates of ocean warming, the net transport of seawater in ocean currents, regional tectonics, isostatic adjustments, shoreline subsidence, and regional gravitational anomalies.

6 Conclusions

6.1 General conclusions

Inland and coastal water quantity management depends on proper information on the state of the hydrological cycle and of the coastal system at various spatial and temporal scales and is often used in models to assess the effects of changes or forcings in the hydrological or coastal system. In general, most of the variables treated in this study are equally important in this respect.

Typically, observations by remote sensing of variables relevant for inland and coastal water management are mostly indirect and need various different sensors in combination with in-situ measurements and models. Validation using in-situ data is important in building confidence with end-users.

Over the past 20 – 30 years, earth observation has proven to be increasingly valuable for inland and coastal water management and has already shown to offer indispensable information for all essential variables. Among these applications, accuracy, spatial and temporal resolution differ and as such, not all applications do meet demands posed by water management and end-users.

In terms of societal, economic and scientific applications future demand for adequate information will only be growing due to increased pressures on water resources, increased development of the coastal zone and increased vulnerability to floods and droughts as a result of climate change.

6.2 Conclusions regarding technical user needs

Quantitative estimates regarding evapotranspiration, root zone soil moisture, water extent and sea surface temperature already can be retrieved from earth observation with spatial and temporal resolutions and accuracies which come a long way in meeting requirements for water management.

A significant gap between the capabilities offered by earth observation and the information needed for water and coastal management still exists for adequate information on change in groundwater storage, Snow Water Equivalent (SWE), (sea) water level, topography and coastal bathymetry.

For satellite *precipitation* products there is a gap between spatial and temporal resolution with the requirements for water management. This is especially so for applications in urban areas and mountainous areas and for convective phenomena that require moving from 10 km spatial resolution to at least 1 km and from hourly to sub-hourly sampling.

Currently, satellite instruments relevant for *evapotranspiration* products are further developed and offer opportunities for developing 100 m resolution products. The newly proposed TRISHNA-mission has requirements which contribute to this objective.

Various operational satellite *soil moisture* products currently exist, mostly on a scale of 10 km but new developments in retrieval models offer the opportunity of products with a spatial resolution of 100 m. In terms of operational continuity of the current services, it is observed that current missions reach the end of their design life which imperils continuation of services. There is also room for improving the accuracy of estimates of the soil moisture storage component, since L- and C-band sensors, which are currently used for soil moisture retrieval, only give information about the upper centimetres of the soil. Measuring a larger part of the unsaturated soil column will require measurements at lower frequencies (P-band or lower).

For *groundwater* storage, gravimetric measurements as currently performed by Grace-FO have shown be of great value for continental-scale observations. Improvements in revisit time from monthly to at least biweekly and in spatial resolution from 300 km to at least 50 km are needed to comply with water management user needs.

For estimations of *Snow Water Equivalent* currently no adequate products are available due to difficulties in measurement approach in relation to penetration depth. Additional research is still ongoing taking into account possible combinations of sensors (LiDAR/InSAR/Radiometer-suite).

The planned launch of the Surface Water & Ocean Topography (SWOT) mission carrying a Ka-band altimeter will contribute to improved estimates of *water and sea level* and streamflow. In meeting requirements for water and coastal management there is still a gap to be closed by improving the temporal resolution from 3-weekly to daily and sampling rivers with widths <100 meter.

Current satellite derived global *elevation* models, mostly based on X-band SAR, still do not fully meet the requirements for operational inland and coastal water management, especially in relation to flood forecasting and preparedness. In order to meet expected requirements for water management, spatial resolution and height accuracy have to increase by approximately a factor of 10 (m-scale resolution, dm-scale vertical accuracy).

A great deal of progress has been made in developing satellite derived *bathymetry* maps, though accuracy still remains an issue. For EU H2020 project BASE-platform, a vertical accuracy of 0.5 m and 10% depth was estimated. The technique can be used to a max of 1 – 1.2 times Secchi depth (the depth at which a white disk lowered in the water can be seen). Current coastal bathymetric maps derived from multispectral imagery from Landsat or Sentinel-2 have accuracies in the order of 1.5 m in turbid waters where dm-accuracy is needed for instance for ocean current models and design of coastal defences.

6.3 Conclusions regarding societal, economic and scientific value of earth observation for inland and coastal quantitative water management

The largest societal benefits of earth observation for inland and coastal water management is related to flood and drought protection and to a sustainable use of fresh water resources which become otherwise scarce, especially groundwater. These benefits are primarily derived for global applications where it is inherently difficult to single out one specific variable or a limited set of variables as being singularly important.

Flood protection is seen to be an area of inland and coastal water management where earth observation has potentially the largest socio-economic benefits. Improved observations regarding precipitation, (sea) water level, elevation and bathymetry will contribute most to improved flood mitigation and flood response.

Drought warning and food security is seen as a second area where earth observation has potentially large socio-economic benefit, especially by improving the skill of water resources and crop forecasting models. For those applications observations regarding changes in groundwater storage, soil moisture and evapotranspiration are of particular benefit.

Globally, water resources are becoming increasingly stressed due to global increase in population, increased economic affluence and climate change. Though the effects will vary locally, depleting groundwater resources and decreasing storages of fresh water in snow and glaciers are particularly relevant in this respect as well as observations regarding changes in groundwater storage and snow water equivalence.

Earth observation regarding inland and coastal water management has currently most commercial relevance for crop and energy production. Data on precipitation, evapotranspiration and soil moisture is already commercially exploited for crop forecasting and crop production. Reservoir management for energy production is another commercial application which benefits from earth observation data on snow mapping, estimations on snow water equivalence and water level. The increased development of wind at sea is a growing field of applications which needs long term records of water level and significant wave height.

As the ‘Blue Route’ of the current National Science Agenda, which relates most to issues regarding inland and coastal water management, involves aspects of living in a deltaic environment, sustainable use of water and opportunities of living on water as an answer to climate change, earth observations of all components of the coastal and hydrological system will play an important role for future research objectives. Most relevance might be expected for its opportunity to cover the whole globe and thereby contributing to an understanding of coastal lowland systems under varying conditions. In terms of understanding the mechanisms of climate change, particular interest is paid to observations of land –atmosphere interaction and the coupling of the energy and water balances, such as precipitation, evapotranspiration and soil moisture.

6.4 Recommendations

In drafting specifications for new instruments for inland and coastal water management, it is recommended to involve the hydrological and coastal modelling communities. Part of the benefit will be in applying state-of-the-art global models and their contribution in serving observation system simulation experiments.

As presented in this study, a large number of satellite instruments is used to derive various water and coastal variables. However, an approach which combines the various retrievals in ways that maximizes their potential is largely missing and only recently subject of research. It is recommended, with the current growth in satellite data, to consider development of a data-facility which supports in a user friendly way the feed of satellite data in models used for inland and coastal water management.

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8 Annexes

Annex A – Overview of existing and planned Earth Observation instruments relevant for inland and coastal quantitative water management

Based on:
- Literature used for this study
- CEOS-database
- WMO-OSCAR
- ITC Satellite and Sensor Database

	Instrument Type	Sensor	Mission	Organisation	Operational Timeline	Spatial resolution	Temporal resolution (days)	Frequency/wavelength	Spectral band
Precipitation	Multi-purpose imaging MW radiometer	GMI	GPM Constellation/GPM Core	NASA / JAXA	2014 - 2020	12 X 13 km	1 day	7 bands: 10.65 GHz - 183.31 GHz	X, Ku, Ka, Q, W
		SSM/I	DMSP-F8 - F16	NOAA, US-DoD	1987 - 2026	13–69 km (depends on frequency)	0.5 day	19.35 - 85,5 GHz	Ku, Ka, Q, W
		AMSU-A	Aqua, NOAA-15, 16, 17, 18, 19; Metop-A-, B, C	NASA, NOAA, EUMETSAT	1998 - 2024	48 km	0.5 days	15 channels: 23 - 90 GHz	Ka, V, W
	Cloud and precipitation radar	DPR	GPM Constellation/GPM Core	NASA / JAXA	2014 - 2020	5 km at nadir	daily	35.5, 13.6 GHz	Ka, Ku
	Imaging radar (SAR)	SAR-2000	COSMO-Skymed 1 - 4	ASI	2007 - 2018	1 - 10m	16 days	9.6 GHz	X
		X-band SAR	TerraSAR-X	DLR	2007 - 2020	1 - 6m	11 days	9.65 GHz	X
	Multi-purpose imaging Vis/IR radiometer	AVHRR/3	NOAA-15, 16, 17, 18, 19; Metop-A-, B, C	NOAA, EUMETSAT	1998 - 2024	1.1 km	0,5 days	6 channels: 0.58 - 12.5 µm	VIS, NIR, SWIR, MWIR, TIR, FIR
Evapotranspiration	Medium-resolution spectro-radiometer	MODIS	Terra and Aqua	NASA	1999 - 2020	250 m - 1 km	2 days	36 bands: 0.4 - 14.4 µm	VIS, NIR, SWIR, MWIR, TIR
		Trishna	Trishna	ISRO/CNES	2022 - 2027	50 m	3 days	0.44 - 0.86 µm, 1.3 and 2.1 µm, 8.6, 9.1, 10.3, 11.5 µm	VIS, NIR, SWIR, TIR
	Multi-purpose imaging Vis/IR radiometer	VIIRS	Suomi NPP, NPOESS, JPSS	Suomi National Polar-orbiting Partnership	2011 - present	375 and 750 m	1 day	0.412 - 12.01 µm	VIS, NIR, SWIR, MWIR, TIR
		IR-MSS	CBERS-1 -4	CAST, INPE	1999 - 2024	20 - 80m	26 days	0.45 - 2.35 µm and 10.4 - 12.5 µm	VIS, NIR, SWIR, TIR
		AVHRR/3	NOAA-15, 16, 17, 18, 19; Metop-A-, B, C	NOAA, EUMETSAT	1998 - 2024	1.1 km	0,5 days	6 channels: 0.58 - 12.5 µm	VIS, NIR, SWIR, MWIR, TIR, FIR
		GOES Imager	GOES 13, 14 , 15	NOAA	2006 - 2025	10 km	Earth disk scanning	VIS, IR: 3.9 µm - 12 µm	VIS, NIR, IR
		SEVIRI	Meteosat 2nd generation	EUMETSAT, ESA	2002 - 2033	1 and 3 km	Earth disk scanning	12 channels: 0.6 - 13.4 µm	VIS, NIR, SWIR, MWIR, TIR
		AHI	HIMAWARI-8, 9	JMA	2014 - 2030	0.5 - 2.0 km	Earth disk scanning	16 bands from 0.46 µm to 13.3 µm	VIS, NIR, SWIR, MWIR, TIR
	Narrow-band channel IR radiometer	TIRS, TIRS-2	Landsat-8, -9	USGS, NASA	2013 - 2025	100 m	16 days	TIR 10.5 µm and 12 µm	TIR
	High resolution optical imager	ETM+	Landsat-7	USGS, NASA	1999 - 2021	30 - 60 m	16 days	8 bands: 0.45 - 12.5 µm	VIS, NIR, SWIR, TIR
		OLI, OLI-2	Landsat-8, -9	USGS, NASA	2013 - 2025	30 m	16 days	9 bands: 0.43 - 2.3 µm	VIS, NIR, SWIR
		ASTER	Terra	NASA	1999 - 2020	15, 30, 90 m	16 days	0.52 - 11.65 µm	VIS, NIR, SWIR, TIR
Snow Cover & SWE	Absorption-band MW radiometer/spectrometer	AMSU-A	Aqua, NOAA-15, 16, 17, 18, 19; Metop-A-, B, C	NASA, NOAA, EUMETSAT	1998 - 2024	48 km	0.5 days	15 channels: 23 - 90 GHz	Ka, V, W
	Multi-purpose imaging MW radiometer	SSM/I	DMSP-F8 - F16	NOAA, US-DoD	1987 - 2026	13–69 km (depends on frequency)	0.5 days	19.35 - 85,5 GHz	Ku, Ka, Q, W
		SSM/IS	DMSP-F16 - F20	NOAA, US-DoD	2003 - 2026	25 x 17 km to 70 x 42 km	daily	Microwave: 19 - 183 GHz (24 frequencies)	Ku, Ka, Q, W
	Imaging radar (SAR)	PALSAR, PALSAR-2, -3	ALOS, ALOS-2, -4	JAXA	2006 - 2020>	1–10 m	14 days(PALSAR-2,3) - 46 (PALSAR)	1.27 GHz	L
		SAR-2000	COSMO-Skymed 1 - 4	ASI	2007 - 2018	1 - 10m	16 days	9.6 GHz	X
		X-band SAR	TerraSAR-X	DLR	2007 - 2020	1 - 6m	11 days	9.65 GHz	X
		SAR (Radarsat)	RADARSAT-1, -2, constellation	CSA	1995 - 2019>	1 - 10m	12 (constellation) - 24 days	5.405 GHz	C
		C-Band SAR	Sentinel-1A, -1B, -1C, -1D	ESA	2014 -	5 – 20 m	6 days at equator	5.405 GHz	C
	Medium-resolution spectro-radiometer	MODIS	Terra and Aqua	NASA	1999 - 2020	250 m - 1 km	2 days	36 bands: 0.4 - 14.4 µm	VIS, NIR, SWIR, MWIR, TIR
	Multi-purpose imaging Vis/IR radiometer	AVHRR/3	NOAA-15, 16, 17, 18, 19; Metop-A-, B, C	NOAA, EUMETSAT	1998 - 2024	1.1 km	0,5 days	6 channels: 0.58 - 12.5 µm	VIS, NIR, SWIR, MWIR, TIR, FIR
		VIIRS	Suomi NPP, NPOESS, JPSS	Suomi National Polar-orbiting Partnership	2011 - present	375 and 750 m	1 day	0.412 - 12.01 µm	VIS, NIR, SWIR, MWIR, TIR
		AWIFS	Resourcesat-1, -2, -2A	ISRO	2003 - 2021	55 m	5 days	VIS: 0.52 - 0.59 µm and 0.62 - 0.68 µm, NIR: 0.77 - 0.86 µm, SWIR: 1.55 - 1.7 µm	VIS, NIR, SWIR
		OLS	DMSP F-8 - F-20	NOAA, US-DoD	1987 - 2025	0.56 km, 5.4 km (stereo)	0.5 days	VIS - NIR: 0.4 - 1.1 µm, TIR: 10.0 - 13.4 µm, and 0.47 - 0.95 µ	VIS, NIR, TIR
	Narrow-band channel IR radiometer	TIRS, TIRS-2	Landsat-8, -9	USGS, NASA	2013 - 2025	100 m	16 days	TIR 10.5 µm and 12 µm	TIR
	High resolution optical imager	ASTER	Terra	NASA	1999 - 2020	15, 30, 90 m	16 days	0.52 - 11.65 µm	VIS, NIR, SWIR, TIR
		ETM+	Landsat-7	USGS, NASA	1999 - 2021	30 - 60 m	16 days	8 bands: 0.45 - 12.5 µm	VIS, NIR, SWIR, TIR
		OLI, OLI-2	Landsat-8, -9	USGS, NASA	2013 - 2025	30 m	16 days	9 bands: 0.43 - 2.3 µm	VIS, NIR, SWIR
		LISS-IV	Resourcesat-1, -2, -2A	ISRO	2003 - 2021	5.8 m	5 days	VIS: 0.52 - 0.59 µm, 0.62 - 0.68 µm, NIR: 0.77 - 0.86 µm	VIS, NIR
		MSI	RapidEye	DLR	2008 - 2019	6.5 m	5.5 days	4 VIS + 1 NIR band: 0.44 - 0.88 µm	VIS, NIR
		NAOMI	SPOT	CNES, Spot Image	1986 -	1.5 - 6 m	26 days	0.45 - 0.89 µm	VIS, NIR
		MSI (Sentinel-2)	Sentinel 2A, B, C	ESA	2015 - 2029	10 - 20 m	5 days	13 bands: 0.44 - 2.20 µm	VIS, NIR, SWIR

	Instrument Type	Sensor	Mission	Organisation	Operational Timeline	Spatial resolution	Temporal resolution (days)	Frequency/wavelength	Spectral band
Soil Moisture	Multi-purpose imaging MW radiometer	AMSR-2	GCOM-W	JAXA	2012 -	5–50 km	2 days	7 bands: 6.9–89 GHz	X, Ku, Ka, Q, W
		MIRAS	SMOS	ESA	2009 -	35–60 km, resampled to 15 km	3 days	1.4 GHz	L
		SMAP	SMAP	NASA	2015 -	40 km	2-3 days	1.41 GHz	L
		SSM/I	DMSP-F8 - F16	NOAA, US-DoD	1987 - 2026	13–69 km (depends on frequency)	0.5 day	19.35 - 85,5 GHz	Ku, Ka, Q, W
		WindSAT	Coriolis	NASA	2003 - 2018	25 km	8 days	6.8–37 GHz	C,X, K and Ka
	Radar scatterometer	ASCAT	MetOp-A, -B, -C	EUMETSAT, ESA	2006 - 2024	25–50 km	2 days	5.25 GHz	C
	Imaging radar (SAR)	L, S-Band SAR	NISAR	NASA-ISRO	2021 - 2025	10 m	12 days		L and S
		PALSAR, PALSAR-2, -3	ALOS, ALOS-2, -4	JAXA	2006 - 2020>	1–10 m	14 (PALSAR-2,3) - 46 (PALSAR)	1.27 GHz	L
		SAR (Radarsat)	RADARSAT-1, -2, constellation	CSA	1995 - 2019>	1 - 10m	12 (constellation) - 24 days	5.405 GHz	C
		L-Band SAR (Tandem-L)	TanDEM-L	DLR	2024 - 2036	3–20 m	8 days	1.2 GHz	L
		C-Band SAR	Sentinel-1A, -1B, -1C, -1D	ESA	2014 -	5 – 20 m	6 days at equator	5.405 GHz	C
Groundwater	Satellite-to-satellite ranging system	GRACE	GRACE-1, GRACE-2, GRACE-FO	NASA /DLR	2003 -	~300 km	30		
	Imaging radar (SAR)	L, S-Band SAR	NISAR	NASA-ISRO	2021 - 2025	10 m	12 days		L and S
		X-band SAR	TerraSAR-X	DLR	2007 - 2020	1 - 6m	11 days	9.65 GHz	X
		SAR (Radarsat)	RADARSAT-1, -2, constellation	CSA	1995 - 2019>	1 - 10m	12 (constellation) - 24 days	5.405 GHz	C
		C-Band SAR	Sentinel-1A, -1B, -1C, -1D	ESA	2014 -	5 – 20 m	6 days at equator	5.405 GHz	C
Runoff, Streamflow, River discharge	Radar altimeter	KaRIN	SWOT	NASA, CNES	2021 - 2024	250 m - 1 km	21 days		Ka
		AltiKa	Saral	ISRO/CNES	2012 - 2019	90 km inter track	35 days	35 GHz	Ka
		SRAL	Sentinel-3A, B, C, D	ESA	2016 - 2029	300 m along track/52 km intertrack (in tandem)	27 days		Ku, C
		Poseidon-3, -3B	Jason-2, -3	CNES	2008 - 2021	6 km along track/300 km inter track	10	5.3 and 13.575 GHz	C, Ku
	Multi-purpose imaging MW radiometer	AMSR-2	GCOM-W	JAXA	2012 -	5–50 km	2 days	7 bands: 6.9–89 GHz	X, Ku, Ka, Q, W
	Imaging radar (SAR)	SAR (Radarsat)	RADARSAT-1, -2, constellation	CSA	1995 - 2019>	1 - 10m	12 (constellation) - 24 days	5.405 GHz	C
		C-Band SAR	Sentinel-1A, -1B, -1C, -1D	ESA	2014 -	5 – 20 m	6 days at equator	5.405 GHz	C
	Medium-resolution spectro-radiometer	MODIS	Terra and Aqua	NASA	1999 - 2020	250 m - 1 km	2 days	36 bands: 0.4 - 14.4 µm	VIS, NIR, SWIR, MWIR, TIR
		AVHRR/3	NOAA-15, 16, 17, 18, 19; Metop-A-, B, C	NOAA, EUMETSAT	1998 - 2024	1.1 km	0,5 days	6 channels: 0.58 - 12.5 µm	VIS, NIR, SWIR, MWIR, TIR, FIR
		Vegetation	PROBA-V	ESA	2013 - 2019	100 - 350 m	2 days	Blue (438-486 nm), Red (615-696 nm), Near IR (772-914 nm), SWIR (1564-1634 nm)	VIS, NIR, SWIR
	Multi-purpose imaging Vis/IR radiometer	VIIRS	Suomi NPP, NPOESS, JPSS	Suomi National Polar-orbiting Partnership	2011 - present	375 and 750 m	1 day	0.412 - 12.01 µm	VIS, NIR, SWIR, MWIR, TIR
	High resolution optical imager	ASTER	Terra	NASA	1999 - 2020	15, 30, 90 m	16 days	0.52 - 11.65 µm	VIS, NIR, SWIR, TIR
		ETM+	Landsat-7	USGS, NASA	1999 - 2021	30 - 60 m	16 days	8 bands: 0.45 - 12.5 µm	VIS, NIR, SWIR, TIR
		OLI, OLI-2	Landsat-8, -9	USGS, NASA	2013 - 2025	30 m	16 days	9 bands: 0.43 - 2.3 µm	VIS, NIR, SWIR
		MSI	RapidEye	DLR	2008 - 2019	6.5 m	5.5 days	4 VIS + 1 NIR band: 0.44 - 0.88 µm	VIS, NIR
		MSI (Sentinel-2)	Sentinel 2A, B, C	ESA	2015 - 2029	10 - 20 m	5 days	13 bands: 0.44 - 2.20 µm	VIS, NIR, SWIR

	Instrument Type	Sensor	Mission	Organisation	Operational Timeline	Spatial resolution	Temporal resolution (days)	Frequency/wavelength	Spectral band
Lakes/Reservoir surface levels	Radar altimeter	KaRIN	SWOT	NASA, CNES	2021 - 2024	250 m - 1 km	21 days	35.5 GHz	Ka
		AltiKa	Saral	ISRO/CNES	2012 - 2019	90 km inter track	35 days	35 GHz	Ka
		SRAL	Sentinel-3A, B, C, D	ESA	2016 - 2029	300 m along track/52 km intertrack (in tandem)	27 days	5.4 and 13.58 GHz	Ku, C
		Poseidon-3, -3B	Jason-2, -3	CNES	2008 - 2021	6 km along track/300 km inter track	10	5.3 and 13.575 GHz	C, Ku
	Medium-resolution spectro-radiometer	MODIS	Terra and Aqua	NASA	1999 - 2020	250 m - 1 km	2 days	36 bands: 0.4 - 14.4 µm	VIS, NIR, SWIR, MWIR, TIR
		AVHRR/3	NOAA-15, 16, 17, 18, 19; Metop-A-, B, C	NOAA, EUMETSAT	1998 - 2024	1.1 km	0,5 days	6 channels: 0.58 - 12.5 µm	VIS, NIR, SWIR, MWIR, TIR, FIR
		Vegetation	PROBA-V	ESA	2013 - 2019	100 - 350 m	2 days	Blue (438-486 nm), Red (615-696 nm), Near IR (772-914 nm), SWIR (1564-1634 nm)	VIS, NIR, SWIR
	Multi-purpose imaging Vis/IR radiometer	VIIRS	Suomi NPP, NPOESS, JPSS	Suomi National Polar-orbiting Partnership	2011 - present	375 and 750 m	1 day	0.412 - 12.01 µm	VIS, NIR, SWIR, MWIR, TIR
	High resolution optical imager	ASTER	Terra	NASA	1999 - 2020	15, 30, 90 m	16 days	0.52 - 11.65 µm	VIS, NIR, SWIR, TIR
		ETM+	Landsat-7	USGS, NASA	1999 - 2021	30 - 60 m	16 days	8 bands: 0.45 - 12.5 µm	VIS, NIR, SWIR, TIR
		OLI, OLI-2	Landsat-8, -9	USGS, NASA	2013 - 2025	30 m	16 days	9 bands: 0.43 - 2.3 µm	VIS, NIR, SWIR
		MSI (Sentinel-2)	Sentinel 2A, B, C	ESA	2015 - 2029	10 - 20 m	5 days	13 bands: 0.44 - 2.20 µm	VIS, NIR, SWIR
	Imaging radar (SAR)	SAR (Radarsat)	RADARSAT-1, -2, constellation	CSA	1995 - 2019>	1 - 10m	12 (constellation) - 24 days	5.405 GHz	C
		C-Band SAR	Sentinel-1A, -1B, -1C, -1D	ESA	2014 -	5 – 20 m	6 days at equator	5.405 GHz	C
		PALSAR, PALSAR-2, -3	ALOS, ALOS-2, -4	JAXA	2006 - 2020>	1–10 m	14 (PALSAR-2,3) - 46 (PALSAR)	1.27 GHz	L
Glaciers/ice sheets	Radar altimeter	SRAL	Sentinel-3A, B, C, D	ESA	2016 - 2029	300 m along track/52 km intertrack (in tandem)	27 days	5.3 and 13.575 GHz	Ku, C
		Poseidon-3, -3B	Jason-2, -3	CNES	2008 - 2021	6 km along track/300 km inter track	10	5.3 and 13.575 GHz	C, Ku
		SIRAL	Cryosat, -2	ESA	2005 - 2019	250 m along track/7 km inter track	369	13.575 GHz	Ku
	Lidar altimeter	ATLAS	IceSat-2	NASA	2018 - 2021	17 m along track/3.3 km across track	91 days	0.532 µm	Green laser
	High resolution optical imager	MSI (Sentinel-2)	Sentinel 2A, B, C	ESA	2015 - 2029	10 - 20 m	5 days	13 bands: 0.44 - 2.20 µm	VIS, NIR, SWIR
	Imaging radar (SAR)	X-band SAR	TerraSAR-X	DLR	2007 - 2020	1 - 6m	11 days	9.65 GHz	X
		SAR (Radarsat)	RADARSAT-1, -2, constellation	CSA	1995 - 2019>	1 - 10m	12 (constellation) - 24 days	5.405 GHz	C
		C-Band SAR	Sentinel-1A, -1B, -1C, -1D	ESA	2014 -	5 – 20 m	6 days at equator	5.405 GHz	C
Elevation	Imaging radar (SAR)	SRTM	Space Shuttle Endeavour	NASA/DLR	2000	1 arcsecond	-	5.4 and 9.6 GHz	X, C
		PALSAR, PALSAR-2, -3	ALOS, ALOS-2, -4	JAXA	2006 - 2020>	1–10 m	14 (PALSAR-2,3) - 46 (PALSAR)	1.27 GHz	L
		X-band SAR	TanDEM-X	DLR	2010 - 2020	1 - 6m	11 days	9.65 GHz	X
	High resolution optical imager	ASTER	Terra	NASA	1999 - 2020	15, 30, 90 m	16 days	0.52 - 11.65 µm	VIS, NIR, SWIR, TIR
	Lidar altimeter	ATLAS	IceSat-2	NASA	2018 - 2021	17 m along track/3.3 km across track	91 days	0.532 µm	Green laser

	Instrument Type	Sensor	Mission	Organisation	Operational Timeline	Spatial resolution	Temporal resolution (days)	Frequency/wavelength	Spectral band
Waveheight/Sea Level	Radar altimeter	KaRIN	SWOT	NASA, CNES	2021 - 2024	250 m - 1 km	21 days	35.5 GHz	Ka
		SRAL	Sentinel-3A, B, C, D	ESA	2016 - 2029	300 m along track/52 km intertrack (in tandem)	27 days	5.3 and 13.575 GHz	Ku, C
		Poseidon-3, -3B	Jason-2, -3	CNES	2008 - 2021	6 km along track/300 km inter track	10	5.3 and 13.575 GHz	C, Ku
		AltiKa	Saral	ISRO/CNES	2012 - 2019	90 km inter track	35 days	35 GHz	Ka
		ALT	HY-2A - HY-2H	NSOAS, CAST	2011 - 2027	16 km along track/30 km average spacing	1 month	13.58 GHz, 5.25 GHz	Ku, C
	Radar scatterometer	ASCAT	MetOp-A, -B, -C	EUMETSAT, ESA	2006 - 2024	25–50 km	2 days	5.25 GHz	C
		SCA	MetOp-SG B1, B2, B3	EUMETSAT, ESA	2022 - 2042	25 km	1.5 days	5.3 GHz	C
		SCAT	HY-2A - HY-2H	NSOAS, CAST	2011 - 2027	50 km	14 days	13.5215 GHz	Ku
		SWIM	CFOSAT	CNSA/CNES	2018 - 2021	50-70 km	13 days	13.575 GHz	Ku
Salinity	Multi-purpose imaging MW radiometer	MIRAS	SMOS	ESA	2009 -	35–60 km, resampled to 15 km	3 days	1.4 GHz	L
		SMAP	SMAP	NASA	2015 -	40 km	2-3 days	1.41 GHz	L
Temperature	Medium-resolution spectro-radiometer	MODIS	Terra and Aqua	NASA	1999 - 2020	250 m - 1 km	2 days	36 bands: 0.4 - 14.4 µm	VIS, NIR, SWIR, MWIR, TIR
	Multi-purpose imaging Vis/IR radiometer	MI	COMS	KMA/KARI/ME/MLTM	2010 -	4km	Earth Disk Scanning	10.3 - 11.3 µm, 11.5 - 12.5 µm	TIR
	Multi-channel/direction/polarisation radiometer	SLSTR	Sentinel-3A, -3B, -3C	ESA/EUMETSAT	2016 - 2029	1km (TIR)	1 day	0.55 - 10.85 µm	VNIR. SWIR, TIR
	Multi-purpose imaging MW radiometer	AMSR-2	GCOM-W	JAXA	2012 -	5–50 km	2 days	7 bands: 6.9–89 GHz	X, Ku, Ka, Q, W
		MWRI	FY-3A - 3F	2008 - 2026	2011 - 2027	7.5 x 12 km at 150 GHz, 51 x 85 km at 10.65 GHz	1 day	10.65, 18.7, 23.8, 36.5, 89, 150 GHz	X, Ku, Ka, Q, W
Coastline and Morphology	High resolution optical imager	ASTER	Terra	NASA	1999 - 2020	15, 30, 90 m	16 days	0.52 - 11.65 µm	VIS, NIR, SWIR, TIR
		ETM+	Landsat-7	USGS, NASA	1999 - 2021	30 - 60 m	16 days	8 bands: 0.45 - 12.5 µm	VIS, NIR, SWIR, TIR
		OLI, OLI-2	Landsat-8, -9	USGS, NASA	2013 - 2025	30 m	16 days	9 bands: 0.43 - 2.3 µm	VIS, NIR, SWIR
		MSI (Sentinel-2)	Sentinel 2A, B, C	ESA	2015 - 2029	10 - 20 m	5 days	13 bands: 0.44 - 2.20 µm	VIS, NIR, SWIR
	Imaging radar (SAR)	X-band SAR	TerraSAR-X	DLR	2007 - 2020	1 - 6m	11 days	9.65 GHz	X
		SAR (Radarsat)	RADARSAT-1, -2, constellation	CSA	1995 - 2019>	1 - 10m	12 (constellation) - 24 days	5.405 GHz	C
		C-Band SAR	Sentinel-1A, -1B, -1C, -1D	ESA	2014 -	5 – 20 m	6 days at equator	5.405 GHz	C
Bathymetry	Medium-resolution spectro-radiometer	MODIS	Terra and Aqua	NASA	1999 - 2020	250 m - 1 km	2 days	36 bands: 0.4 - 14.4 µm	VIS, NIR, SWIR, MWIR, TIR
		OLCI	Sentinel-3	ESA	2016 - 2029	300 m	2 days	21 bands in VNIR/SWIR	VNIR, SWIR
	Multi-purpose imaging Vis/IR radiometer	VIIRS	Suomi NPP, NPOESS, JPSS	Suomi National Polar-orbiting Partnership	2011 - present	375 and 750 m	1 day	0.412 - 12.01 µm	VIS, NIR, SWIR, MWIR, TIR
	High resolution optical imager	ETM+	Landsat-7	USGS, NASA	1999 - 2021	30 - 60 m	16 days	8 bands: 0.45 - 12.5 µm	VIS, NIR, SWIR, TIR
		OLI, OLI-2	Landsat-8, -9	USGS, NASA	2013 - 2025	30 m	16 days	9 bands: 0.43 - 2.3 µm	VIS, NIR, SWIR
		NAOMI	SPOT	CNES, Spot Image	1986 - (7th instrument)	1.5 - 6 m	26 days	0.45 - 0.89 µm	VIS, NIR
		WV110	WorldView 2,3,4	Digital Globe	2010 - 2022>	0.46 m (PAN) - 1.84 m (MS)	6 months; 3 days by strategic pointing	8 channels: 0.425 - 0.950 µm	VIS, NIR
		MSI	RapidEye	DLR	2008 - 2019	6.5 m	5.5 days	4 VIS + 1 NIR band: 0.44 - 0.88 µm	VIS, NIR
		ASTER	Terra	NASA	1999 - 2020	15, 30, 90 m	16 days	0.52 - 11.65 µm	VIS, NIR, SWIR, TIR