Interreg
2 Seas Mers Zeeën
PROWATER
European Regional Development Fund

The water system map for Europe

A spatial prioritisation tool for climate change adaptation measures

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Abstract

Many landscapes in Western Europe have been altered for agricultural intensification and urban development. These changes have decreased the resilience of hydrological systems. Climate change is increasing the frequency and extremity of weather events, resulting in droughts and floods that have an unacceptable impact on society. The challenge for land use planning is to restore sufficient natural diversity of ecosystems and create (semi-)natural opportunities for ecosystem service development that can compensate for climate change and anthropogenic impact. This is known as Ecosystem-based Adaptation (EbA) and is considered an important approach to increase resilience against flooding and droughts. However, random implementation of EbA measures in the limited available space of our landscapes is not effective.

To provide guidance to the implementation of Ecosystem-based Adaptation (EbA) measures, we produced a ’water system map‘ for the 2 Seas region, including catchments in the Netherlands, England, Flanders and France. This spatial prioritisation tool displays how the landscape functions from a hydro-geomorphic point of view. It identifies hotspots of hydrological functioning that are conditional to sustain system functioning (e.g. key recharge zones, landscape depressions, seepage areas, moorlands, frequently inundated areas). Restoring functional ecosystems in these hotspots within the landscape would provide an increased resilience to system disturbances.

The development of this spatial prioritisation tool is an output of the Interreg 2 Seas project PROWATER, which aims to build resilience against droughts, water scarcity and extreme precipitation events through targeted EbA measures that increase the raw water retention and infiltration capacity of the landscape. This report starts with an overview of EbA measures and principles, followed by a technical description of the water system map.

1 Introduction

Many landscapes in Western Europe have been altered for agricultural intensification and urban development. These changes have decreased the resilience of hydrological systems. Climate change is increasing the frequency and extremity of weather events, resulting in droughts and floods that have an unacceptable impact on society.

The aim of the Interreg 2 Seas project PROWATER is to build resilience against droughts, water scarcity and extreme precipitation events, exacerbated by climate change and anthropogenic change. Within PROWATER we specifically aim at increasing the raw water retention and infiltration capacity of the landscape. This will improve long term stability of groundwater levels and result in less extreme fluctuation in river flow. We tackle this challenge by restorating the natural diversity of ecosystems and creating (semi-) natural opportunities for ecosystem service development. This is known as 'Ecosystem-based Adaptation' (EbA).

This Ecosystem-based Adaptation (EbA) approach requires a new perspective for land use planning that includes spatial objectives for the multitude of ecosystem services that need to be generated on the limited land surface. Random implementation of measures throughout the landscape is not very effective. Thus, a key objective of PROWATER is to develop a spatial prioritisation tool that identifies opportunities in the landscape for implementation of specific EbA measures. We applied the 'water system map' developed by the University of Antwerp (Staes, 2014 & 2021) to the 2 Seas regions, including catchments in the Netherlands, England and Belgium (Flanders).

The water system map displays how the landscape functions from a hydro-geomorphic point of view. It identifies hotspots of hydrological functioning that are conditional to sustain system functioning (e.g. key recharge zones, landscape depressions, seepage areas, moorlands, frequently inundated areas). The occurrence and extent of these hotspots is primarily dependent on morphology and soil characteristics but also require functional ecosystems to provide the services in regulating water and nutrient cycles. Restoring ecosystem functional ecosystems in these hotspots within the landscape would provide an increased resilience to system disturbances.

This report starts with an overview of EbA measures and principles, followed by a technical description of the water system map applied to the 2 Seas region, including catchments in the Netherlands, England and Belgium (Flanders).

2 Targeted Ecosystem-based Adaptation measures

There is evidently a broad suite of potential measures that enhance the residence time of water and nutrients within a landscape. With PROWATER we focus on specific types of measures that: (1) improve soil permeability through agricultural soil management, (2) reduce interception through forest conversion/management practices, (3) promote and prolong water storage in floodplain wetlands, (4) promote deferred infiltration through restoration of upstream depressional wetlands and (5) remediate soil sealing impacts through infiltration ponds.

Spatial prioritisation methods for Ecosystem-based Adaptation (EbA) measures were reviewed in the PROWATER report ‘Review of spatial prioritisation methods for Ecosystem-based Adaptation measures to drought risks’ (Van der Biest K et al. 2019). Each type of adaptation measure has its own prerequisites in terms of abiotic characteristics (e.g. topography, soil) that make the area suitable for the targeted hydrological function. The water system map applied to the 2 Seas region for PROWATER makes use of a multiscale topographic position index (TPI) to define priority areas for the application of measures. The tool developed based on this topographic indicator distinguishes landforms with distinct hydrological functions (e.g. recharge zones, permanent wetlands, temporary wetlands, runoff retention zones, ditches).

Depending on the context (soil/topography/geology) and the type of interventions/measures, the user can focus on either small scale runoff driven processes or more large scale groundwater flow driven processes. Combining both scales is useful, as at the large scale infiltration seepage patterns depict main recharge areas while the small scale patterns depict local opportunities for erosion control and runoff collection. Retaining water in small scale landscape depressions can sustain downstream base flow for longer periods and promote groundwater recharge through deferred infiltration. Depending on the combination between soil, landscape position and land management, there are several options to enhance infiltration and retention.

In the next section different key-EbA measures that are implemented in the context of PROWATER are explained. The final objective is to quantitatively assess the impact of these EbA inspired restoration scenarios on targeted Ecosystem Services.

2.1 Reducing interception losses through forest conversion

Interception is the process where rainfall is captured in the canopy and evaporates back into the atmosphere. This water is not actively used in any biological process. Interception and forest cover in general has strong positive effects on heavy soils as it buffers extreme precipitation events, reduces runoff and promotes infiltration. The interception losses are minor compared to the runoff losses a sparsely vegetated soil would generate. On sandy, well-permeable soils, the opposite occurs. These soils are unlikely to generate runoff and interception losses reduce groundwater recharge.

During the 19th century, large areas of mixed deciduous forest in Western Europe were converted to productive coniferous forest plantations (Verstraeten 2013). This has had serious impact on the water balance of the landscape. Changes in forest cover affects water yield, runoff, infiltration and evaporation and therefore groundwater recharge (Allen and Chapman 2001). Several studies prove in general that coniferous trees consume more water than deciduous trees. This can be attributed to higher evaporation and interception compared to deciduous hardwoods (e.g. Adane et al. 2018; Brown et al. 2005; Dams et al. 2008; Filoso et al. 2017; Nisbet 2005).

Especially coniferous species have high interception rates and therefore reduce the infiltration capacity. Forest conversion to broadleaf forest or more open vegetation types allows building up additional groundwater head during winter, which mitigates impacts of droughts.

2.2 Improving soil permeability through soil management practices

Soils are a key asset in protecting and restoring the ability of a catchment to provide clean water. Soil can absorb, store and hold water before allowing it to drain to groundwater, rivers or be taken up by plants. The ability of soils to infiltrate and store water depends on soil texture (for example sandy soils have higher infiltration rates than clay soils) and structure (the way that soil particles are combined or aggregated). Soil organic matter content (SOM) plays an important role due to its impact on soil structure. Soil cover and water content are additional characteristics that influence soil water infiltration and retention.

In practice, a huge range of factors influence soils and their behaviour, including weather, altitude, depth, drainage, and past treatment. While general conclusions can be drawn on infiltration rates based on soil types, the specific context and situation will determine behaviour, for example reduced infiltration rates on sandy soils due to slaking or increased infiltration rates on dry clay soils due to cracking.

A healthy soil is able to store and release water slowly over time and therefore capable of buffering variations in precipitation surplus. As infiltration is affected by soil structure, processes that lead to the deterioration of soil structure, namely a loss of larger macropores, will affect infiltration. Soil retention capacity also depends on pore size distribution. Soil degradation changes soil characteristics significantly and reduces soil water retention capacity. Reduced infiltration may cause an increase in overland flow and the risk of downstream flooding because of the reduced time lag between rainfall and peak flow.

Soil amendments such as compost and wood chips can be used, but even better is to allow crop residues to remain or to plant catch and cover crops during winter. All of these measures can be used to improve infiltration and soil health in general. Cover crops grow during the fallow periods. They have the potential to protect the soil from erosion, reduce nitrate leaching and losses of nutrient, pesticides and sediment, increase soil organic matter and carbon sequestration and reduce pest and weed pressure. Leaf cover prevents physical degradation of soil aggregates and decayed plants roots form channels (De Baets et al. 2011). They therefore improve water infiltration and water and soil quality (Basche et al. 2014; Dabney et al. 2001; Kaspar and Singer 2011).

Although most literature attributes generally positive effects of conservation agriculture (reduced to zero tillage), the use of catch/cover crops and increased soil organic matter, there are a considerable number of studies that show no effects or even negative effects on plant growth. It is clear that one cannot transform from one management practice to another and expect immediate effects. It takes time for the soil ecosystem to mature to a new equilibrium. A lot depends on the state of the soil before measures are taken. We can assume that applying no-till on heavily degraded soils with low SOM will have negative effects. Firstly because subsoil compaction is likely to be present and secondly because the topsoil is very vulnerable to physical degradation. Therefore it is crucial to apply deep ripping and sufficient SOM amendments (or fallow period with deep rooting vegetation) before transforming to no-till management.

2.3 Creation and restoration of permanent wetlands

While infiltration and deferred infiltration in upstream areas results in a strategic long-term aquifer recharge that spans multiple seasons, there is also need for water retention in downstream valley wetlands. Under natural conditions, these valley bottom wetlands have permanently wet conditions. But most often, these valley systems are (partly) in agricultural use and heavily drained. Valley bottom wetlands act as sponges and can provide base flow during drought periods. Important measures are to decrease the drainage basis of both the drainage network and the main drain. In the past, a lot of streams have been straightened to improve drainage and parcel layout for agriculture. This river normalisation has reduced flow friction and accordingly aggravated flood frequency and magnitude. River re-meandering and floodplain restoration does not only alleviate downstream floods, but also has the potential to store a lot of water in the peaty subsoil. This is even more important when groundwater abstractions are present. Many abstractions from rivers and groundwater take place in the more downstream valleys.

Decreasing the drainage basis often requires re-meandering, providing more in-stream water storage and creating a more gradual river bed slope along the floodplain. In addition, the groundwater level may rise as a result of the increased route length, allowing weirs to be removed. The smaller attenuation of the new remodelled course results in a higher flow velocity, despite the less steep slope than canalised watercourses. The increase in river length will cause a general decrease in river slope and therefore an increased flood frequency and inundation of the alluvial plain. Usually the flow rate will decrease, especially in the most upstream areas of the restored watercourse.

The most drastic consequences of a change in a watercourse, whether natural or forced, are an increase in its total length, in other words a reduction in the suspension S of the watercourse and an increase in total friction. As a result, peak flows at a certain geographical location in the river will be more flattened, which will reduce the risk of flooding at that location.

2.4 Creation and restoration of temporary wetlands

Wetlands play an important role in the hydrological cycle (Bullock and Acreman 2003) and provide numerous environmental functions (Bertassello et al. 2018; Mitsch and Gosselink 2000). There is growing evidence that small scale wetlands play a disproportionally large role in regulating hydrology (Bertassello et al. 2018; Colvin et al. 2019). A number of recent papers specifically focus on the flow regulating functions of wetlands that are not hydrologically connected to the river network. Different terminology is used in the literature to refer to such wetlands, namely “depressional wetlands” (Evenson et al. 2018), “non-floodplain wetlands” (Jones et al. 2019; Lane et al. 2018) or “geographically isolated wetlands” (Cohen et al. 2016; Evenson et al. 2016; Rains et al. 2016). Due to their topographical position, these areas are naturally characterized by a high fluctuation in water levels (hydroperiod with short lag time, high frequency, low amplitude). This creates possibilities for deferred infiltration which recharges groundwater reserves and increases base flow during subsequent periods of drought (Lee et al. 2018). Available studies show that the actual groundwater recharge by wetlands depends on the interplay of buffer volume, retention time and hydraulic conductivity of the subsoil. Despite recognizing the importance of hydrological function of wetlands, basin-scale wetlands services have rarely been investigated (Wu et al. 2020). The representation of (small) wetlands in catchment models is a known issue (Evenson et al. 2016; Sharifi et al. 2016). This caveat is only recently being addressed. Results from a study in North-East China revealed that when wetlands are properly represented exert significant impact on basin hydrological processes by decreasing streamflow and altering streamflow regime (magnitude, frequency, duration and time of flow events).

Although their importance is now recognised, small scale temporary wetlands have long been viewed as problematic in terms of agricultural production and, consequently, have been subject to land drainage or infilling (Acreman and McCartney 2009). Without artificial drainage, temporary wetlands would occur at many locations in upstream (dry) valleys and landscape depressions. These sites are dependent on local seepage and runoff dynamics. Periods of excess precipitation can lead to temporarily water logged conditions. Centuries ago, most of these wetlands were drained by drainage channel networks (Staes et al. 2009), but under natural conditions delayed infiltration would take place when the groundwater levels naturally decline during spring. Instead if draining these sites, water should be retained locally until infiltration is achieved.

3 A water system perspective

The principles are easy. We want to promote infiltration in elevated upstream areas by improving soil permeability, reducing runoff and interception. Next we need to retain runoff and groundwater in headwater wetlands and landscape depressions. Finally we need to retain water in valley systems by meandering and rewetting. But how can we identify these elevated zones, headwater wetlands, landscape depressions and even old meanders in the landscape?

Through an innovative topographical analysis we can identify these zones. At the core of the method, we make use of the topographic position index (TPI). The TPI can be calculated as the difference between the elevation at one central point and the mean elevation within the neighbourhood around that point (Gallant and Wilson 2000; Weiss 2011). Therefore, the TPI is a scale-dependent indicator and determines the relative position of each pixel, compared to the surrounding pixels within the landscape. An advanced pre-and post-processing was developed to make optimal use of the strengths of the TPI. A pre-processing attempts to “abrade” the topographic elevations without filling up the depressions, mimicking a shallow groundwater layer beneath the surface. Small topographic elevations are erased from the surface. Next, a post-processing is applied to standardize the TPI values. This procedure thus allows mimicking subsurface flows, by removing topographic elevations without filling up depressions. A “gradient” of infiltration to seepage (resp. run-off generation and collection) can be calculated for a range of spatial scales.

The advantage of this procedure is that the final map can be interpreted as a gradient of wet-dry soils (%) for a user defined spatial scale. When this procedure is applied on a range of scales, we can unravel the interplay of flow patterns. By combining small scale and large scale indicators, we can make distinction between temporarily and permanently wet areas and potentially even estimate the hydro-period of wetlands. The hydro-period is an overarching hydrological metric that refers to the timing, frequency and duration of water-logged conditions (Riley et al. 2017).

Such a landscape analysis (and classification) allows to differentiate where particular measures are more effective in achieving hydrological resilience. Evidently, there is need for further interpretation of the water system map to make sensible decisions. We will outline the principles, but leave it up to local experts to combine the water system maps with local data on soil texture and soil depth.

3.1 Methodology

To produce the water system maps, we preferably use a high resolution digital elevation map. Yet this is not available for the whole of Europe. We compiled a 10 m Digital Elevation Model (DEM) for Flanders, the South of England and the coastal areas of the Netherlands. We combined available national datasets and used the 25m EU-DEM (Copernicus) to fill up remaining data gaps. Large areas of NoData compromise the result of the calculations.

Next we used the WISE Water Framework Directive’s dataset of river basin districts to calculate the maps for each river basin. This was needed because the procedure makes a distribution of infiltration zones, permanently wet and temporary wet zones at the basin scale. The DEM was clipped with a buffer of 25 km surrounding the basin, then TPI maps were calculated. The TPI maps were then clipped to the basin delineation before combining them into the final water system maps.

For the macroscale, TPI maps were calculated for 10 spatial ranges (resp. 1 km, 1.5 km, 3 km, 4 km, 8 km, 12 km, 20 km & 30 km) and combined by applying an equal weight average. At the macroscale we can distinguish the infiltration seepage patterns that identify the main recharge areas and (potential) permanent wetlands.

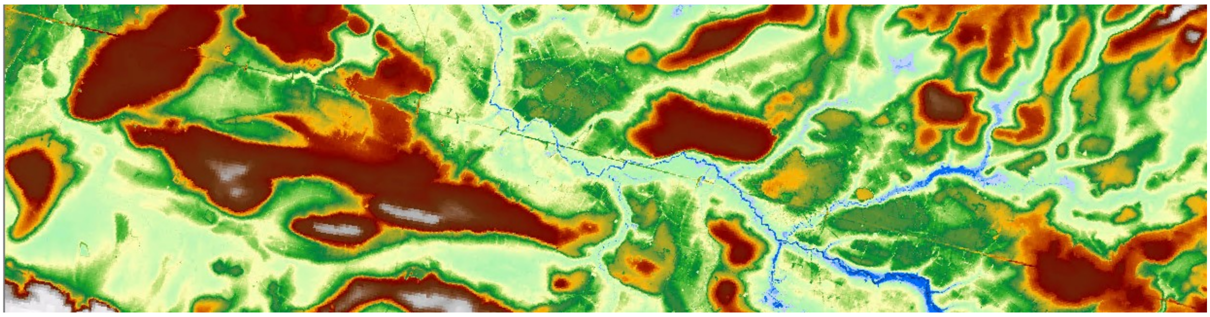


Figure 1: Macroscale patterns (1-30 km) for a catchment in the UK (Medway basin). Blue indicates where flows converge. Brown areas are source areas.

For the mesoscale, TPI maps were calculated for 6 spatial ranges (resp. 0.1 km, 0.2 km, 0.4 km, 0.6 km, 0.8 km, 1 km) and combined by applying an equal weight average. At smaller scales we can observe more differentiated infiltration seepage patterns. Especially in upstream catchments we can detect the (temporary) headwater wetlands and landscape depressions. Because the recharge areas are relatively small, there is a strong seasonal effect of the seepage intensity.

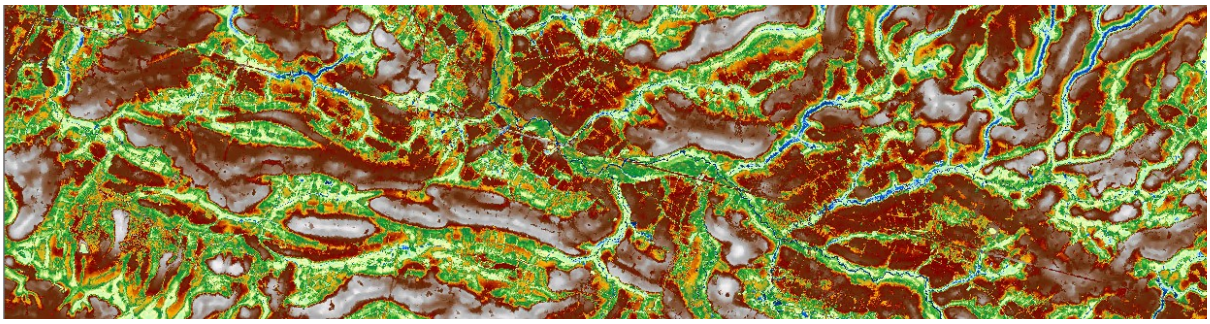


Figure 2: Mesoscale patterns (0.1-1 km) for a catchment in the UK (Medway basin). Blue indicates where flows converge. Brown areas are source areas.

Finally, the macro- and mesoscale maps were combined. This was done at the catchment scale and resulted in three non-overlapping maps. Blue colours indicate permanently wet conditions (permanent seepage & floodplains), green colours indicate temporary wet conditions (local runoff-accumulation & temporary seepage) and yellow-to-brown gradients indicate recharge areas.

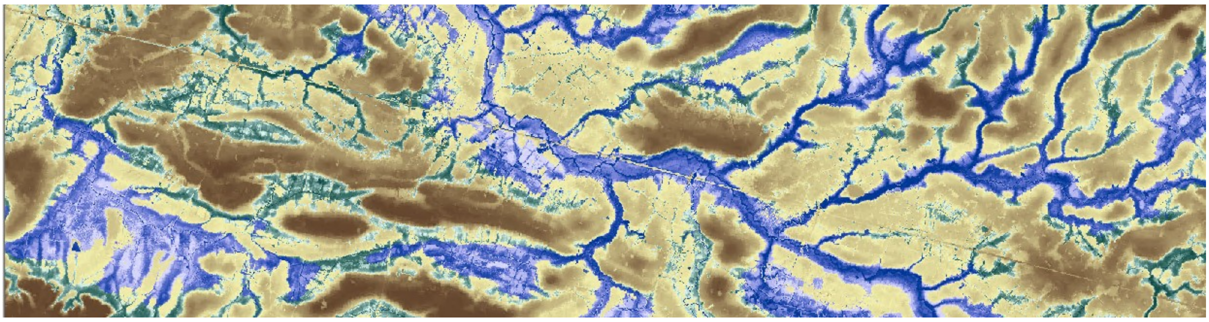
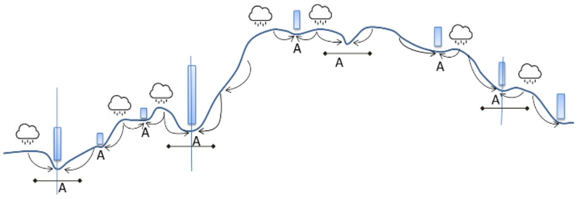


Figure 3: Water system map depicting permanently wet conditions (blue), temporary wet conditions (green) and recharge areas (yellow-to-brown gradient).

The procedure to combine the macro- and mesoscale index aims to distinguish between areas that receive strictly local water flows from zones that receive both local and larger scale water flows. First the macroscale index (0-100) was used to select the 15% most wet pixels. These were then combined with the mesoscale index (0-100) to further differentiate the wetness within the selected zones. Contribution of local runoff and seepage can intensify the wetness within the permanently wet areas.

Then we took the mesoscale index (0-100) and remove the pixels that have been identified as permanently wet zones. From the remaining pixels we selected 20 % of the most wet pixels. These are considered to be temporary wet zones. These pixels only receive local water flows.

The remaining pixels that are not considered to be either permanently of temporary wet zones are infiltration zones. To differentiate their importance for infiltration/retention, we multiplied the mesoscale and macroscale index and applied an equal area classification.

<table>
<tr>
<td>Relative position in the landscape at MESOscale (100 - 1000 m)
 </td>
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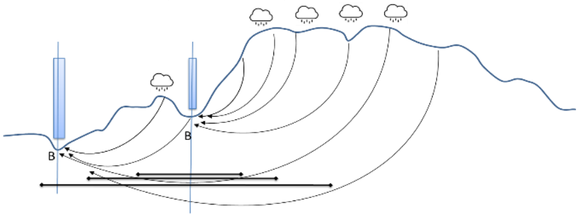 </td>
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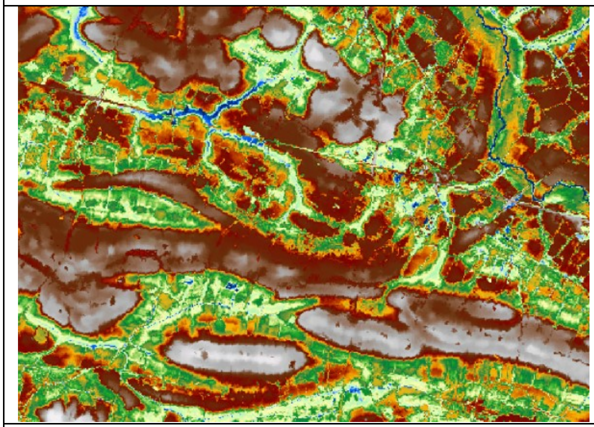
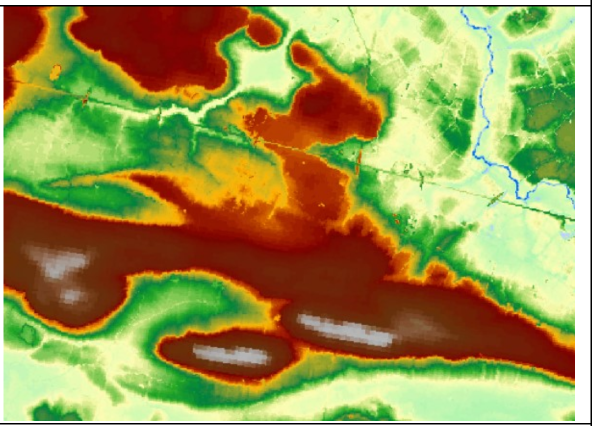
<td></td>
<td></td>
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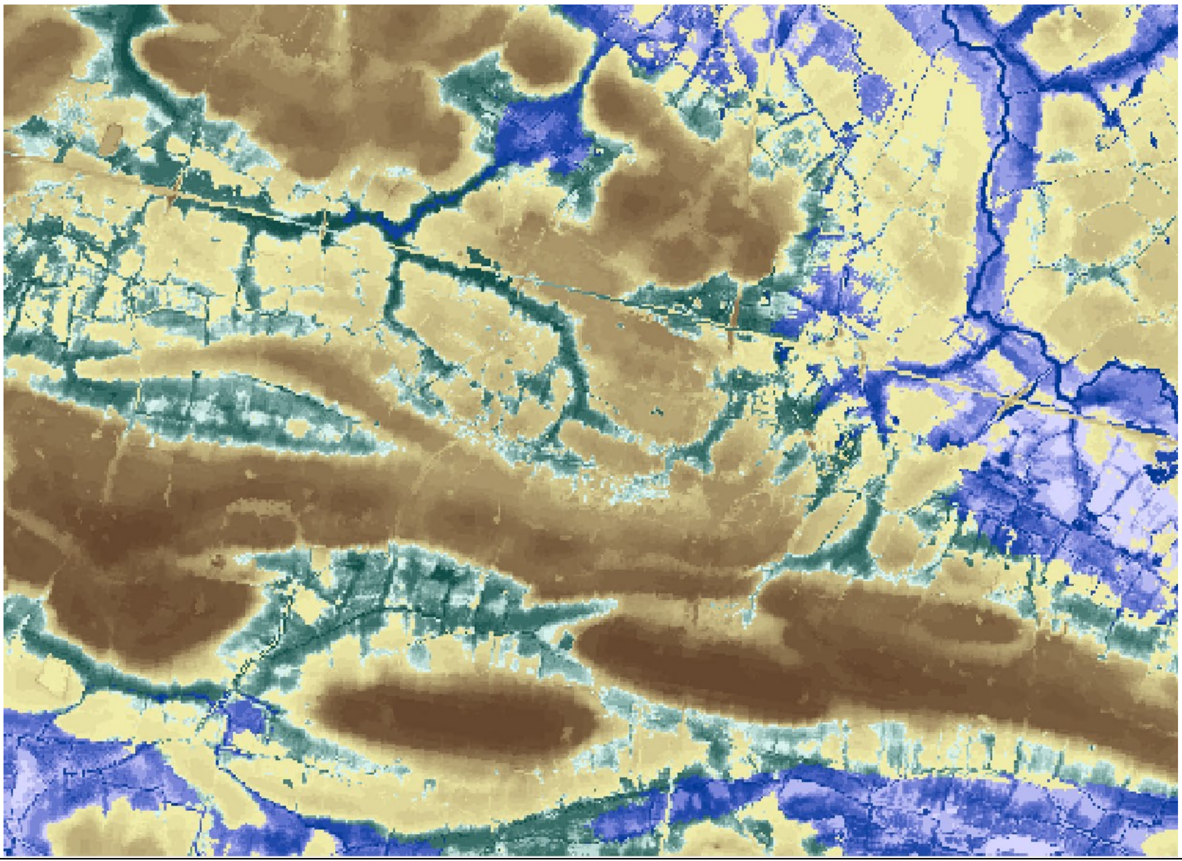
<td colspan="2"></td>
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Figure 4: Visual representation of macro- and mesoscale patterns and their combination into the waters system map.

3.2 Coverage

The maps have been produced for South England, the western part of the Netherland and part of the Flemish Region. There was no regional DEM available for the Northern part of France. If this becomes available before the PROWATER project ends, it may be possible to provide an updated version. As mentioned under the section drawbacks and limitations, the European DEM (25 m pixels) has a poor resolution and poor accuracy.

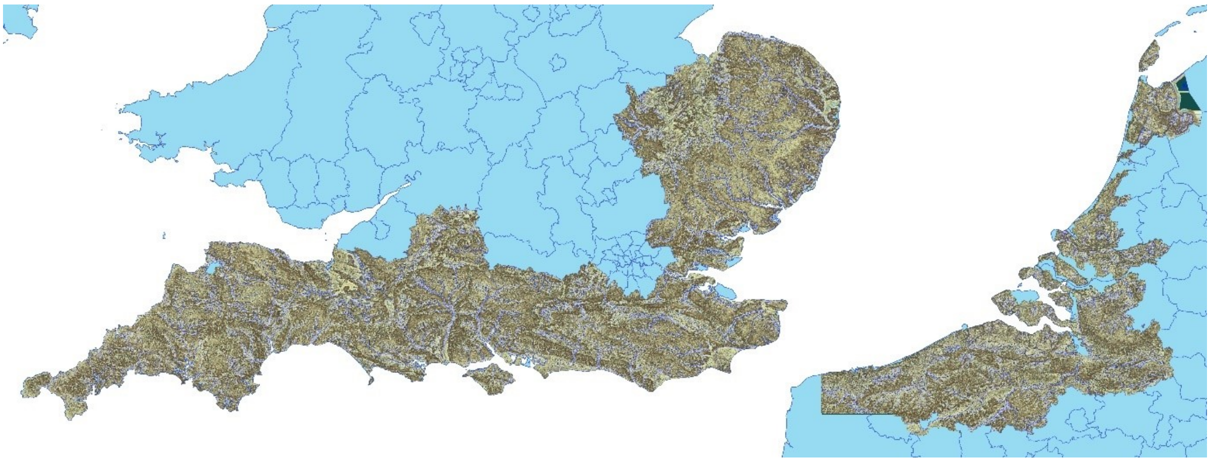


Figure 5: coverage of the water system map applied to the 2 Seas region within the project PROWATER.

3.3 Limitations & drawbacks

3.3.1 Processing artefacts at basin boundaries

The mapping procedure resulted in a small strip of erroneous data at the catchment borders for the final product, and is especially visible on the layer for temporary wet zones. The reason for this artefact is yet unclear and may be resolved in later versions.

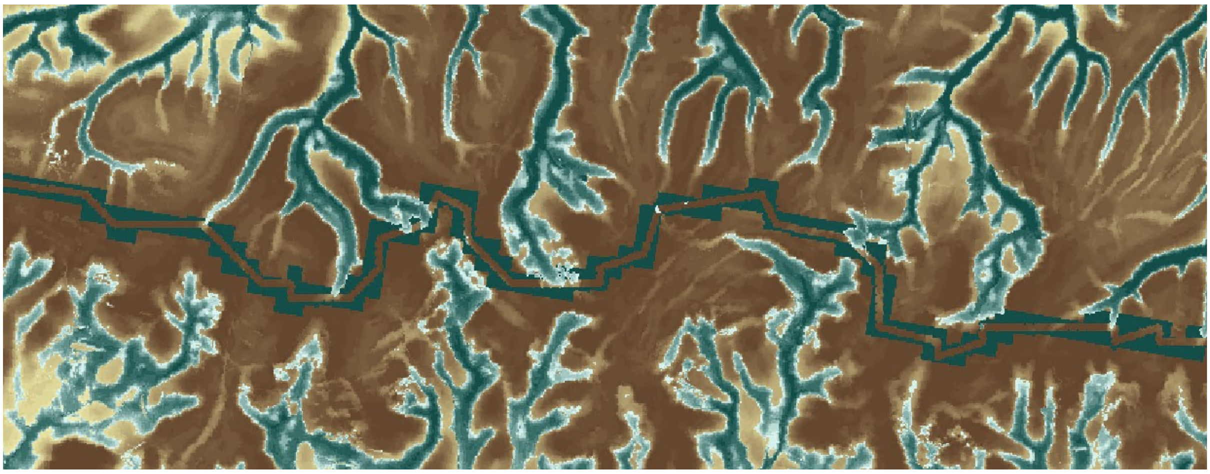


Figure 6: Example of a data processing artefact at the catchment borders.

3.3.2 Small catchments are missing in the dataset

Very small catchments could not be processed because the macroscale patterns require a minimal distance (width/length) of at least 50 km. These catchments are usually small coastal basins or islands.

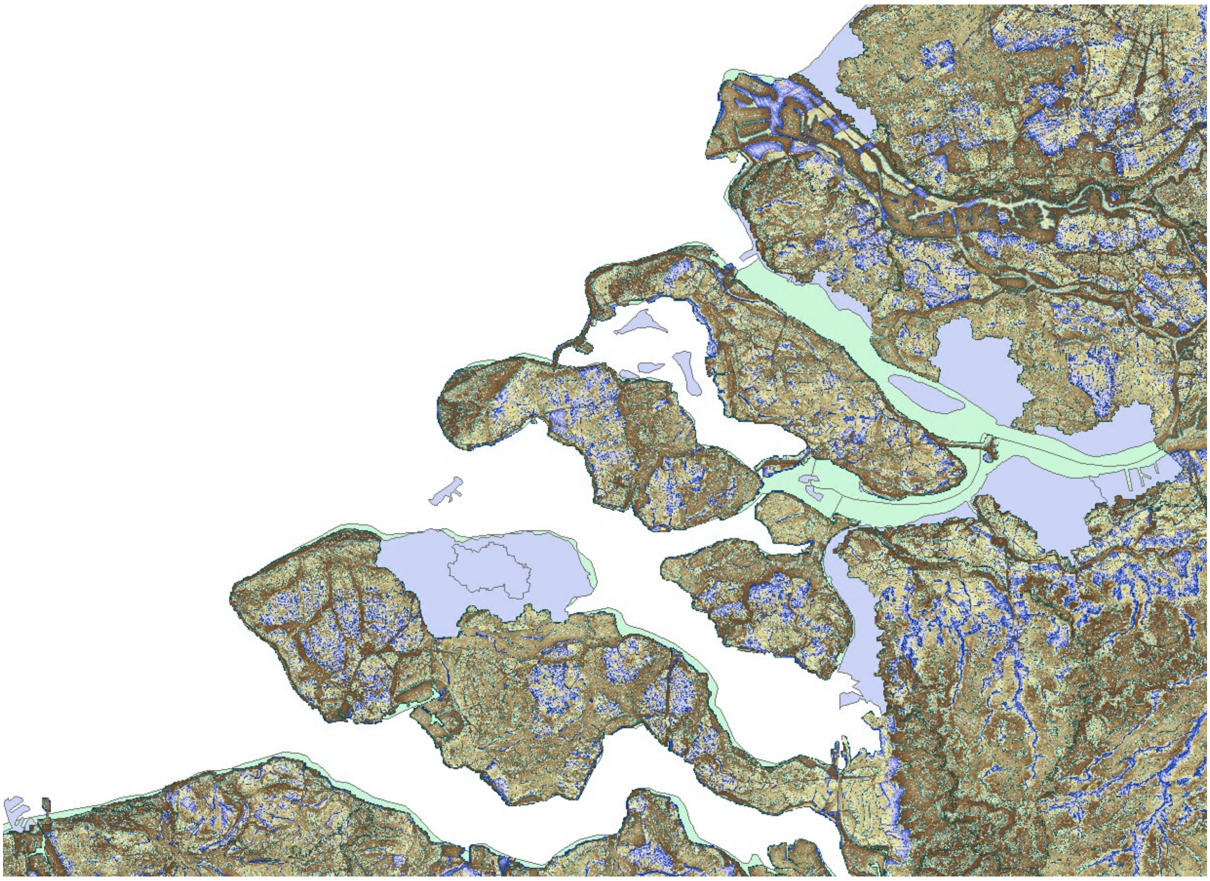


Figure 7: examples of small catchments for which we could not process the water system maps.

3.3.3 Effects of using lower resolution and accuracy DEM for NoData areas

In the UK, LIDAR data collection has been done in a more fragmented way than for Flanders and the Netherlands. Several catchments only have partial LIDAR data. There seems to be a focus on larger valleys and floodplains. To resolve this, we have used the EU-DEM to fill these gaps. We have resampled the EU-DEM to a 10 m pixel resolution to achieve a DEM without data gaps. From a distance, the impact cannot be observed. But a closer look reveals discontinuities and a more fuzzy graphical representation. The EU-DEM and the UK-DEM's have vertical differences up to several meters.

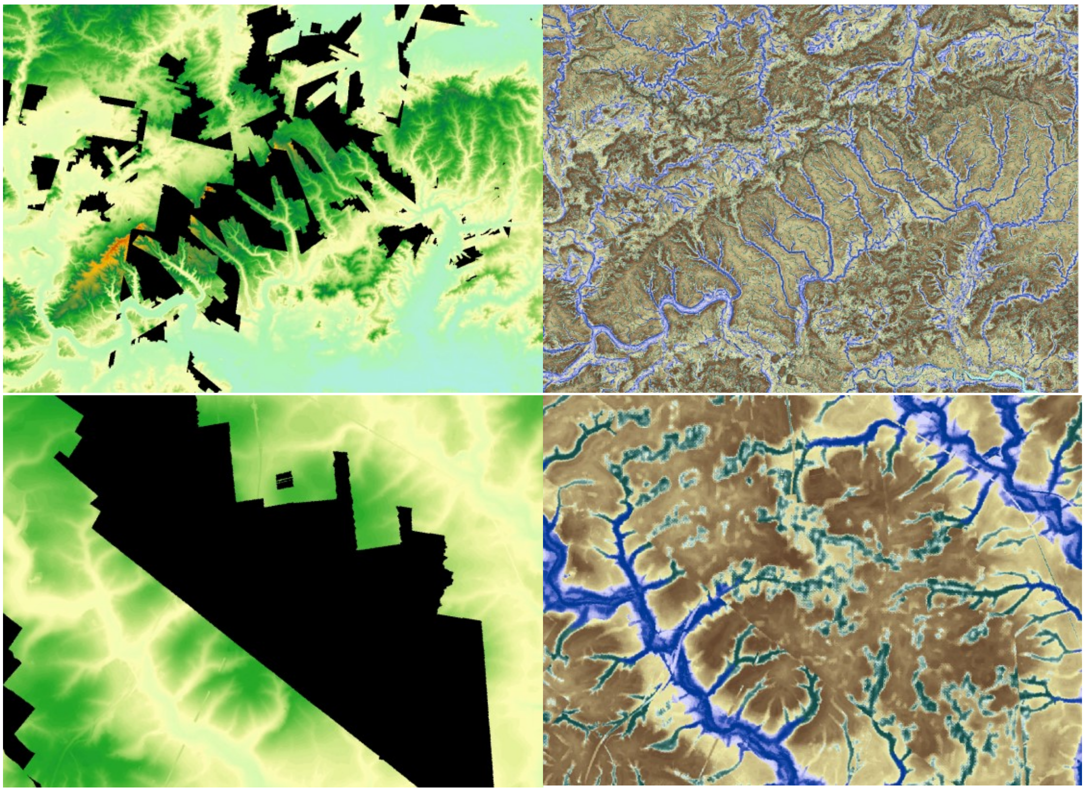


Figure 8: Data gaps in the UK-DEM and impacts of using the coarser EU-DEM to fill the data gaps. General patterns remain, but discontinuities and less distinct patterns can be observed.

The impact of using the coarse EU-DEM is limited for the rather hilly UK catchments. An error of a few meters in elevation is not that problematic in regions with strong gradients. In contrast, we can see the huge impact of using the coarse EU-DEM for the French coast. Patterns are erratic and seldom correspond to the situation on the ground. Although the EU-DEM has a spatial resolution of 25m, the resulting map show block patterns at a much larger scale. This can be well-observed at the border between the Flemish Region and Northern France (fig 9). The EU-DEM is a hybrid product based on SRTM (Shuttle Radar Topography Mission) and ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) GDEM data fused by a weighted averaging approach. It is evident that airborne LIDAR data is more accurate than spaceborne remote sensing. But a covering EU-DEM, based on compiled regional datasets is not available.

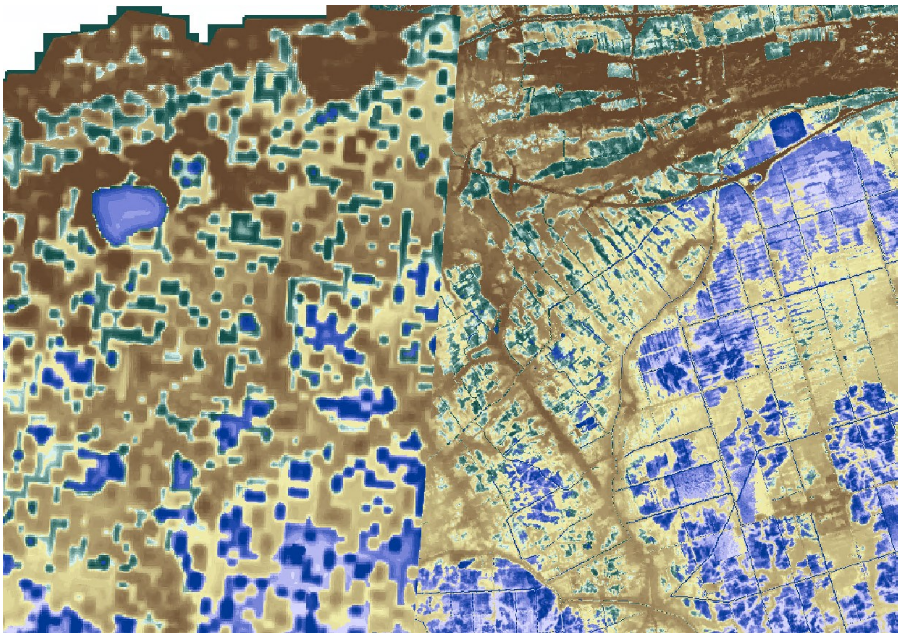


Figure 9: Impact of using the 25m EU-DEM in France versus the 10m national DEM for Belgium. The observed area is the French-Belgian border between De Panne en Bray-Dunes (Dunkirk).

4 Results – remarkable patterns across the 2 Seas region

The methodology for map production includes a correction for topographical variation at the different spatial scales. This allows the model to self-adjust when applied on regions with a very different topography. When applied on mountainous regions the TPI patterns are very distinct. But when applied on gently sloping or even flat areas, these differences in TPI are very subtle. We show some examples for respectively hilly landscapes, rolling, landscapes, flat areas (polders, estuaries) and regions with local topographical variation.

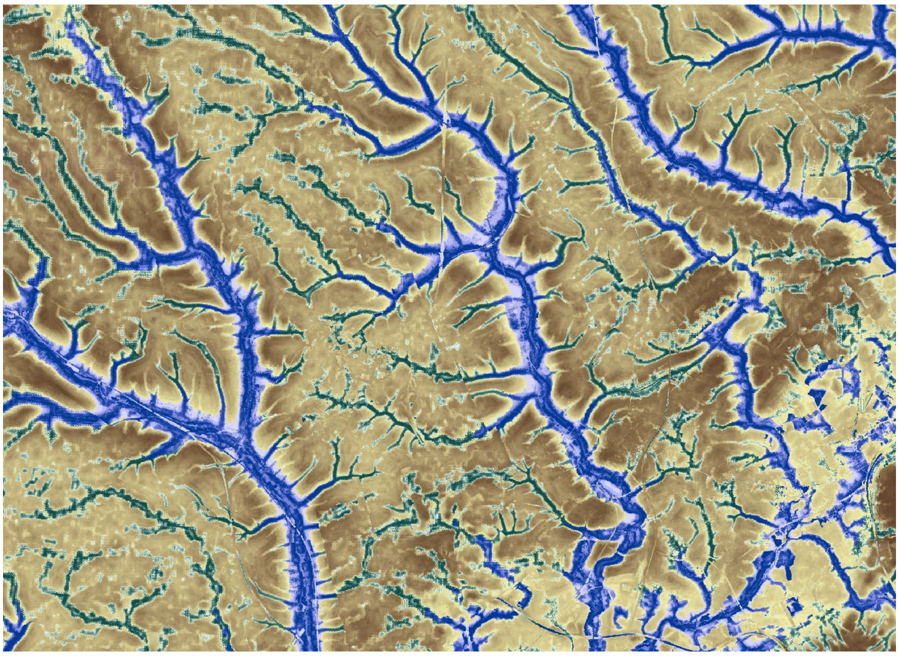


Figure 10: a hilly landscape in the UK. Narrow headwater valleys that end up in larger streams.

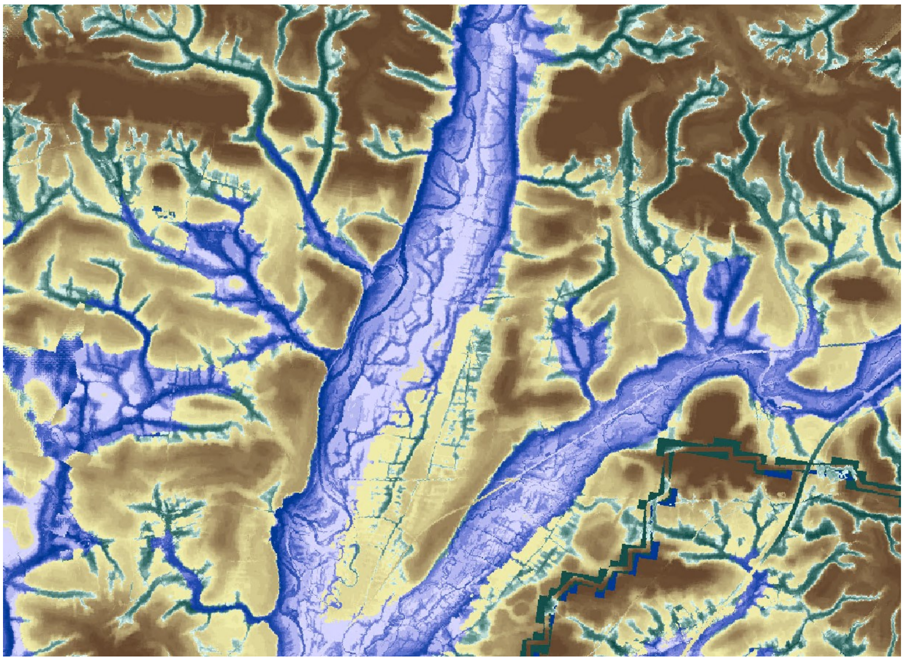


Figure 11: A more downstream part where the hilly landscape has a transition to a rolling landscape. The valley here is more wide and all the old meanders are still clearly visible.

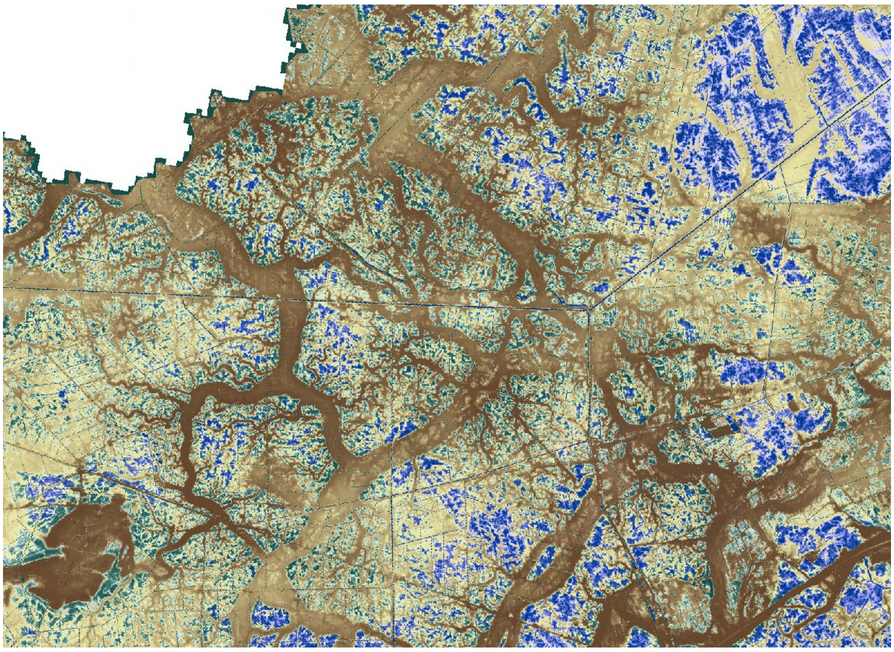


Figure 12: A coastal flat where you can see inversion. Landscape inversion is the process whereby relative topographic elevations become inverted such that previously low-standing features become high-standing. The old tidal creeks have been filled with sand, while the surrounding mudflats (clay-peat) have subsided or eroded.

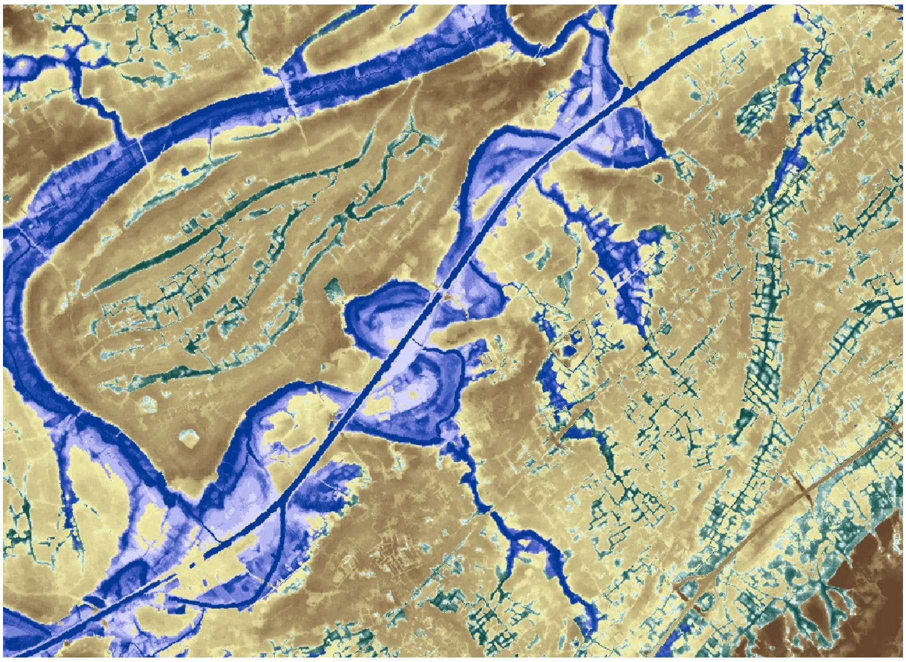


Figure 13: Old meanders in the landscape. This part of the Lys river has been straightened and transformed to a canal for navigation in 1939. The meander in the left upper corner is a paleo-meander that is still visible in the landscape. There is a high potential to retain water in these old meanders.

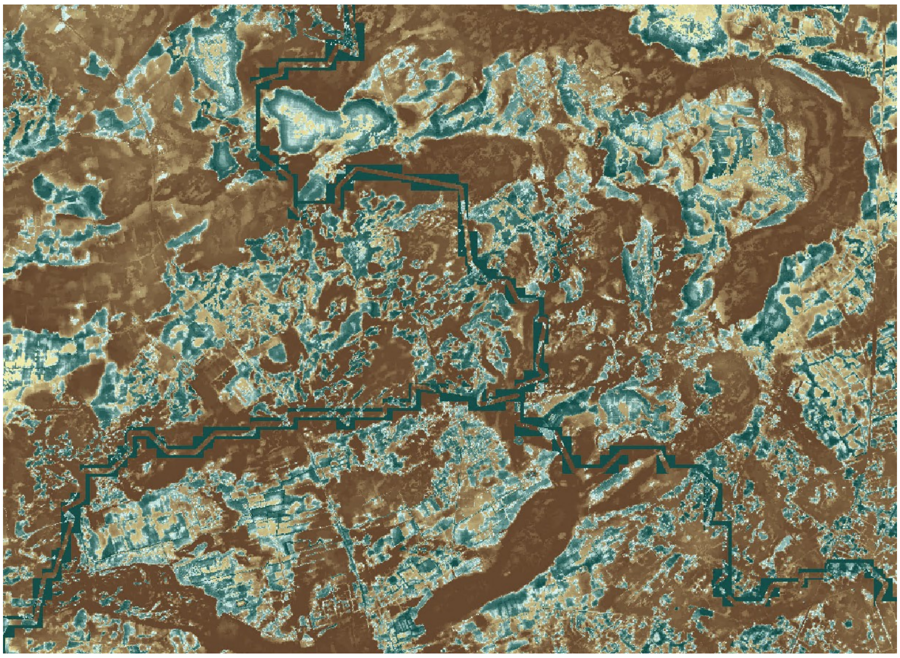


Figure 14: the Belgian-Dutch border near Antwerp. This landscape still has a natural topography. A patchwork of smaller and larger Inland dunes can be seen here. The dark brown areas sometimes show parabolic patterns shaped by strong north-east oriented winds of the last ice age (Weichselien, about 126,000 - 11,700 years ago).

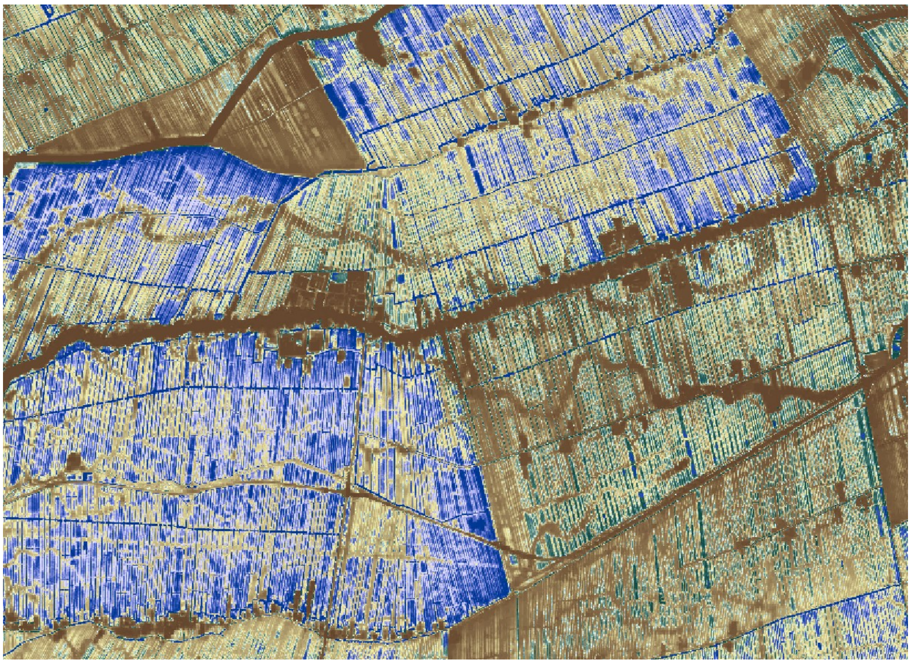


Figure 15: Polder landscape in the Netherlands. Also here landscape inversion took place. The old creeks are still visible in the landscape, although these are rather subtle differences in elevation. We can also observe thousands of drainage channels.

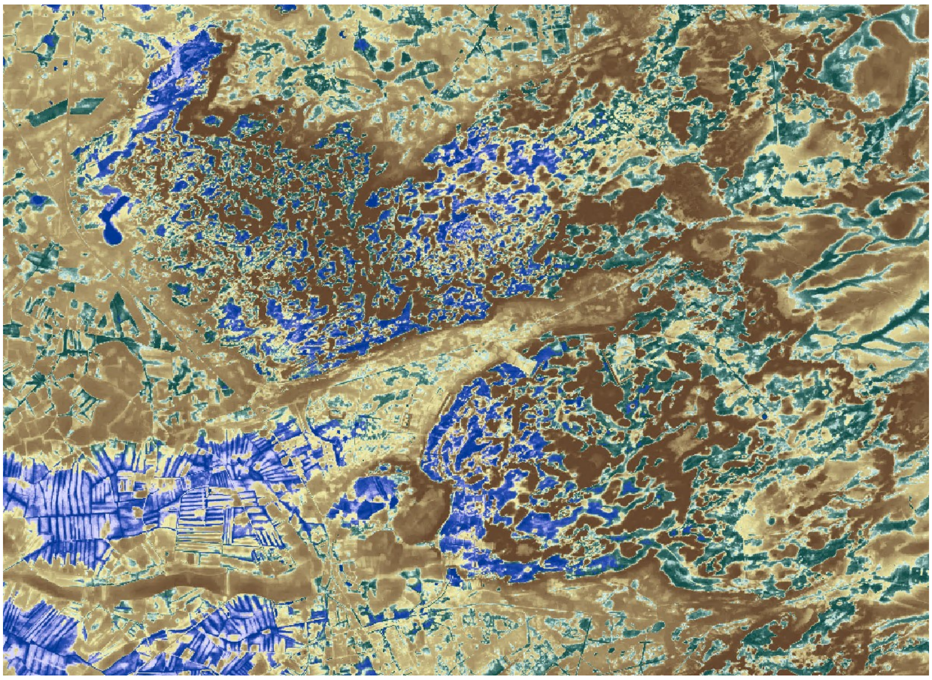


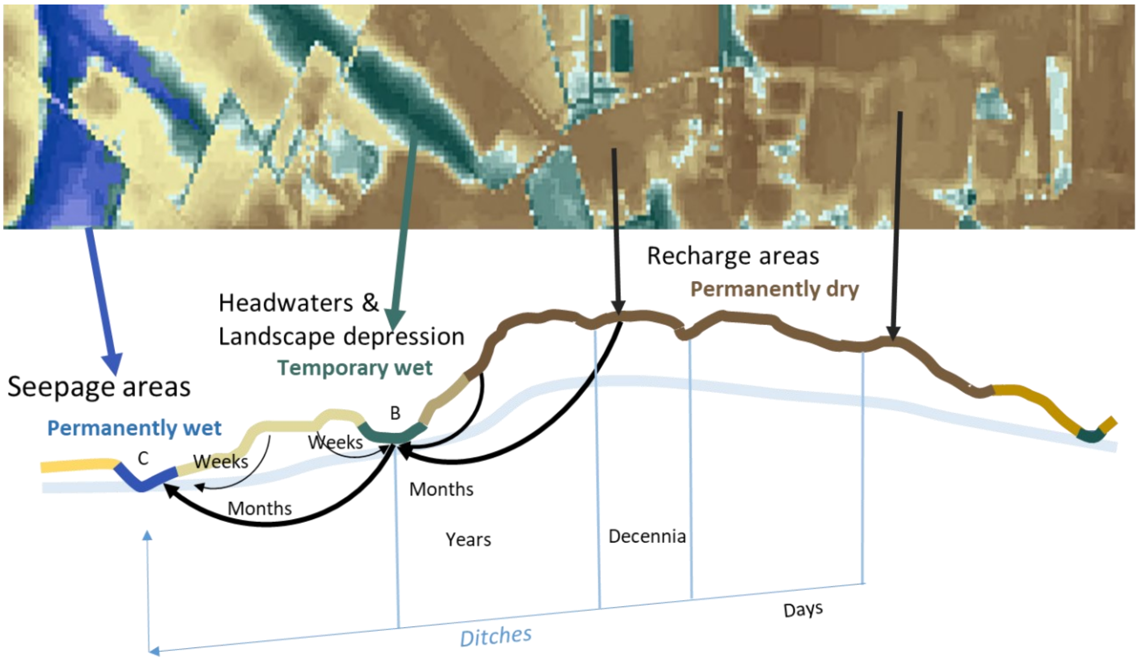
Figure 16: Here you can see part of the landscape with a high occurrence of wet-dry gradients. The Kootwijkerzand is a "shifting sand" area in the Dutch province of Gelderland. It is the largest shifting sand area in Western Europe. The nature reserve covers 700 hectares and is located in the western part of the Veluwe.

5 Using the Water System Maps to prioritise EbA measures

The water system maps is topography based and consists of three separate non-overlapping layers. We distinguish permanently dry recharge areas, temporary wet headwater wetlands (including upstream landscape depressions) and permanently wet seepage zones. Evidently, the water system maps needs to be interpreted differently for each catchment. Each catchment has a unique interplay of topography, geology and soil. There are many different types of catchments across the 2 Seas region, including those with free draining chalk soils and karst hydrogeology, low-lying polder catchments, steep mountainous catchments with shallow soils, etc. Within the PROWATER project we have interpreted the water system maps within the catchments of our investment sites. Based on these experiences we can illustrate how the water system maps can be used to prioritise specific locations in the landscape for implementation of specific EbA measures. In Belgium and the Netherlands, the water system maps have been applied on sandy, groundwater dominated catchments. In the UK, there have been more varied experiences, ranging from heavy clay soils to highly permeable chalk soils. Yet, the water systems maps depicted geomorphological features in an amazingly accurate manner.

Below, we describe the principles for a catchment with sandy soils and considerable soil depth. For such catchments groundwater will play a determining role in the catchment's hydrology. For catchments with a limited soil depth or heavy soils, groundwater will not play a significant role. Although the general principles remain the same, these catchment will have a more surface water dominated hydrology. In general we need actions to reduce runoff, slow down water flows upstream and provide storage capacity in the valleys. But to achieve this, different actions are needed. We have explicitly chosen, not to combine the water system maps with European soil data as these datasets are too coarse and often have a low thematic accuracy. There is much more accurate national soil data available for the countries within the 2 SEAS area. We encourage planners and water managers to use this local data in combination with the water system maps.

<u>We distinguish the following zones on the water system map:</u>



Topographically elevated, permanently dry soils with a deep groundwater level offer opportunities for building up groundwater reserves to bridge dry years. These zones are marked in dark brown on the water system map.

At the other extreme are the **low lying, permanently wet zones**, where groundwater seepage takes place. These zones are marked in dark blue. In such zones, peat soils develop and can act as a natural sponge. The rewetting of such zones provides a buffer, which means that the feed of watercourses fluctuates less.

In addition, we have areas that are **temporarily wet**, marked in green. These are **natural depressions in the landscape** that are situated on elevated parts of the landscape. Also lower parts of slopes and headwater streams are identified. Such systems receive a supply of runoff water and shallow soil water that collects and moves on less permeable soil layers. Due to their relatively small catchment area and topographic location, these areas are naturally characterised by **high water level fluctuation.** Most of these landscape depressions were already reclaimed and drained centuries ago. Hand-dug canals connect them directly to the network of watercourses. Such landscape depressions have the potential to fulfil their role as natural water reservoirs again. A number of recent scientific publications pay specific attention to the regulating functions of wetlands that are not hydrologically connected to the river network (Evenson, 2018; Golden, 2017; Rajib, 2020). These are pre-eminently zones where, by installing weirs, additional buffering and groundwater recharge can be achieved.

The **yellow zones are transitional areas between wet and dry**. The groundwater is naturally fairly shallow here. The yellow zones adjacent to the blue areas are of less importance for groundwater recharge. For each measure, the impact on the adjacent blue zone must also be considered. If adjacent blue zones are drained, the impact of measures on water availability is rather limited. Water that is infiltrated there will only be on its way to the watercourse for a few weeks. Obviously, measures that limit runoff will also contribute to limiting water problems here.

5.1 Interpretation of the water system map for **groundwater dominated catchments**.

In the 2 Seas region many areas rely on groundwater sources to supply water for human use and industrial processes. As weather patterns are predicted to become increasingly unpredictable it is crucial that our hydrological catchments are resilient, ensuring that there is enough water for people and nature to thrive. One way to achieve this resilience is to protect and restore the natural water infiltration and retention capacity of catchment landscapes.

Groundwater dominated hydrological systems have light soil texture (sandy soils) and absence of shallow impermeable layers. Groundwater levels typically show smooth trends with a lag in the response to rainfall patterns as the response is dictated by the time it takes water to infiltrate through the soil. Nonetheless, these catchments are equally vulnerable to droughts, especially when winter precipitation has been insufficient.

Groundwater dominated catchment are naturally more resilient to droughts if infiltration is not impeded through anthropogenic effects such as surface sealing, excessive and fast drainage and soil compaction. When the surface of the land is altered in a way that affects the natural movement of water down to groundwater these catchments can be very vulnerable to droughts. There are key principles that can be applied to decrease the drought vulnerability of groundwater dominated catchments.

5.1.1 What to do in dark brown zones?

Avoid afforestation, especially with species that have a dense canopy cover.

During the 19th century, large areas of mixed deciduous forest in Western Europe were converted to productive coniferous forest plantations (Verstraeten 2013). This has had serious impact on the water balance of the landscape. Changes in forest cover affects water yield, runoff, infiltration and evaporation and therefore groundwater recharge (Allen and Chapman 2001). Several studies prove in general that coniferous trees consume more water than deciduous trees. This can be attributed to higher evaporation and interception compared to deciduous hardwoods (e.g. Adane et al. 2018; Brown et al. 2005; Dams et al. 2008; Filoso et al. 2017; Nisbet 2005). Interception is the amount of rainfall that is intercepted, stored and subsequently evaporated by all parts of vegetation. Interception leads to losses, but also a more gradual infiltration because extreme precipitation is partly stored in the canopy an slowly released as throughfall. Converting existing (plantation) forests on dark brown zones to more open vegetation types, can increase groundwater recharge and reduce drought sensitivity.

Avoid and remediate soil sealing.

Although this is not strictly and EbA solution, it is of high importance to restore infiltration in urban areas, especially in the dark brown zones. While permeable paving allows a certain level of infiltration, it is vulnerable to clogging and infiltration rates may be insufficient to deal with extreme precipitation events. Systems that collect, store and infiltrate runoff will become increasingly important. When designed as EbA measure, they can evidently deliver a lot of services.

Avoid soil degradation and remediate existing soil degradation.

Soil compaction and soil erosion are considered as two most costly and serious environmental problems caused by conventional agriculture (FAO 2003). These two processes creates excessive runoff and reduces infiltration. Soil compaction is the increase of bulk density or decrease in porosity of soil due to externally or internally applied loads, often caused by agricultural machinery, grazing of livestock, timber harvesting and industrial activities (Batey 2009; Hamza et al. 2011; Troldborg et al. 2013).

Agricultural management is decisive for soil health. Intensive tillage, combined with low inputs of organic matter will result in soils that have reduced permeability, even on sandy soils. Soils with a low soil organic matter (SOM) content are poor in forming soil aggregates that ensure a certain soil porosity. Low SOM also decreases the amount of water that can be stored within the soil. Ecosystem-based Adaptation measures, such as non-reversing tillage, compost amendments, catch crops, cover crops and crop residues, can be implemented to restore and protect soil health.

Much attention is given to soil quality without addressing the problem of (deep) soil compaction. Deep soil compaction predominantly occurs when wet soils are trafficked. Soil compaction causes a decrease in large pores (called macropores), resulting in a reduced permeability to water and air, much lower water infiltration rate into soil, increased surface runoff, erosion, reduced groundwater recharge, as well as a decrease in saturated hydraulic conductivity. Compaction can adversely affect nearly all physical, chemical and biological properties and functions of soil. Vegetation suffers from restricted rooting depth, reduction in nutrient uptake and the formation of waterlogged or anoxic zones, which can lead to denitrification and slow nitrification (Batey 2009; Cui et al. 2010).

In the past, soil compaction on sandy soils was not considered problematic for agriculture. In recent years it has become apparent that soil compaction contributes to floods and droughts and that it also impacts agricultural production. Over the past decades, agricultural machines have become larger and heavier, compressing soil to considerable depth. Tillage loosens the shallow soil up to 30 cm depth, but leaves the compacted layer untouched. With climate change, precipitation becomes concentrated in time. As water percolates through the soil it encounters this compacted, slowly permeable layer. During wet periods, the water accumulates on the compacted layer and saturates the soil with water. When farmers decide to harvest during these wet conditions, the smallest soil particles get suspended and deposit on the compacted layer, further reducing soil permeability. On sloping parcels, subsurface run-off may result in prolonged wet spots on agricultural fields. These zones are most suitable to install permanent infiltration zones. Deep soil decompaction may transform these problematic zones to groundwater recharge hotspots. Mechanical decompaction may be needed, but also deep rooting trees can penetrate compacted layers. Adding large amounts of coarse organic matter and growing deep rooting crops help to preserve soil permeability.

In contrast to clay-loam soils, sandy soils do not recover easily from compaction. Clay-loam soils have shrink-swell properties which allows them to partly recover from compaction.

Compartmentalize all ditches to retain and infiltrate runoff from extreme precipitation events. Restore hedgerows along ditches to promote infiltration.

Many landscapes are veined with ditches (and hedgerows). Hedgerows and/or ditches demarcated land property. Over time, hedgerows disappeared and ditches became deeper and needed to evacuate increasingly more water due to soil sealing and soil compaction. Today, we need to slow down water and avoid that runoff is leaving the infiltration zones. Many ditches in infiltration zones have a poor permeability.

Wide shallow vegetated infiltration swales are more effective than the deep narrow ditches. In ditches, fine particles that eroded from the fields will silt up the bottom of the ditch. Studies show that even high sediment deposition rates do not pose a problem for infiltration capacity, as long as it can remain vegetated. The vegetation provides a better spread of sedimentation and the grass roots create macropores in the soil (Ahmed, Gulliver and Nieber, 2015). In narrow deep ditches vegetation development is not possible due to a poor light climate. The siltation will then cause further stagnation and vegetation die-off. Vegetation is crucial to maintain adequate infiltration rates.

Especially the combination of ditches and hedgerows is a perfect combination, because the input of organic matter and associated soil macro-fauna results in a large quantity of macro-pores. The roots of the hedgerows and rodent activity further boosts the infiltration capacity. In the past ditches and hedgerows used to be a perfect match. Agriculture and hedgerows apparently developed together, and today coexist over about 10% of our planet's land surface. The primary role of hedgerows was to demarcate land property and to confine/exclude of livestock from certain part of the land. Over time, hedgerows came to be highly valued features of the rural landscape and economy, especially for smaller landholders and the landless, providing fuel and wood, food and medicine, and providing additional fodder for livestock, together with shelter for the latter in winter and shade in summer. We now need to revitalise the use of hedgerows to increase recharge.

Ditches along roadsides should also be compartmentalized in the yellow-brown infiltration areas. The degree of compartmentalization depends on the slope of the canal. In any case, more compartments should be provided when the water system map shows a gradient from brown to yellow to green. It also applies here that an overflow profile will buffer more than a pinch profile since the latter still provides an admittedly delayed drainage.

5.1.2 What to do in green zones?

Identify and restore the hydrological functioning of temporary wetlands: landscape depressions and headwater wetlands.

Temporary wetlands are depicted on the water system map by green-blue colours. These zones receive strictly local water flows from less than 1 km distance. This means their hydrology responds quickly to precipitation surplus or deficit. Such temporary wetlands have been poorly protected as they are often relatively small (< 1 ha), are not permanently waterlogged and therefore fall outside the remit of most wetland inventories and associated conservation programmes.

There is growing evidence that such small scale wetlands play a disproportionally large role in regulating hydrology (Bertassello et al. 2018; Colvin et al. 2019). A number of recent papers specifically focus on the flow regulating functions of wetlands that are not hydrologically connected to the river network. Different terminology is used in the literature to refer to such wetlands, namely “depressional wetlands” (Evenson et al. 2018), “non-floodplain wetlands” (Jones et al. 2019; Lane et al. 2018) or “geographically isolated wetlands” (Cohen et al. 2016; Evenson et al. 2016; Rains et al. 2016). Large parts of Europe, especially in regions with sandy soils, are covered with numerous small-scale landscape depressions. These landscape depressions were formed by strong winds during the last ice-age. Due to their topographical position, these areas are naturally characterized by a high fluctuation in water levels (hydroperiod with short lag time, high frequency, low amplitude). This creates possibilities for deferred infiltration, which recharges groundwater reserves and increases base flow during subsequent periods of drought (Lee et al. 2018). Available studies show that the actual groundwater recharge by wetlands depends on the interplay of buffer volume, retention time and hydraulic conductivity of the subsoil.

Although their importance is now recognised, small scale temporary wetlands have long been viewed as problematic in terms of agricultural production and, consequently, have been subject to land drainage or infilling (Acreman and McCartney 2009).

Their restoration could provide opportunities to reduce floods and droughts as they are designed by nature to buffer hydrological extremes. They can accommodate large quantities of run-off, generated by compacted soils and paved surfaces. If we do not drain these zones, delayed infiltration would take place when the groundwater levels naturally drop during spring.

Blocking the drainage of green zones is obviously the most effective way to restore their hydrological functioning. Where such drastic changes are not possible due existing land use (planning) and land cover, it may be possible to partly restore their infiltration capacity by installing controllable weirs on the drainage ditches. These allow drainage blocking during times of the year where the land can be rewetted without conflicting with other activities in the green zones.

The extent to which increased water retention (and delayed infiltration) can be combined with agriculture depends on the morphology of the landscape depression. How do changes in water levels increase the area under water logged conditions? Also, the hydro-period of the groundwater will determine whether the increased water retention will result in (delayed) groundwater recharge (i.e. when groundwater levels drop later in spring, the retained water will eventually infiltrate). To do so, groundwater levels need to drop fast enough in spring. Benefits resulting from increased water retention in green zones are limited when most of the retained water is eventually drained away to the river network.

5.1.3 What to do in (dark) blue zones?

The waters system map depicts zones that are fed by permanent groundwater seepage as (dark) blue areas. Under natural conditions, these zones have permanently wet conditions and would develop as wetlands with peat formation. But most often, these valley systems are (partly) in agricultural use and heavily drained.

Rewetting drained areas allows to create extra water storage. From a drought mitigation perspective it is more effective to restore upstream wetlands than downstream wetlands. Although the water system map does not provide information on the upstream-downstream aspect of the permanent wetlands, it can be easily derived through visual interpretation.

Upstream valley wetlands are usually more narrow valleys with more intense seepage. These can act as sponges and can the retained water can provide base flow during drought periods.

More downstream, valleys become wider and flatter floodplains. Intense seepage still occurs on the valley edges and the most low-lying parts of the valley. Usually, the downstream valley wetlands are more dependent on surface water and are flooded regularly. The flood waters deposit sediments and nutrients. Consequently, floodplain wetlands have more productive vegetation and evaporate large amounts of water during periods of drought.

Evidently rewetting **downstream floodplain wetlands** is useful for many reasons. But from the perspective of drought risk reduction, it is more effective to rewet upstream wetlands.

Important measures are to decrease the drainage basis of both the drainage network and the main river channel. In the past, a lot of streams have been straightened to improve drainage and parcel layout for agriculture. This river normalisation has reduced flow friction, increased the hydrological connectivity and accordingly aggravated downstream flood frequency and magnitude. River re-meandering and floodplain restoration does not only alleviate downstream floods, but also has the potential to store a lot of water in the peaty subsoil. This is even more important when groundwater abstractions are present. Many abstractions from rivers and groundwater take place in the more downstream valleys. Decreasing the drainage basis often requires restoring the river morphology. Through re-meandering, more in-stream water storage is created. It also results in a more gradual river bed slope along the floodplain.

5.2 Interpretation of the water system map for **runoff dominated catchments**.

Catchments with heavy soils and/or the presence of impermeable layers in the subsoil are quite different from groundwater dominated catchments. Heavy soils are less drought vulnerable as they have a much higher water holding capacity than sandy soils. The risk of agricultural droughts is therefore lower, while the risk for hydrological droughts is higher. The river flow often closely mirrors the amount of recent rainfall. There is a very limited and slow infiltration. Depending on the geology, there may be local zones with seepage.

In the 2 Seas region, including regions in the Netherlands, Belgium (Flanders), England and France, many areas rely on surface water to supply water for human use and industrial processes. Because of the impermeable layers in the subsoil, surface water storage in downstream locations has a high potential for positive impact on water supply. These locations are sometimes artificially enhanced to store water, including building water reservoirs through the construction of dams. As weather patterns are predicted to become increasingly unpredictable it is crucial that these catchments control the amount of runoff. High runoff also generates flows of sediments and nutrients to these reservoirs. Sediments fill up reservoirs, decreasing their capacity and nutrient inputs lead to poor water quality and greenhouse gas emissions. Therefore, it is equally important to slow down water flows and maximise water storage capacity of the landscape. Yet, the principles are slightly different than for groundwater dominated catchments.

5.2.1 What to do in dark brown zones?

Promote afforestation, especially on sloping areas.

Afforestation of sloping areas with heavy, erosion sensitive soils is a very good strategy to reduce peak flows and soil erosion. High quantities of organic matter increase the soil water storage capacity and infiltration rate. The volume of organic matter accommodates space for water in the soil matrix. Roots extract water from the soil but at the same time the stem-root system increases soil permeability and infiltration capacity. In addition, the canopy interception allows a more gradual infiltration and storage because extreme precipitation is partly stored in the canopy an slowly released as throughfall. So for catchments with **heavy** soils, we promote the opposite compared to catchments with sandy soils. Deep rooting trees species with dense canopies and high litter production will result in more water storage in the subsoil and consequently a more gradual release of that water to the river network.

Avoid and remediate soil sealing.

Soil sealing is also a problem for runoff dominated catchments. Although the heavier soil types are considered to have a low infiltration rate and low water storage, this can be artificially enhanced in urban areas by planting vegetation and adding organic matter. This will enhance soil macrofauna, which is by nature much more abundant in such soil types. Rooftop runoff can be stored in tanks and reservoirs, re-used where possible and eventually slowly released.

Avoid soil degradation and remediate existing soil degradation.

Also here soil compaction and soil erosion are considered as problematic. Increasing soil organic carbon in the topsoil and leaving the soil covered with vegetation is crucial to avoid high runoff and by consequence erosion. Attention for soil health is no different than for sandy soils. As explained earlier, heavy soils have shrink-swell properties which allows them to partly recover from compaction. During dry phases, heavy soils shrink and develop cracking of the soils. In subsequent rainfall events, water infiltration occurs preferentially down these cracks until swelling causes the cracks to seal up again. This pattern especially develops in undisturbed soils. No till management can preserve these preferential flow mechanisms much better than tilled soils.

Avoid runoff water to enter preferential flow paths as this may lead to gully erosion. In addition to measures that improve soil permeability and water storage capacity, contour ploughing may also help to avoid erosion. At the bottom of parcels, swales (i.e. marshy depressions) can be installed along the contour lines to capture, buffer and infiltrate run-off water. Planting hedgerows, especially those along contour lines, is also a good strategy. Hedgerows increase soil organic matter and have highly permeable soils, even on heavy soils. The activity of rodents and other soil macro-fauna increases the capability to buffer high quantifies of runoff water.

Compartmentalize all ditches to retain runoff from extreme precipitation events. Restore hedgerows along ditches to promote infiltration.

In essence, the same principles are valid, but the focus is on storage capacity, rather than recharge. The placement of sills or weirs in the ditches helps to retain and slow down water flows. The placement of small dams at key locations with an overflow system can be used to fill water retention ponds.

5.2.2 What to do in green zones?

Identify and restore the hydrological functioning of temporary wetlands: landscape depressions and headwater wetlands.

For runoff dominated catchments, the green colour depicts zones where run-off may converge. These can be landscape depressions, although such landforms are rather exceptional for loamy/clay soils. Most often the green colour shows so-called dry valleys where water flows following heavy precipitation events. Ideally, such dry valleys have permanent, deep rooting vegetation to slow down these water flows. If needed, such dry valleys can be equipped with leaky dams that slow down water flows and allow sediments to deposit.

An effective way to reduce water flow and increase water availability is the use of contour channels. Water is retained by small dams and excess water is diverted to irrigation channels that run along the contour lines. To stabilize the contour channels and increase soil water storage, hedgerows are planted on the downhill side of the contour channel. This may provide irrigation water to fields following short extreme precipitation events.

5.2.3 What to do in (dark) blue zones?

The waters system map depicts the streams and their valleys in the (dark) blue zones. There may be some seepage and peat formation present, but most of the floodplains are largely surface water dominated in heavy soil catchments. The water system maps successfully identifies historic patterns characteristic to floodplain morphology, such as old meanders which are hardly visible with the bare eye today. These historic patterns show opportunities to restore the floodplain morphology. Creating meanders and multi-channels system in the floodplains, slow down water flows in a natural manner and provide opportunities for peat formation. In addition, the topographical variation provides opportunities for biodiversity to survive increasingly extreme water level fluctuation.

6 Conclusion

The water system map will show which location and measure-combinations have the greatest potential to strengthen raw water availability. We focus on replenishing and retaining shallow soil water. The more and the longer we can retain that soil water, the more likely it is to become effective groundwater. The water system map shows the natural potential for this in the landscape. Even when soil water stagnates in less permeable layers and does not replenish the groundwater reserves, this soil water remains important to limit the impact of droughts. We are building, as it were, a much larger natural water reserve. The water system map shows exactly where measures have the greatest impact, and allows a targeted policy to be rolled out.

The water system map is not a groundwater model. The important difference with groundwater models is that we focus on the behaviour of the (very) shallow soil water and analyse this at a local scale level. The water system map is topography-based and does not take into account soil characteristics and/or the presence of impermeable layers. It also does not take into account all kinds of interventions that strongly influence the hydrology of ground and surface water, such as infrastructure, dikes, soil sealing, surface/groundwater abstractions, dewatering and drainage, etc. So the zones indicated as temporarily wet or permanently wet can in practice be influenced by such interventions.

The strength of the map is that it mainly shows the natural potential for retention and infiltration. The water system map gives a picture of the potentially natural situation. The map is intended for visioning purposes. Where possible these natural potentials for infiltration and retention can be taken into account.

The purpose of the water system map is not to make a quantitative assessment of the current state, but rather to inspire and make use of the natural potentials where possible. When plans and interventions are systematically in line with these potentials, the functioning of the water system can be optimally restored. Even in areas where there can be no groundwater recharge due to the presence of impermeable layers, it is desirable to infiltrate and retain soil water locally. The principles of the water system map also remain valid here.

Because the layout of the water system map always uses a relative position within a certain sphere of influence, the final result is also always adapted to a certain region. In relatively flat areas, small elevations in the landscape will be designated as important infiltration areas. In more hilly areas, these will be the land ridges.

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