Integrated approach for the **d**evelopment across **E**urope of user oriented **c**limate **i**ndicators for GFCS high-priority **s**ectors: Agriculture, disaster risk reduction, energy, health, water and tourism

Work Package 6

Deliverable 6.4

Present and future potential groundwater recharge at European scale

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Introduction

Groundwater recharge can be defined as the downward flow of water through the unsaturated zone to the water table, increasing the quantity of water stored in the aquifer formation (Vries and Simmers, 2002). In other words, it is the proportion of rainfall that infiltrates and replenishes the groundwater reservoir. It depends not only on the meteorological context, but also on geomorphological characteristics (slope, hydraulic roughness, etc.), the surface of the catchment area, soil properties (vegetation, soil type, available water capacity), and the hydrodynamic properties of the subsurface formations.

Many methods to estimate groundwater recharge are described in the literature (e.g. Scanlon et al., 2002). They vary depending on both the time scale (from a daily step to a yearly step) and the type of data used (meteorological or hydrologic). According to the type of data used and the way recharge is computed, these methods deal with different types of recharge (direct recharge only or total recharge including indirect recharge). Nonetheless, only some of the existing recharge estimation methods allow mapping groundwater recharge at aquifer, regional or multinational scale.

We evaluated groundwater potential recharge from effective precipitation infiltration, as this method allows to work at different scales, from watersheds to countries. Moreover, this is the only approach that can be applied both with historical meteorological data to evaluate past and current recharge, and with climate projections to predict groundwater recharge future trends.

Water budget methods to evaluate effective precipitation

At the aquifer scale, effective precipitation, defined as the sum of runoff and infiltration, is equal to total precipitation minus actual evapotranspiration and storage variations (in soil and aquifer). The water bugdet methods considers that in the water cycle, the soil acts as a reservoir caracterized by its water storage capacity (Soil Water Storage capacity).

The Thornthwaite model (1948) considers that water in soil is instantly available for evapotranspiration and that effective precipitation can be produced only when the SWS reaches its maximum capacity.

- if P > PET, (P-PET) first replenishes the water in the soil reservoir and then recharges the aquifer.
- if P < PET, the difference between PET and P is drawn from the soil until the soil storage capacity is depleted.

Successive improvements to Thornthwaite's equation have been proposed to introduce a progressive emptying of soil water reserves. Dingman (2002) has introduced an exponential decrease of the soil water storage when precipitation are less that PET. Edijatno&Michel (1989) prefered a quadratic law, which is also apply to distribute the positive difference between precipitation and evapotranspiration between effective rainfall and soil storage.

The mathematical translation of these water budget methods are presented in Figure 1.

	Thornthwaite	Dingman	Edijatno&Michel
P < ETP	• $SWS_k = max\ (0\ ; SWS_{k-1} + P_k - PET_k)$ • $CET_k = min\ (PET_k\ ; SWS_{k-1} + P_k)$ • $EffP_k = 0$	• $SWS_k = SWS_{k-1} * exp[-(PET_k - P_k) / SWSmax]$ • $CET_k = P_k + SWS_{k-1} - SWS_k$ • $EffP_k = 0$	• $dSWS = [\ (SWS/SWSmax)^2 - 2 * SWS/SWSmax\ ] * dE_n$ • $dETC = - dSWS$ • $EffP = 0$
P > PET	• $SWS_k = min\ (SWSmax\ ; SWS_{k-1} + P_k - PET_k)$ • $CET_k = PET_k$ • $EffP_k = max\ (0\ ; SWS_k + P_k - PET_k - SWSmax)$	• $SWS_k = min\ (SWSmax\ ; SWS_{k-1} + P_k - PET_k)$ • $CET_k = PET_k$ • $EffP_k = max\ (0\ ; SWS_k + P_k - PET_k - SWSmax)$	• $dSWS = [\ 1 - (SWS/SWSmax)^2\ ] * dP_n$ • $CET = PET$ • $dEffP = (SWS/SWSmax)^2 * dP_n$

Figure 1: Mathematical desription of the three water budget methods with: P=total precipitation, PET=potential evapotranspiration, CET=calculated actual evapotranspiration, SWS=soil water storage, SWSmax=soil water storage maximum capacity, EffP=effective precipitation.

Crop coefficient (Kc)

The potential evapotranspiration data supplied by meteorological centers are computed from weather data, oftenly by applying a formula derived from that of Penman-Monteith which requires solar radiation, air temperature, humidity and wind speed data. Several simplified formulations can be found in litterature to calculate potential evapotranspiration everywhere on Earth according to latitude and only temperature records (e.g. Hamon, 1963, Hargreaves, 1985 or Oudin, 2005).

This potential evapotranspiration corresponds to the evapotranspiration rate from a hypothetical grass reference crop, not short of water. It is called reference evapotranspiration (ETo) by agronomists. To assess the evapotranspiration from crops, one should consider the crop type, variety and development stage (Allen et al., 1998). This can be done through the crop coefficient (Kc) approach, which assumes that PET = Kc*ETo with K_c variying during the growing period (Nistor & Porumb, 2015).

For temperate climate, the growing curve can be described by 4 seasonnal Kc: Kc_ini for initial season (March, April and May), Kc_mid for mid-season (June, July and August), Kc_end for the end of crop season (September and October), and Kc_cold with no vegetation growing (November, December, January and February).

Infiltration ratio

The Effective Precipitation Infiltration Ratio (EPIR) allows distributing effective precipitation between runoff and infiltration. Infiltration flow correponds to potential groundwater recharge. It may be different from the actual water table recharge as apart of infiltrated water could contribute to sub-surface flows which rapidly meet rivers.

Methods

The methodology applied to assess the potential groundwater recharge at the european scale combines a water budget approach and the use of an Effective Precipitation Infiltration Ratio (EPIR):

Recharge = EPIR * Effective Precipitation

It is applied to evaluate both present and future groundwater recharge.

Meteorological data

Meteorological data that are used to calculate effective precipitation are the E-OBS daily gridded observational dataset (Cornes et al., 2018). Daily cumulated precipitation and mean temperature are available over the geographical extent of Europe. The v21.0 dataset includes data from 01/01/1950 to last month. As agreed at the beginning of INDECIS project, we worked with the 0.25° resolution mesh.

As only total precipitation data were available in the choosen dataset, snowfall was taken into account by applying a melting coefficient, which vary linearly betwwen 0 and 1 when temperature varies between 0°C and 6°C (Dingman, 2002).

The potential evapotranspiration daily data at the 0.25° spatial resolution were computed by CSIC/IPE INDECIS project partner for the 1950 – 2017 period according to the Penman-Monteith formula. As it requires atmospheric temperature, humidity, net radiation and wind speed data, ERA5 reanalysis dataset had to be used to complement the E-OBS observational dataset.

In order to illustrate these data, inter-annual averages on the 1981-2010 30-years reference period are presented on Figure 2.

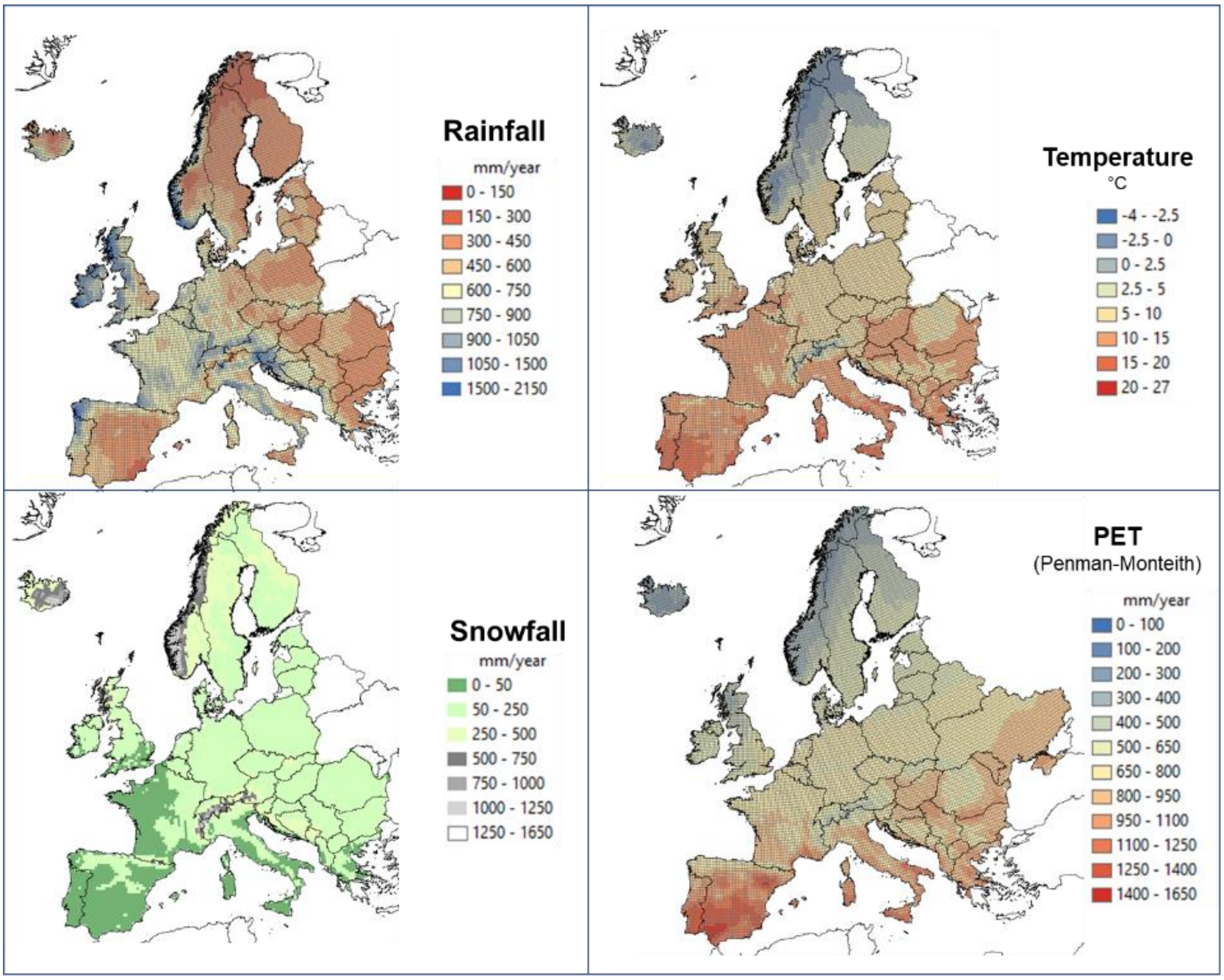


Figure 2: Meteorological data used for effective precipitation calculation (1981 – 2010 inter-annual mean)

Climate projections data

Climate projections dataset was taken from the EURO-CORDEX initiative which has produced ensemble climate simulations based on several downscaling models forced by multiple global climate models from the CMIP5 project (see for example Jacob et al., 2020). The spatial resolution of the data is 0.44 degree (~50 km over Europe). We considered two greenhouse gas emission scenarios corresponding to stabilization of radiative forcing after the 21st century at 4,5 W/m² (RCP4.5) and rising radiative forcing crossing 8,5 W/m² at the end of 21st century (RCP8.5). Long-term projections are available at a daily-time step up to 2100.

Future projections presented in this report rely on the result of 6 different Global Circulation Models (GCM) all downscaled with the same Regional Circulation Model (RCM). Details on the used GCMs and RCM are provided into the table of Figure 3.

GCM : General Circulation Model			
	France	IPSL: Institut Pierre-Simon Laplace	IPSL-CM5A-MR
	Canada	CCMa: Canadian Centre for Climate Modelling and Analysis	CanESM2
	France	CNRM: Centre National de Recherches Météorologiques	CNRM-CM5
	Australia	CSIRO: Commonwealth Scientific and Industrial Research Organisation	Mk3-6-0
	Norway	NCC: Norwegian Climate Centre	NorESM1-M
	USA	NOAA GFDL: Geophysical Fluid Dynamics Lab	GFDL-ESM2M
RCM : Regional Ciculation Model			
	Sweden	SMHI : Swedish Meteorological and Hydrological Institute	RCA4

Figure 3: GCM and RCM used for climatic projection datasets

The projections were choosen considering the simulated climatic variables which were available on the EURO-CORDEX dataservers, especially to calculate the evapotranspiration.

These daily data were projected on a 0.25° mesh and debiaised with respect to the E-OBS observational data over the historical period (1986-2005) using the Empirical Quantile Mapping proposed in the Climate4R package (Iturbide et al., 2019) provided by the *Santander Meteorology Group*.

Using these corrected datasets, the daily potential evapotranspiration was produced for each cell of the 0.25° mesh applying the Penman-Monteith formula (FAO, Allen et al. 1998). Then daily effective precipitation could be calculated on the 0.25° mesh over the 1979 – 2100 period for each of the six selected GCM/RCM pairs.

Effective precipitation calculation

PeffDayGRID, a Matlab© application was developed by BRGM to compute the effective precipitation at a daily time step on any area provided that meteorological data and parameters are available on a regular mesh. It includes three water budget methods, which vary by the way they calculate actual evapotranspiration and soil water storage: Thornthwaite (1948), Dingman (2008) and Edijatno & Michel (1989). This latter method has been implemented in several rainfall-runoff models (e.g. GR4J from Perrin et al., 2003 or GARDENIA from Thiery, 2014). Considering that the best evaluation of the effective precipitation is the average of the three methods, the range of the three results allowing to estimate the uncertainty associated to the parametrization of the water budget method.

To calculate effective precipitation, the PeffDayGRID application uses meteorological daily data (at least total precipitation and temperature) for each cell of a given mesh, and only one gridded parameter: the soil water storage capacity. The resulting time series are provided with the same spatial resolution as the initial data (Figure 4).

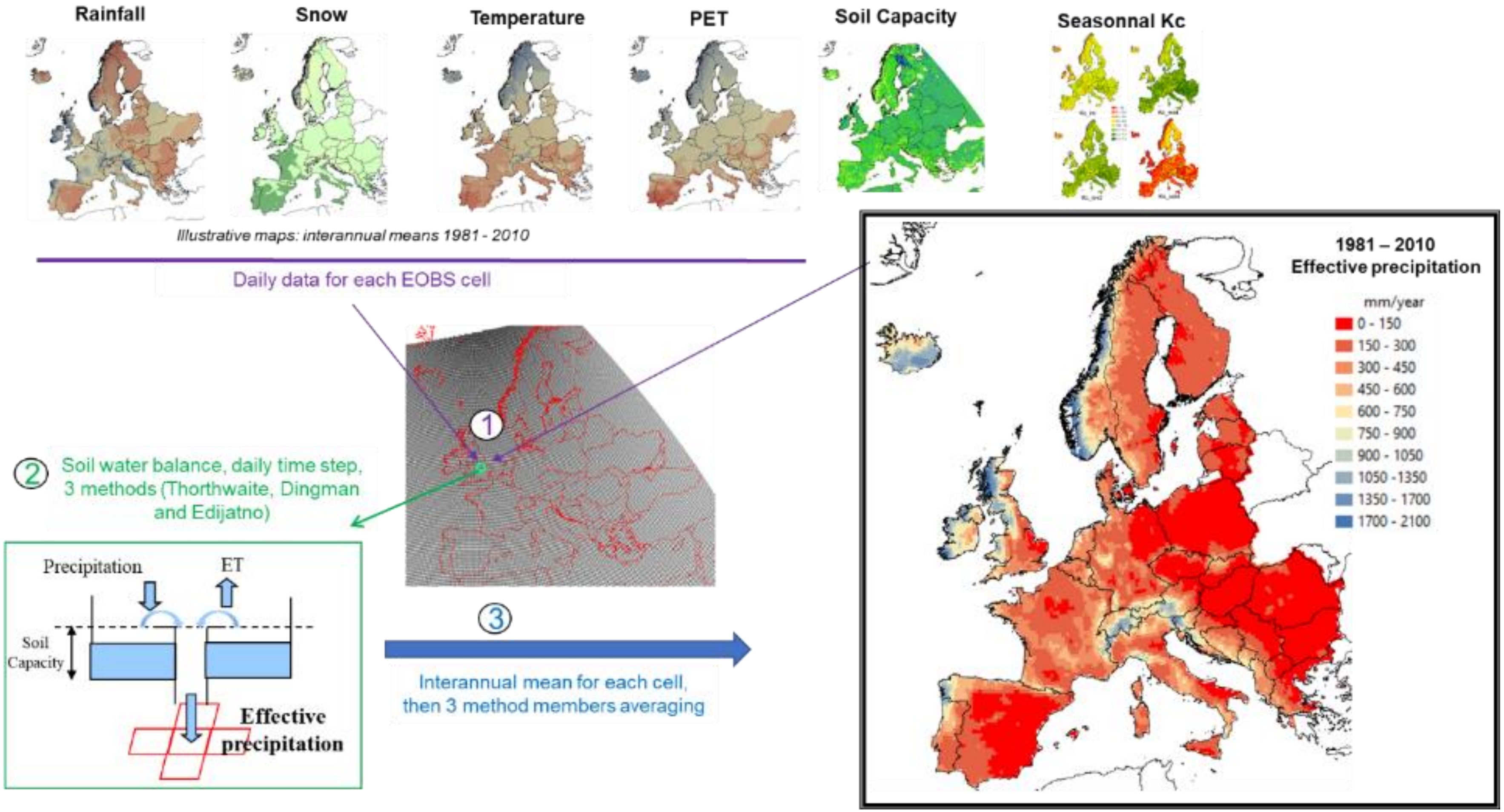


Figure 4: Sketch of the methodology applied to compute effective precipitation at the European scale.

Soil Water Storage capacity (SWS)

A number of layers describing soil properties at continental scale are available on the European Soil Data Centre website (https://esdac.jrc.ec.europa.eu/). They were created based on data from the European Soil Database in combination with data from the Harmonized World Soil Database (HWSD) and Soil-Terrain Database (SOTER). Pedo-Transfer Rules (PTRs) can be used to derive estimates of additional parameter such as the Total Available Water Capacity (TAWC). TAWC was calculated from the difference between the water content at field capacity and permanent wilting point (determined following the Van Genuchten equation, 1980), the coarse fragments ratio and the depth of soil (Hiederer, 2013).

We downloaded the topsoil and subsoil TAWC from PTRs at Soil Mapping Unit resolution and projected the sum on the 0.25° mesh. The mean value for each cell is calculated to provide the final dataset of Soil Water Storage capacity needed to apply water budget models (Figure 5).

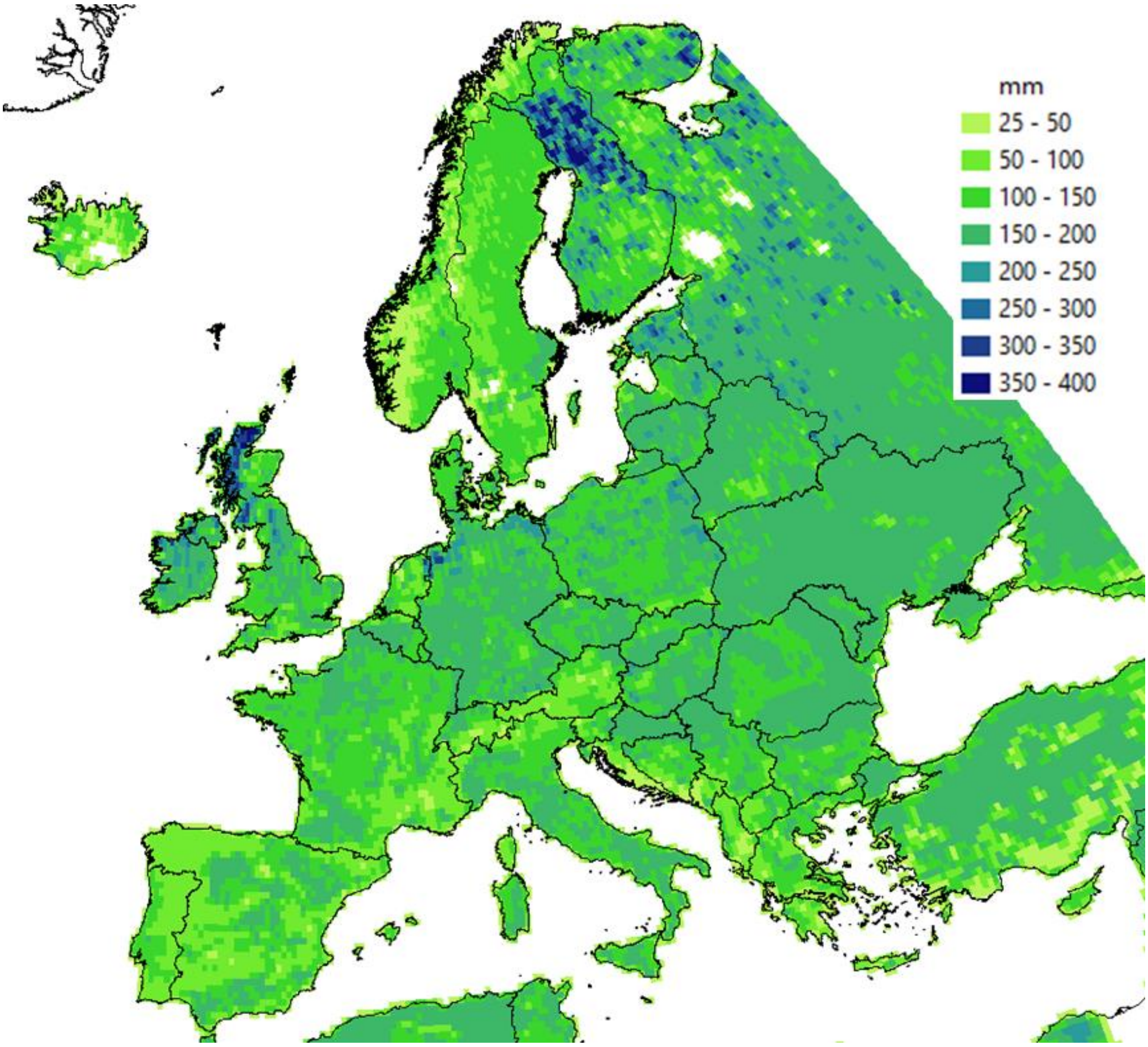


Figure 5: Soil Water Storage capacity map (0.25° mesh).

Seasonnal Kc maps

In order to account for land cover in the estimation of effective precipitation, seasonnal crop coefficients are needed for each cell of the calculation mesh to convert PET climatic daily data into crop evapotranspiration daily data.

Corine Land Cover (CLC) datasets provide consistent and thematically detailed information on land cover across Europe (https://land.copernicus.eu/pan-european/corine-land-cover/clc2018). In order to spatialize crop coefficients for large areas, Nistor et al. (2018) associated to each of the 44 Corine Land Cover classes in Europe a set of 4 seasonnal Kc, relying on FAO tables (Allen et al. 1998). We thus constructed each seasonnal Kc map at the CLC2018 resolution (100 meters) and then projected them on the EOBS mesh (0.25°) to calculate the mean value for each cell. The four resulting maps are presented on Figure 6.

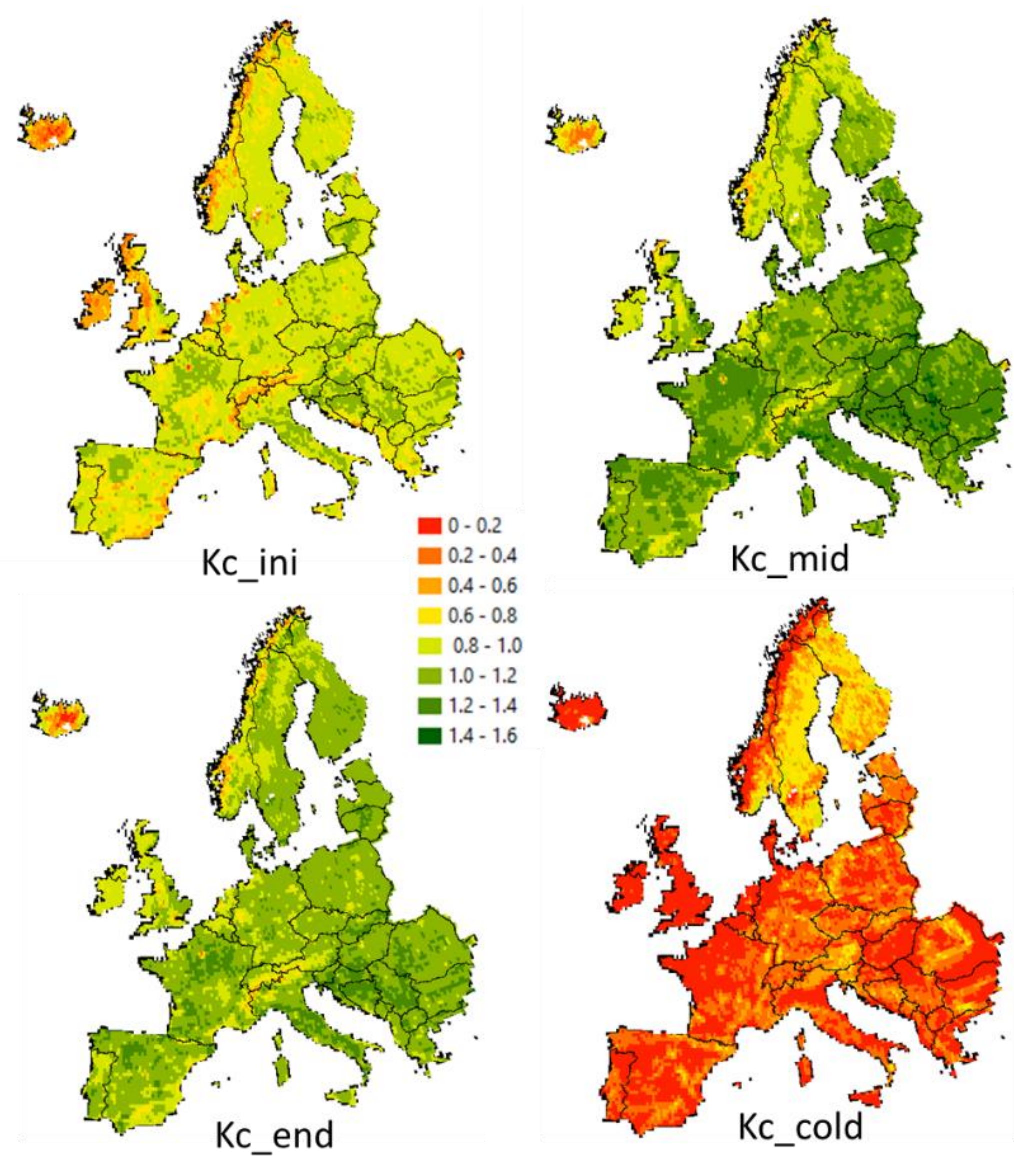


Figure 6: Seasonnal spatialized Kc (0.25° mesh)

EPIR evaluation

Assuming that the EPIR is constant over time, the European map of EPIR has been established taking advantage of a relationship between two indexes related to infiltration: the IDPR and the BFI.

The IDPR Concept

The network development and persistence index (IDPR) (Mardhel et al., 2021) allows qualifying an area in terms of "pathways used" by meteoric water. Rainfall that flows across the surface of natural terrain (because it is not absorbed by plants or subject to direct evaporation) leaves its drainage basin in two different ways:

- It flows along the surface and concentrates in streams and rivers;

- It infiltrates into the subsurface, is concentrated into an aquifer, and leaves the aquifer through an outlet that is often different from that of the river network.

The IDPR provides a qualitative approach to the relationship between these two "pathways". It provides an indication of ability of surface and subsurface formations to promote surface water infiltration or run off toward or away from the underground environment.

The idea behind IDPR comes from the following hypothesis: organization of the hydrographic network depends primarily on the hydrologic and hydrogeologic properties of underlying geologic formations.

Using the hypothesis of a perfectly homogeneous and isotropic medium, only slope and thus landscape morphology will control the emplacement of watercourses. But in the natural environment, geologic structures, the lithological composition of the subsurface, the pedology, and plant cover have a significant influence on the establishment of hydrographic networks. These factors control the permeability and roughness of the surface, which in turn affect runoff velocity and the ratio between flow and infiltration.

Drainage density in an area is thus a revealing indicator of the properties of the geologic formations of which it is composed. A basin composed of highly permeable materials in general will have a low drainage density. Conversely, a basin composed of impermeable but loose and erosive rocks, such as marls and clays, will often have a higher drainage density.

Following this idea, the IDPR calculation is based on a comparison between a theoretical hydrographic network which considers the presence of a river in each thalweg (Development Index) and the natural hydrographic network (Persistence of Networks).

The network development and persistence index (IDPR) used in this study quantifies the offset between an observed natural network that results from complex factors and the theoretical network calculated solely by topography (Figure 7).

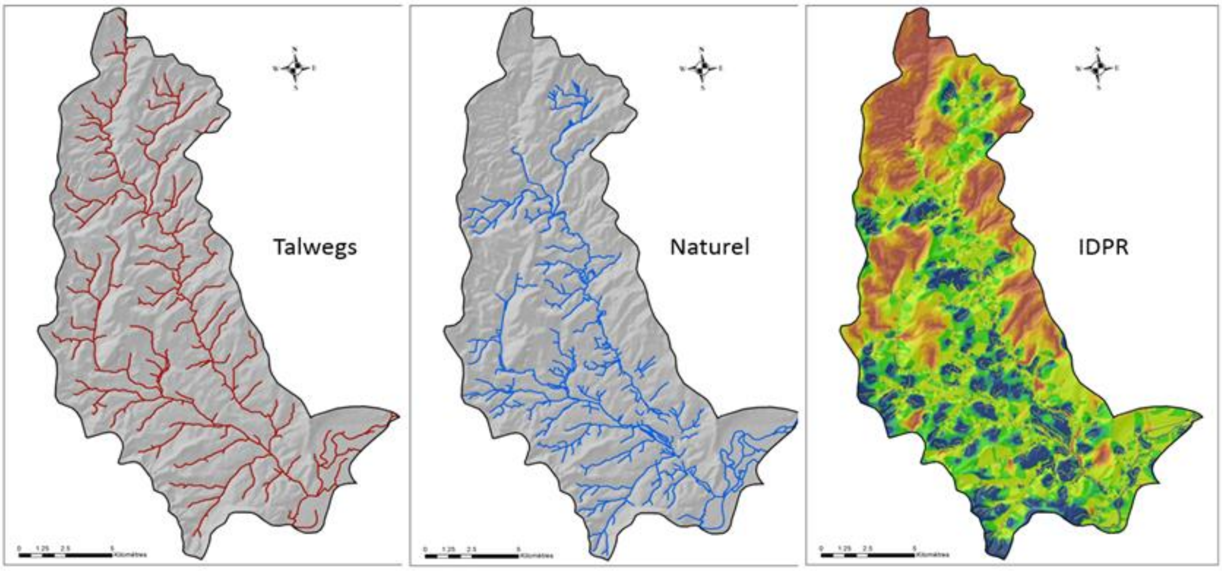


Figure 7: Thalweg network natural, hyrographic network and corresponding IDPR

Hydrographic network

The IDPR method uses as first input the natural hydrologic network digitized according to a river representation deduced from observations of geographers and photo-interpreters. It results from observation of flows (perennial and intermittent) and from transferring the vectorized path of the major bed onto maps that are more of less precise.

It is used in the IDPR calculation process and comes from reference data such as the BD TOPO IGN© or the BD CARTHAGE in metropolitan France.

Both permanent and intermittent river systems can be considered for the calculation of the IDPR. By default, the IDPR refers to the use of the permanent and intermittent network, which accounts for the runoff capacities when flows occur in periods of high water, such as during floods.

Thalweg network natural

A Digital Elevation Model (DEM) is a representation of landforms, of elevation in a form suitable for use by geo-referenced data treatment software. For the IDPR calculation, the digital elevation model is a set of data in the form of grid of points on a square mesh. Each point is labeled with the elevation of the closest point assigned to the grid of which it is the center.

To model valley bottoms on the scale of the French territory, the 25-m resolution BDALTI V2 IGN© database was used. BDALTI V2 IGN© is an elevation database used to derive a range of DEMs and isohypses that describe the relief of the national territory at various resolutions (Figure 8). For the 25-m DEM, the use of several data-acquisition techniques made it possible to improve its precision: Lidar and Radar technology and aerial photography correlation techniques.

Only the altitude is provided "raw" by the DTM. The calculation of slopes, watersheds and talwegs uses spatial processing techniques integrated into Geographic Information System software.

The processing (calculation of talwegs) was carried out with the ArcView© application. They are based on three steps:

- The first uses an algorithm based on the search for "talwegs points". In a window centered on the pixel to be processed, the neighborhood is examined to detect a change in concave slope.

- The second step calculates the "derived graph" of the DTM which assigns to each point the direction of the neighbouring mesh following the greatest slope. This set of "drainage cells" describes a drainage basin when the outlet is located on the edge of the DTM or a "depression basin" when all the paths described by following the cells end in a local minimum.

- Finally, the application dynamically draws lines, starting from certain selected points and following the line of greatest slope until arriving either at the edge of the image, or at a local minimum, or finally until it meets a line already drawn.

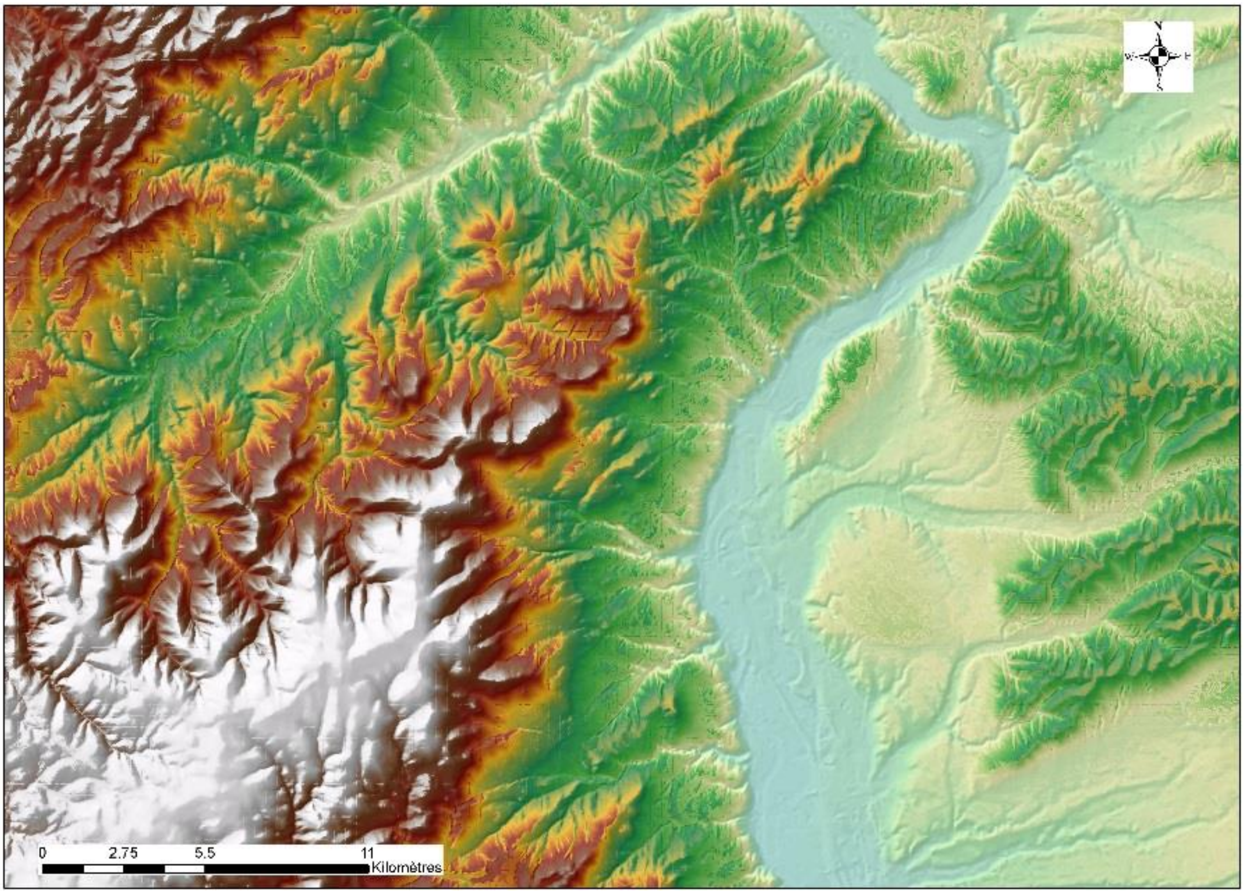


Figure 8: Excerpt from the DTM at 25-metre spacing (BDALTI V2 IGN©)

Slopes traitement

The IDPR is weighted by the natural slope of the land. This operation allows a better restitution of the contrasts between the alluvial valleys and their enclosures (Figure 9).

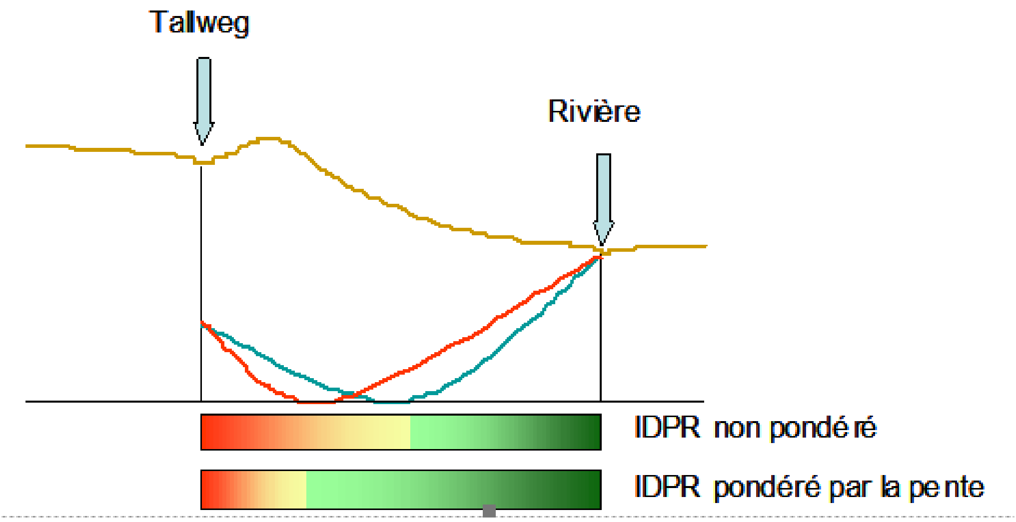


Figure 9: slope weighting

For the calculation of IDPR version 2017, slopes had to be smoothed due to the presence of artifacts in areas of low slope such as coastal areas and valley bottoms (Figure 10). These are introduced by the slope calculation which produces a "terracing" effect. These artifacts are corrected by resizing the slope according to a symmetrical linear transformation mathematical function available in the ARCGIS tools.

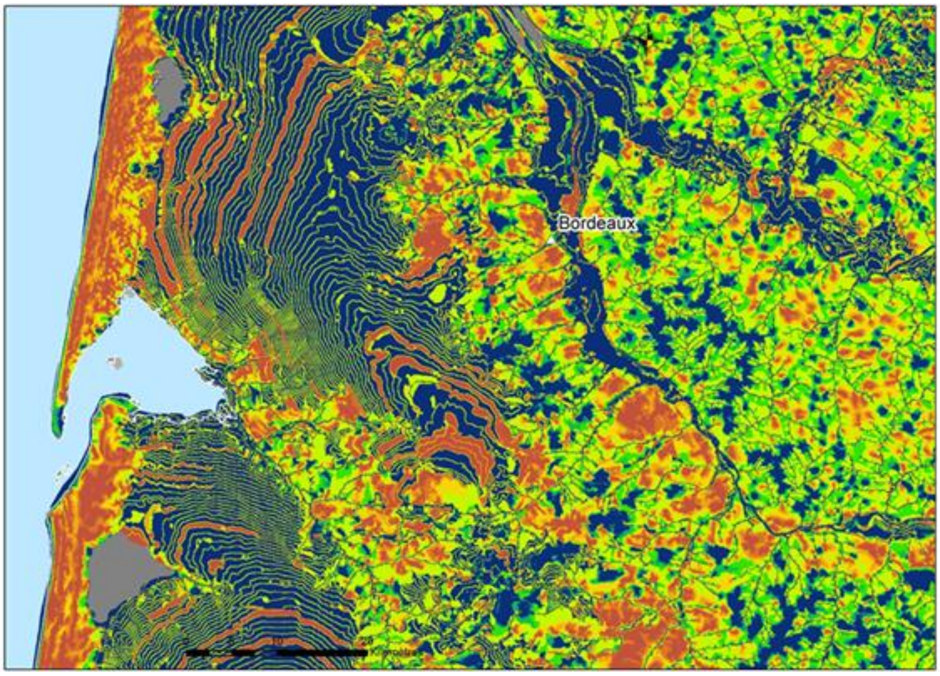


Figure 10: Terrace" effects produced by the slope calculation

Treatment of watercourses and lakes

At the scale of the metropolitan territory, the distribution of IDPR index values ranges from 0 to n, with 99% of the values being less than or equal to 2. By convention, the index calculation is multiplied by 1000 and limited to 2000 to simplify usage and to decrease the volume of data. By simplifying the interpretation (Figure 11):

- The value 0 corresponds to a thalweg for which no watercourse exists,
- The value 1000 corresponds to a thalweg which has a watercourse,
- The value 2000 corresponds to a water zone that is not described by a thalweg (lake).

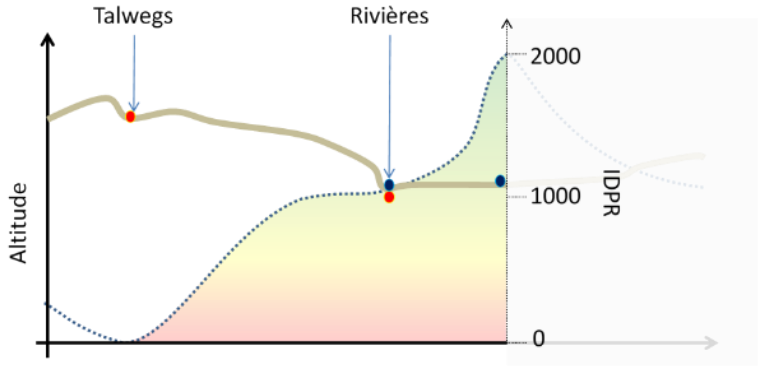


Figure 11: treatment of watercourses and lakes by the IDPR method

A different approach for the bedrock context

In the bedrock zone the IDPR values are usually equal to the value 1000 (Infiltration/Equal Inflow). In this case, the IDPR is not a sufficiently discriminating indicator and is therefore ill-suited in this context. For the calculation of the IDPR (2017), a new method has been applied to the bedrock zones, based mainly on the principle of discontinuity and continuity of the river systems (Desfontaines (1990), Crave (1995), …).

The observation of the longitudinal profiles of rivers located in bedrock areas show rupture zones where land fracturing plays a role (Figure 12). These often flat areas can be assimilated to sectors where infiltration can potentially be favoured .

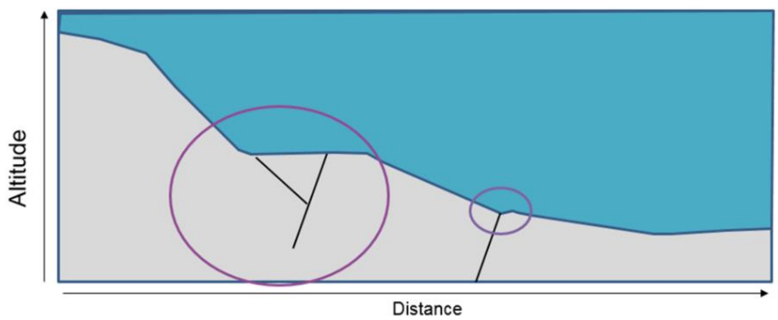


Figure 12: Diagram of a longitudinal profile of a river in the bedrock zone

To detect these rupture zones, geomorphological treatments are carried out with the tools of the Topographic Position Index TPI (Jenness, 2006). Depending on the discontinuity zones found by these tools, the hydrographic network is re-cut and re-injected into the calculation of the IDPR in the bedrock domain only.

European IDPR

The European IDPR was calculated in the framework of the INDECIS project using the following specific european datasets.

The Digital Terrain Model (DTM)

The Digital Terrain Model (DTM) is a representation of the terrain model and altimetry in a form suitable for use by geo-referenced data processing software. For the calculation of the IDPR, the digital terrain model used is a dataset in the form of a grid of square-meshed points. Each point is filled with the average altitude assigned to the mesh of which it is the centre.

In the case of european IDPR, the data used comes from the European Digital Elevation Model (EU-DEM v1.1) made available by Copernicus. The Geoscience Laser Altimeter System (GLAS) instrument onboard the Ice, Cloud, and land Elevation Satellite (ICESat) provides a globally distributed elevation data set that is well-suited to independently evaluate the accuracy of continent-wide digital elevation models (DEMs), such as EU-DEM. EU-DEM is a hybrid product based mainly on SRTM and ASTER GDEM but also public available Russian topographic maps. The EU-DEM v1.1 is a resulting dataset of the EU-DEM v1.0 upgrade which enhances the correction of geo-positioning issues, reducing the number of artefacts, improving the vertical accuracy of EU-DEM using ICESat as reference and ensuring consistency with EU-Hydro public beta. EU-DEM v1.1 is available in Geotiff 32 bits format. It is a contiguous dataset divided into 1000 x 1000 km tiles, at 25m resolution with vertical accuracy: +/- 7 meters RMSE.

The spatial reference system is geographic, lat/lon with horizontal datum ETRS89, ellipsoid GRS80 and vertical datum EVRS2000 with geoid EGG08.

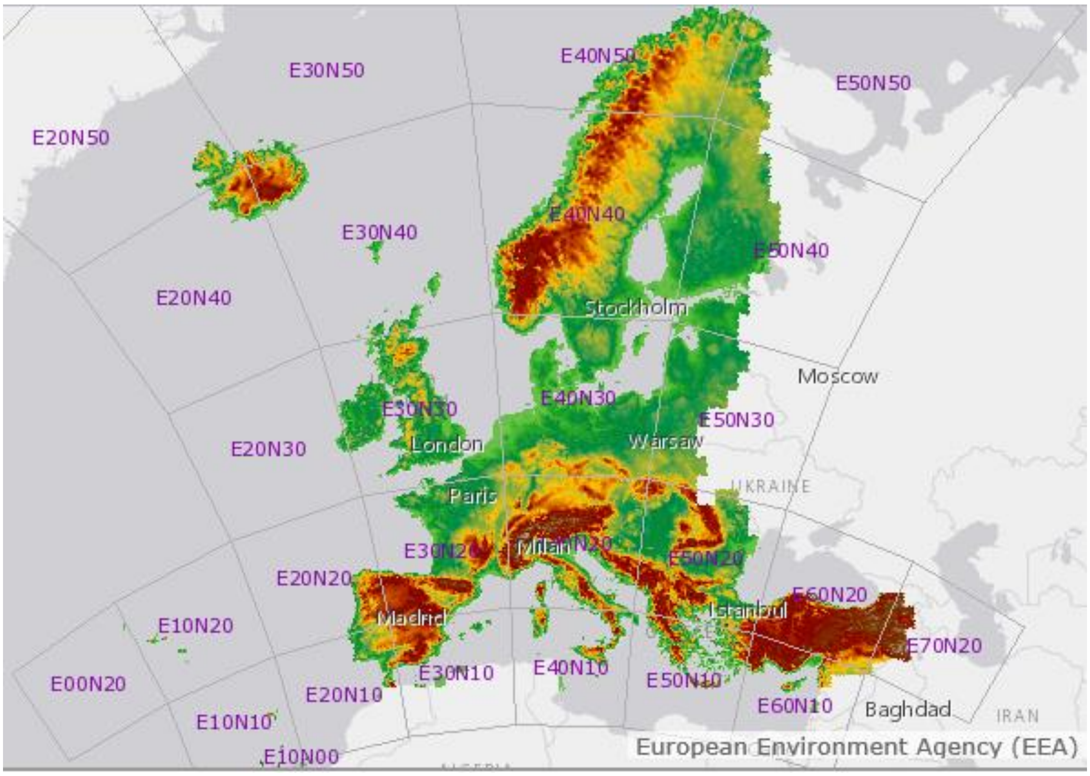


Figure 13: the DTM tiles

The assembly of all the DTM tiles generated a very large file (Figure 13). To optimize the calculation of the European IDPR, the resolution of the DTM was therefore changed from 25 m to 50 m (Figure 14).

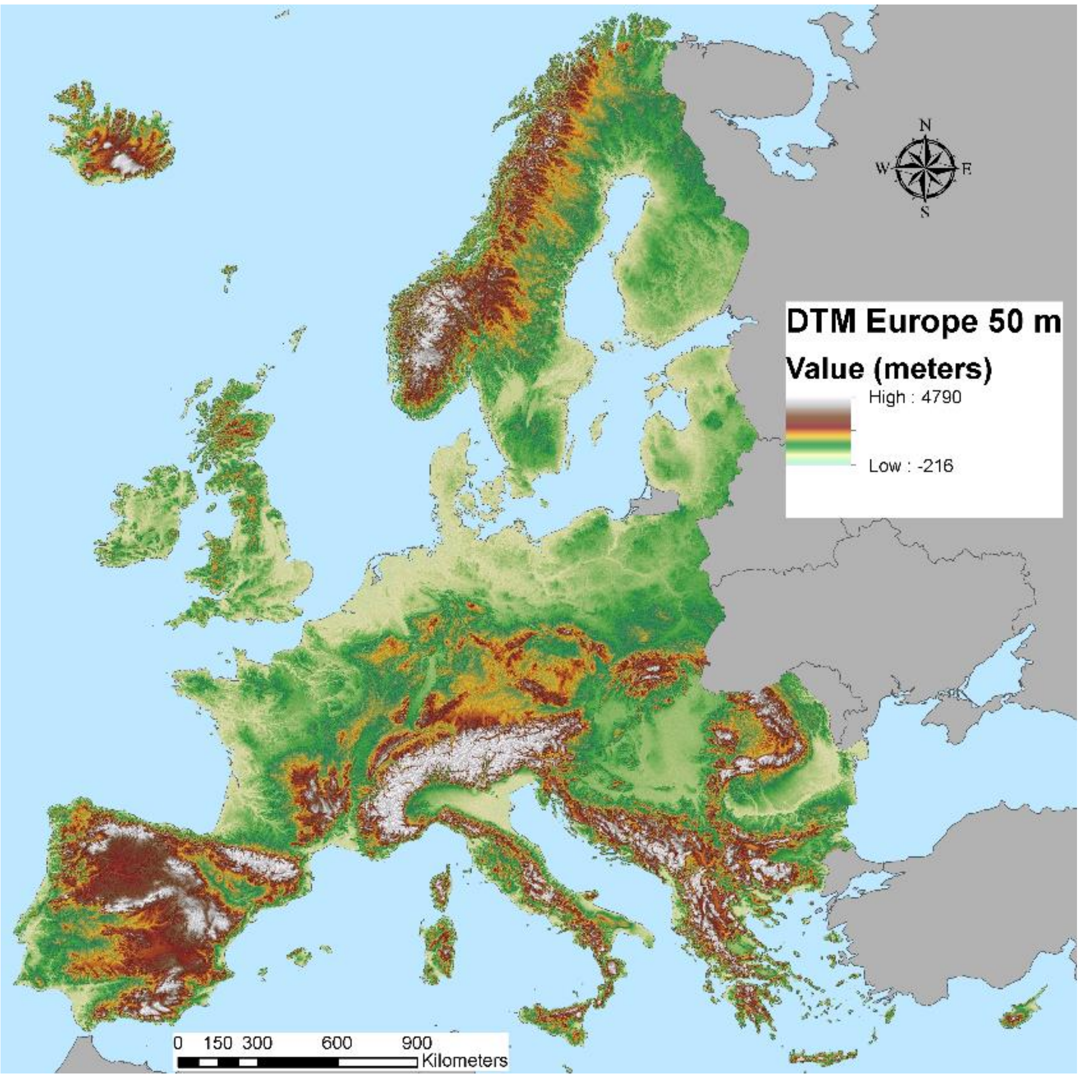
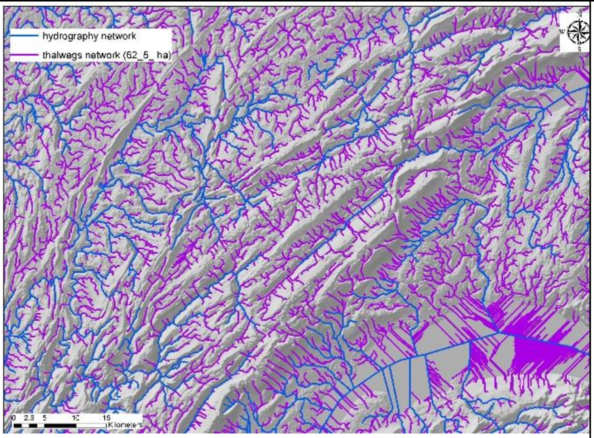


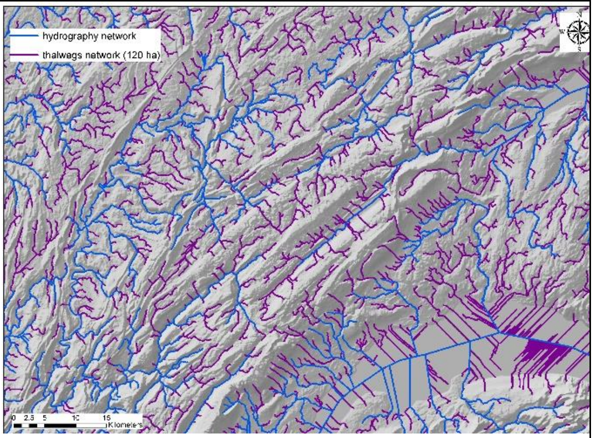
Figure 14: the European DTM (resolution 50 meters)

The thalwegs network

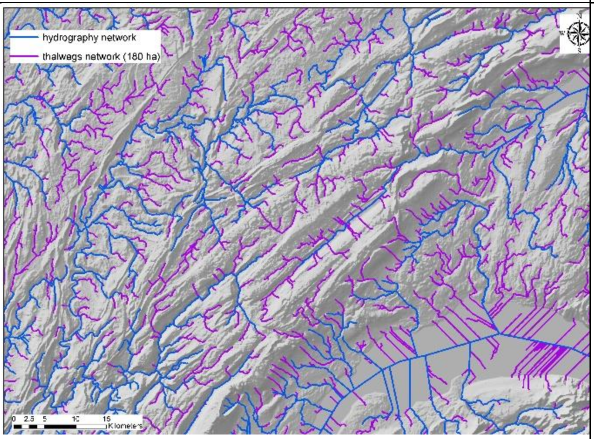
To calculate the theoretical thalweg network from the DEM, the method used is based on the algorithms of Tarboton and distributed by the Environmental Systems Research Institute (ESRI). The calculation processes are simple and can be summarized into a data treatment set largely described in the bibliography available in GIS tools. Some prior treatment is necessary to extract thalwegs, such as searching for depressions or endorheic zones and the overlaying of the natural hydrographic network on the DEM. The calculation tools used are available in the ARCGIS 10.2.2 software (®ESRI). The choice of the accumulation threshold necessary and sufficient to establish the upper end of basins results from a simple statistical analysis of the assumed distribution of sources of the natural river network. These supposed sources correspond to a unique upstream point forming the upstream of the stream trace. Four tests were carried out to determine the optimal size of the elementary watershed used to draw the thalweg network: 62.5, 120, 180 and 360 ha (Figure 15).



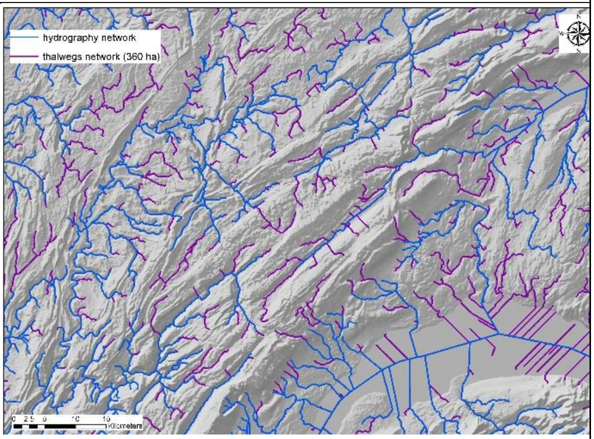
Network thalwegs (62.5 ha)



Network thalwegs (120 ha)



Network thalwegs (180 ha)



Network thalwegs (360ha)

Figure 15: Extracts from the four talwegs networks

With the objective of reproducing an equivalent reality as close as possible to a natural watercourse, the search for a minimal basin surface capable of initiating a water course in an average climate environment like that of the European territory is 360 hectares. The calculated talwegs network is composed of 731 337 separate arcs. The elementary watershed used to initiate the calculation is 1440 cells or 360 hectares (1440 X 2500 m²). The limit constraint of 1440 cells was retained to be said by an expert after analysis of the natural network of rivers. The talweg network produced in this way has a distribution similar to that of the natural network (Figure 15).

The natural hydrographic network

For the calculation of the European IDPR, the natural hydrographic network that was used comes from Pan-European hydrographic dataset EU-Hydro. Pan-European hydrographic dataset EU-Hydro was created in the frame of Preparatory action for Copernicus Reference Data Access (RDA) in 2009-2012. EU-Hydro (also called Hydrographic database, Hydrographic Network or River Network) is a dataset for all EEA39 countries providing photo-interpreted river network, consistent of surface interpretation of water bodies (lakes and wide rivers), and a drainage model (also called Drainage Network), derived from EU-

DEM, with catchments and drainage lines and nodes. The feature data extraction has been performed with imagery from 2006, 2009 and 2012. The dataset is mainly used by Copernicus Land Monitoring Service, and for the assessment of water resources at the European level. The river network was derived from 20 metres resolution imagery and the feature data extraction performed with 2.5 metres resolution imagery. Its resolution scale for linear objects is 1:30,000 and a minimum scale resolution of 1:50,000 for derived polygons.

Content of River Network dataset :

- Culverts: an enclosed channel for carrying a watercourse (for example: a stream, a sewer, or a drain) under another watercourse (for example: a stream, a canal, or a ditch).
- Nodes: a point joining two segments. They are placed on headwaters and mouths of each watercourse, on confluences of watercourses, on inlets and outlets of watercourses into water polygons and in dams derived from ECRINS.
- Canals_l: an artificial waterway with no flow, or a controlled flow, usable or built for navigation.
- Ditches_l: an artificial waterway with no flow, or a controlled flow, usually unlined, used for draining or irrigating land.
- River_Net_l: a naturally flowing watercourse.
- Canals_p: an artificial waterway with no flow, or a controlled flow, usable or built for navigation.
- Ditches_p: an artificial waterway with no flow, or a controlled flow, usually unlined, used for draining or irrigating land.
- River_Net_p: a naturally flowing watercourse (Figure 16).
- InlandWater: a large body of water entirely surrounded by land.
- Transit_p: any water the level of which changes periodically due to tidal action.
- Coastal_p: coastlines and shorelines of these feature class are used as additional feature for orientation to attach inland hydrologic features.
- RiverBasins: is the area that a river drains including its tributaries.

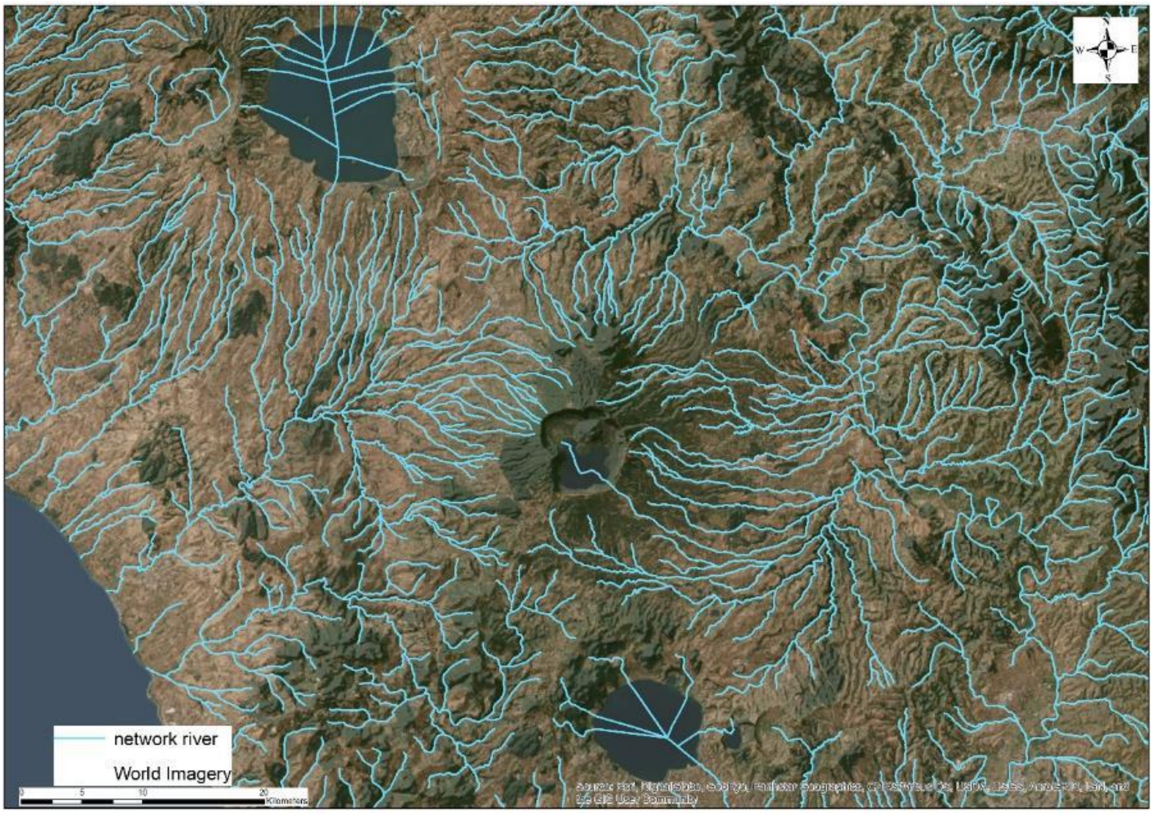


Figure 16: Example of EU-Hydro (River_Net_l)

The TPI method developed for basal areas (paragraph 1.1.4) has not been applied on the European river network. The integrity of this network was therefore used to calculate the IDPR.

Resulting European IDPR

The European IDPR was calculated on the basis of a DTM with a 50 m pitch, talwegs deduced from this DTM and a natural river network. The method developed on the bedrock zones for the last calculation of the French IDPR has not been applied to this scale, and the results of the calculation of this IDPR are shown in Figure 17.

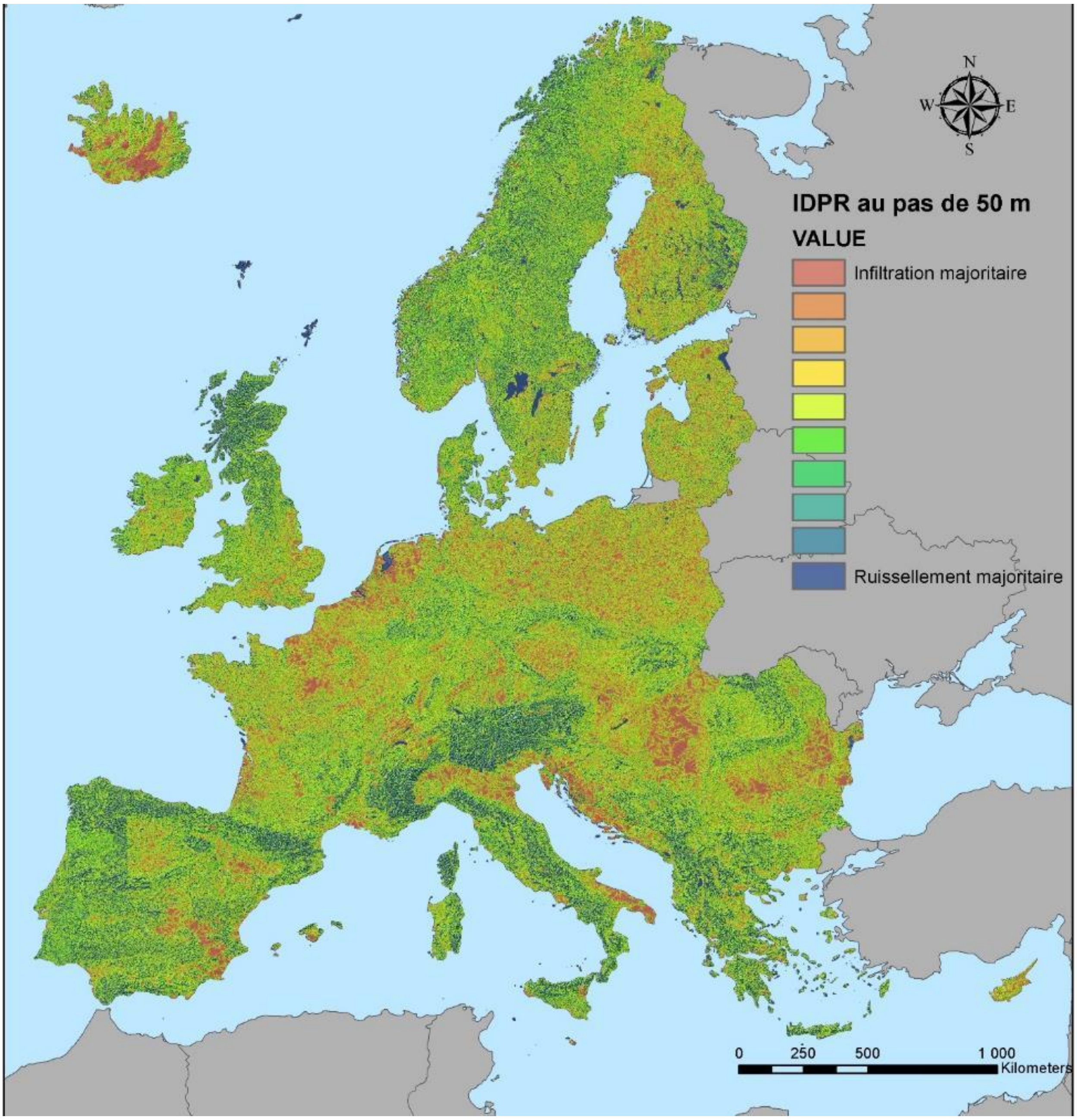


Figure 17: European IDPR calculation (grid with a 50 m spacing)

IDPR proposes new data that can substitute for data linked to soil permeability (surface water) or subsurface permeability (groundwater). This is a simplified approach to characteristics of these environments for which, as we have seen, IDPR qualitatively describes permeability as areas of infiltration and runoff.
The readers guide in Figure 18 provides a key for interpreting the calculated IDPR, considering the entire permanent and intermittent network as flowing.

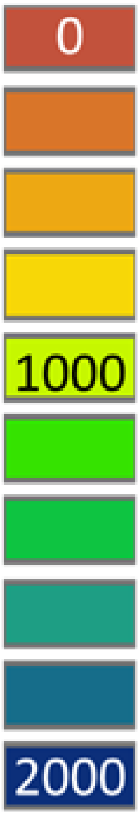
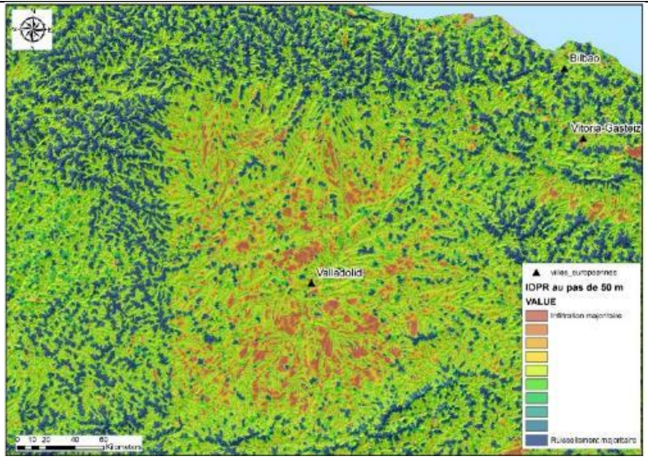
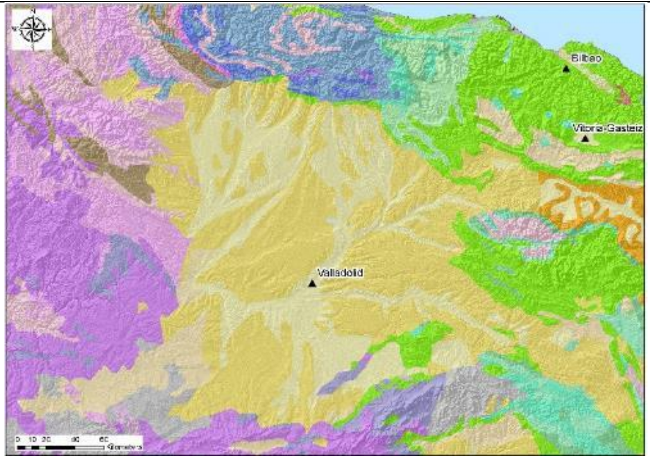
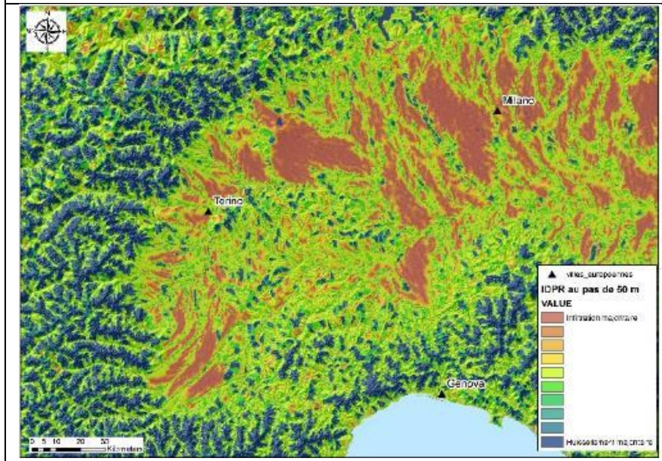
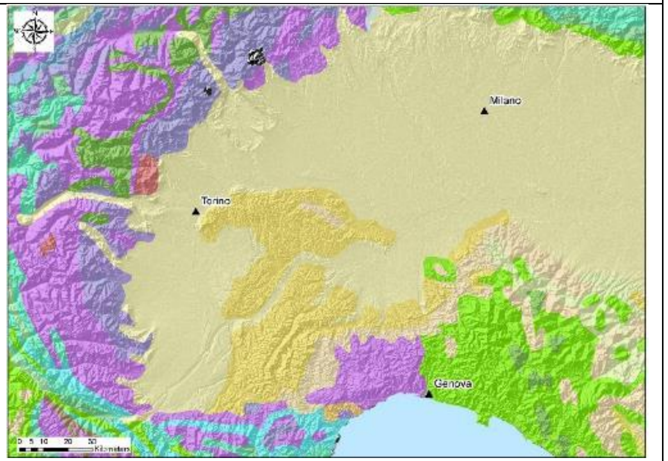
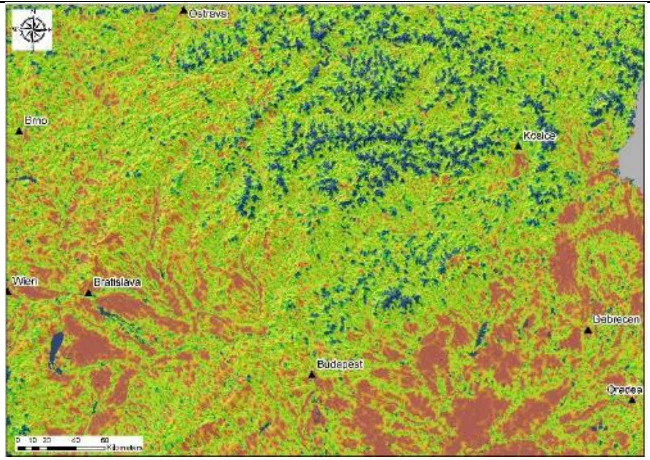
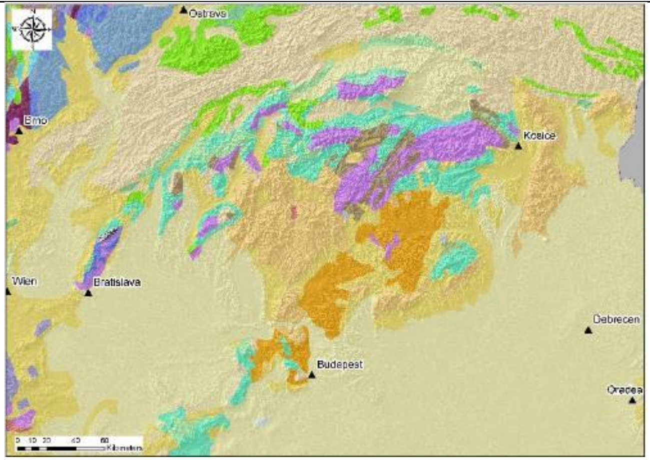
IDPR		Interpretation	
	< 1000	Primarily Infiltration rather than surface runoff	There is non-conformity between the availability of drainage axes linked to thalwegs and observed hydrologic axes. Runoff on natural terrain joins a drainage axis defined by thalweg analysis without showing a concrete expression of a natural hydrologic axis. Development of a thalweg network of higher density than the expression of the natural drainage network.
	= 1000	Infiltration and surface runoff of equal importance	There is conformity between the availability of drainage axes linked to thalweg and in-place flows.
	> 1000	Primarily surface runoff as compared to infiltration toward the subsurface.	Runoff on natural terrain rapidly joins a natural hydrologic axis without its presence being directly justified by a thalweg.
	> 2000	Primarily comparable to a wet environment.	Transitory or permanent water stagnation, which leads to two different interpretations. If the water-bearing layer is near the natural ground surface (watercourses and humid zones), the land is saturated and water will not infiltrate. If the waterbearing layer is deep, the flowing nature may demonstrate impermeability of natural terrain. We offer the hypothesis that IDPR values higher than 2000 are primarily applicable to wet environments (possibility of flooding by the hydraulic barrier effect).

Figure 18: IDPR Reader's Guide (ZNS: UNZ = unsaturated zone)

At larger scales, IDPR also reproduces lithology changes and a comparison of the European IDPR map with the European geological map reveals many correspondences between infiltration or runoff zones with geological contours already established elsewhere (Figure 19). The calculation of IDPR is based on two inputs: the natural hydrographic network and the digital terrain model. The quality of these data is therefore essential to obtain results that are as consistent as possible with the field data.

		
European IDPR (spacing 50 m) SPAIN	Extract of European Geology map (USGS) 1/5 000 000 Spain	
		
European IDPR (spacing 50 m) ITALY	Extract of European Geology map (USGS) 1/5 000 000 - Italy	Legend of European Geology map (USGS)

		
European IDPR (spacing 50 m) Slovakia / Hungary	Extract of European Geology map (USGS) 1/5 000 000 Slovakia / Hungary	

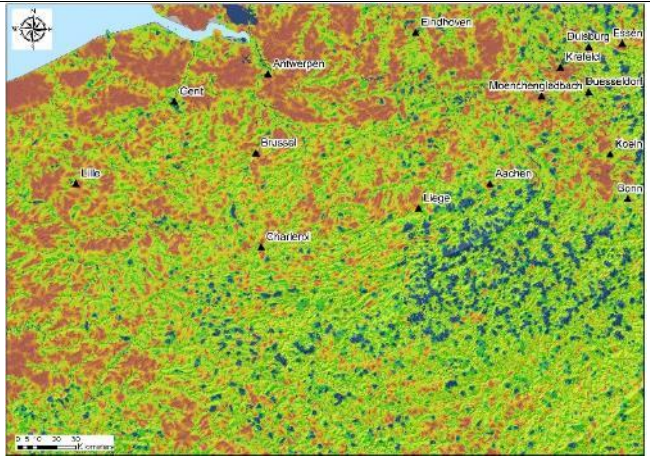
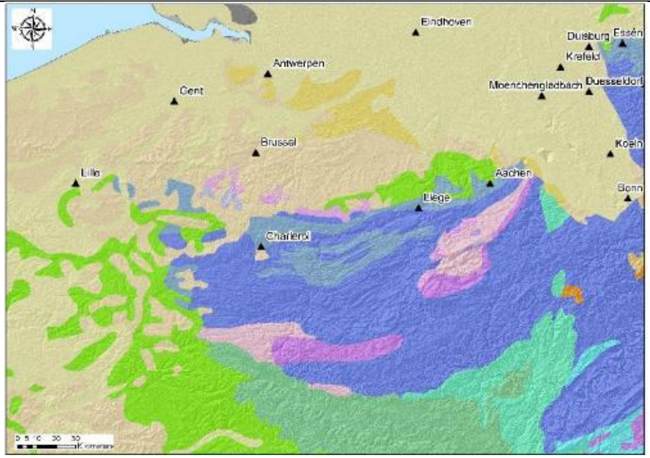
		
European IDPR (spacing 50 m) Belgium / Deutschland	Extract of European Geology map (USGS) 1/5 000 000 / Belgium/Deutschand	Legend of European Geology map (USGS)

Figure 19: Comparison between European IDPR and Extract of European Geology map (USGS).

Linking IDPR and BFI

The baseflow is defined as the delayed contribution to river flow that is not related to direct runoff. It can be calculated from rivers discharge data by applying hydrograph separation algorithms, such as those proposed by the Wallingford Institute (see e.g. Gustard, 2008) or Lyne and Hollick (1979). The baseflow index (BFI) is the long-term ratio of the baseflow to the total stream flow. For undisturbed hydrogeological basins, with no inter-basins lateral exchanges nor vertical leakage, and at an annual scale (negligible storage), the **BFI appears to be a fair proxy of the EPIR**. Obviously, the BFI is only available on gauged watersheds.

A first survey has been conducted by BRGM over 376 gauged river basins distributed over France, for which discharges data are known to be undisturbed by pumping or dams. The mean interannual BFI over the 1981 – 2010 period was computed. At the meantime, the spatial average of the IDPR over the watersheds was calculated. Correlation between the two datasets were found, especially when sorting the basins according to their lithology (Lanini et al., 2019). In order to work at the European scale, the study was extended within the INDECIS project. Data for pirenean catchments were provided by the PIRAGA european project. Data for 72 other european basins come from GRDC (https://www.bafg.de/GRDC/EN/Home/homepage_node.html). In most cases, daily data were available at least over the 1981-2010 period. Finally, 500 gauged watersheds distributed over France and Europe, and representing various geological and climatic contexts were included. For all these watersheds, BFI were calculated with the Wallingford method. The european IDPR with 50m resolution was spatially averaged over all the hydrogeological units defined by the International Hydrogeological Map of Europe (IHME1500, scale 1:1500000) (Duscher et al., 2015).

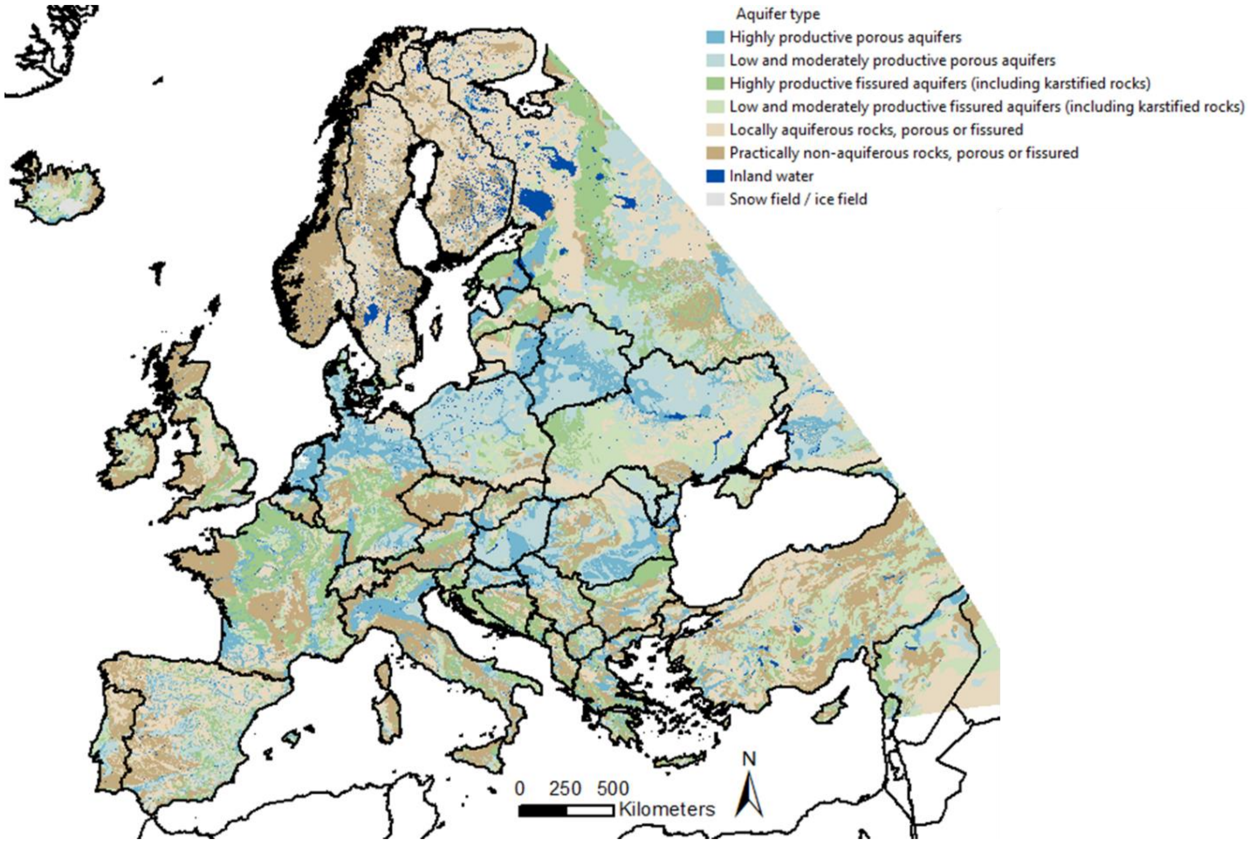


Figure 20: IHME Aquifer type map (data dowloaded from IHME1500_V1.2 website: https://www.bgr.bund.de/ihme1500).

Then a quantile regression was applied to produce the best linear fit between the two datasets that allows to reproduce the statistical distribution of BFI. Thus, the following relationship estimates BFI for the 500 gauged basins with a mean absolute error of 23.6% (Figure 21 and Figure 22).

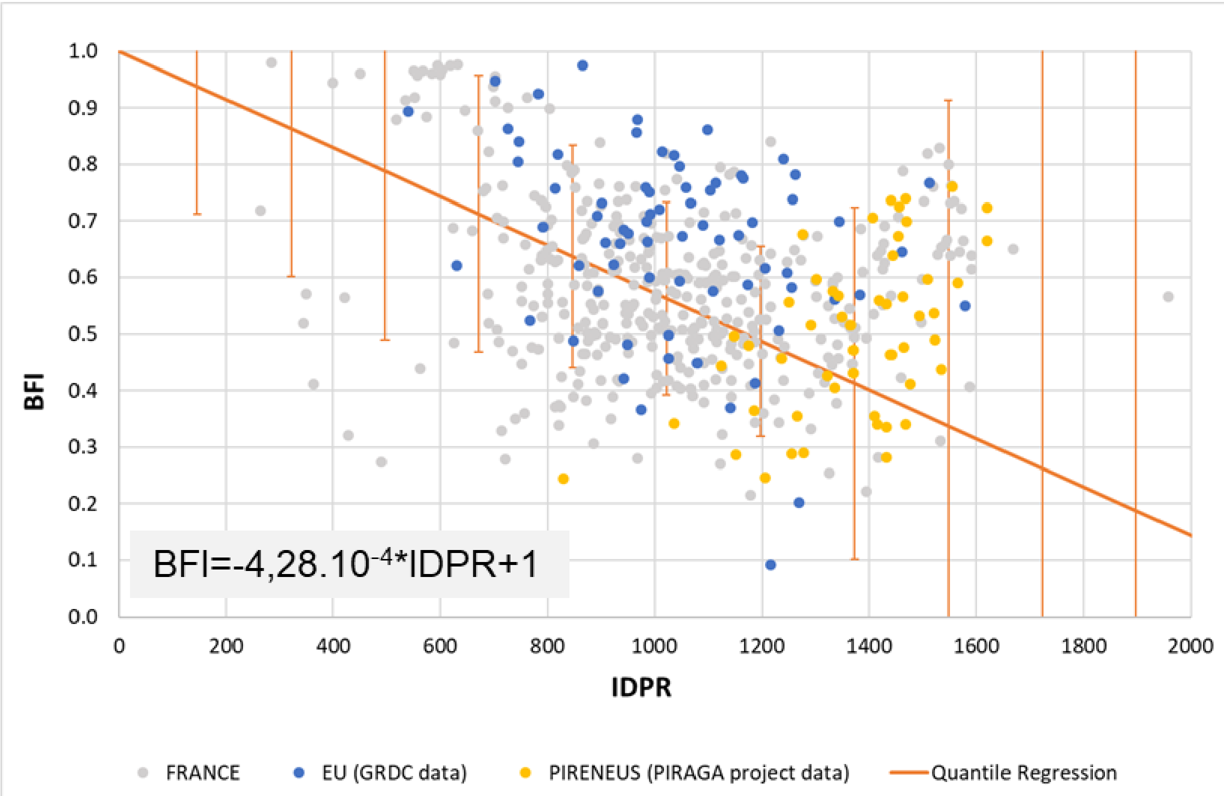


Figure 21: Quantile regression between BFI and mean IDPR over 500 european watersheds

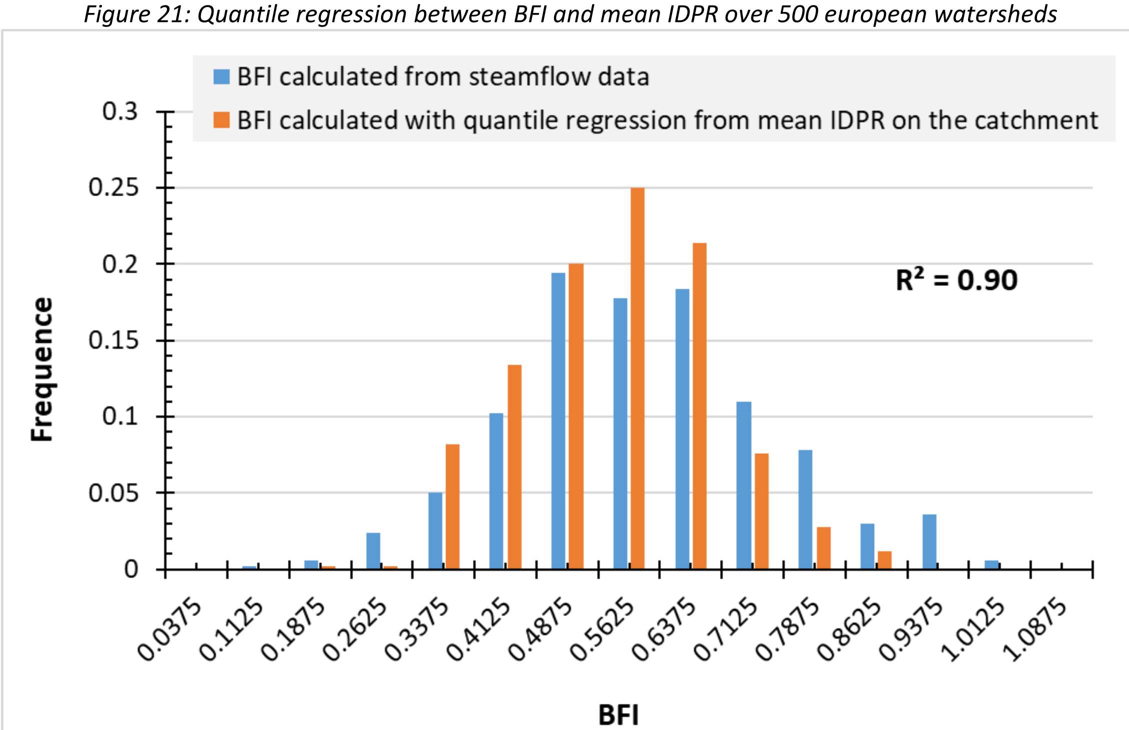


Figure 22: Observed and calculated distribution of BFI over the 500 gauged watersheds

Results

European effective precipitation

The daily effective precipitation was first computed using the E-OBS daily gridded dataset presented in Figure 2, SWS capacity and seasonnal Kc maps presented in Figure 5 and Figure 6 respectively, for the 1950-2017 period, on a 0.25° regular grid, following the method presented in Figure 4. The resulting mean annual effective precipitation map for the Europe averaged over the 1980-2010 period is presented in Figure 23 (up, left). The mean effective precipitation value averaged over the modelling domain is around 340 mm/year. Lower values ranging between 10 and 50 mm are obtained over eastern Spain, Poland, Czesch Republic, Hungary and eastern Romania. Higher values ranging between 2000 and 3000 mm/year are obtained over western Norway and Scotland.

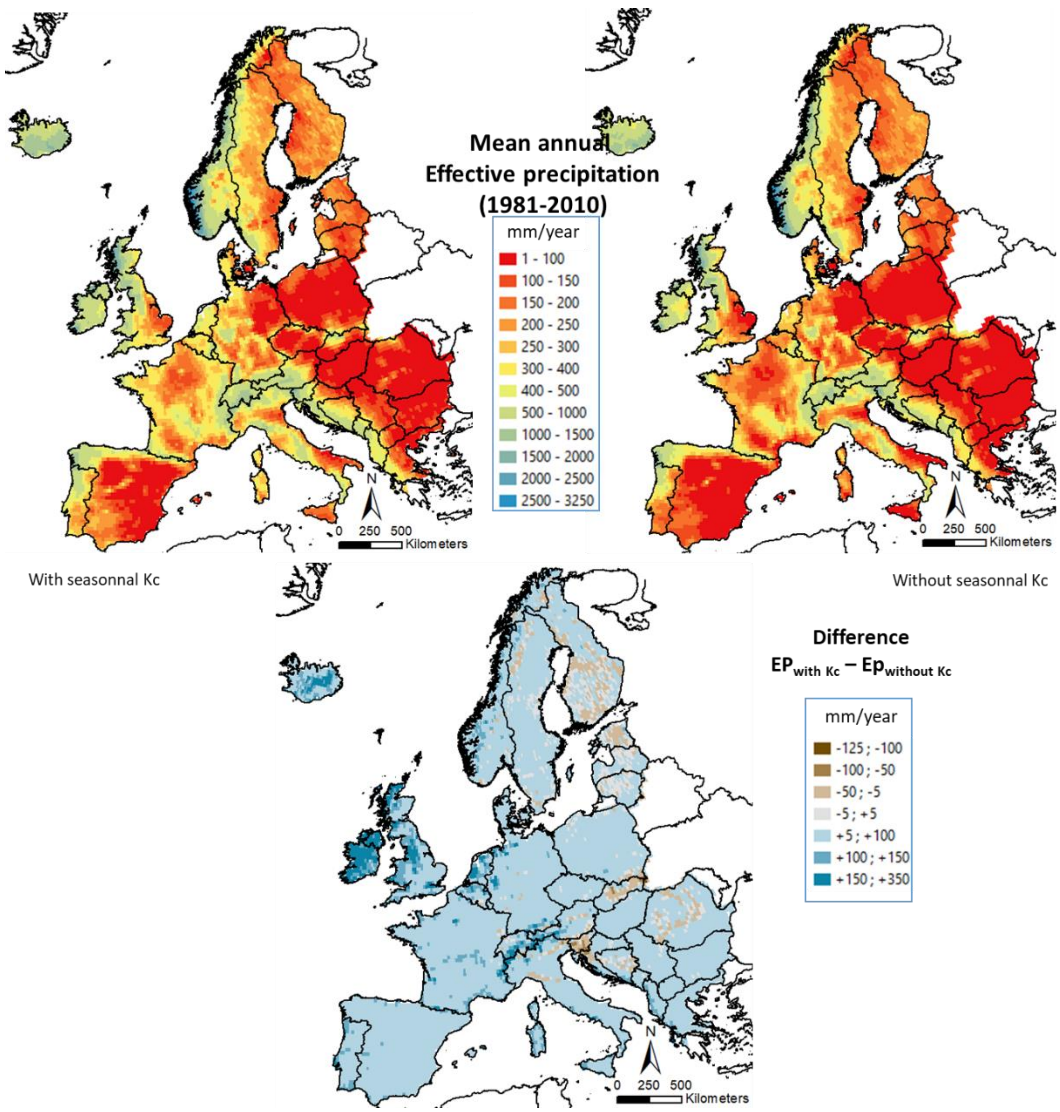


Figure 23: Annual mean effective precipitation over Europe and iInfluence of the land cover (using seasonnal Kc).

Accounting for land cover influence on the estimation of the effective precipitation using seasonnal crop coefficients has a strong influence, generally leading to higher values (difference ranging between +10 mm/year and +100 mm/year globally over most of Europe and even higher over the United Kingdom, Figure 23, down) compared to the computation without considering it (Figure 23, up, right). Locally, lower values of effective precipitation can be computed (not exceeding – 125 mm/year) considering seasonnal Kc, over the eastern (Romania, Slovakia, Croatia and Slovenia) and the northern (Sweden, Finland, Estonia, Lithuania, Latvia) Europe.

European EPIR map

Assuming that BFI is a good proxy of EPIR, the relationship presented in Figure 21 allowed converting the IDPR map into an EPIR map (Figure 24), at the spatial resolution of hydrogeological unit scale presented in Figure 20. EPIR values range between 0.15 and 0.9 with a mean value of 0.52 and close to 90% of the groundwater bodies have EPIR values lower than 0.65. The Pyrenean, Cantabric, Alpine, Corsican and Scotish Highlands mountain chains clearly stand out in the map with EPIR values generally lower than 0.4.

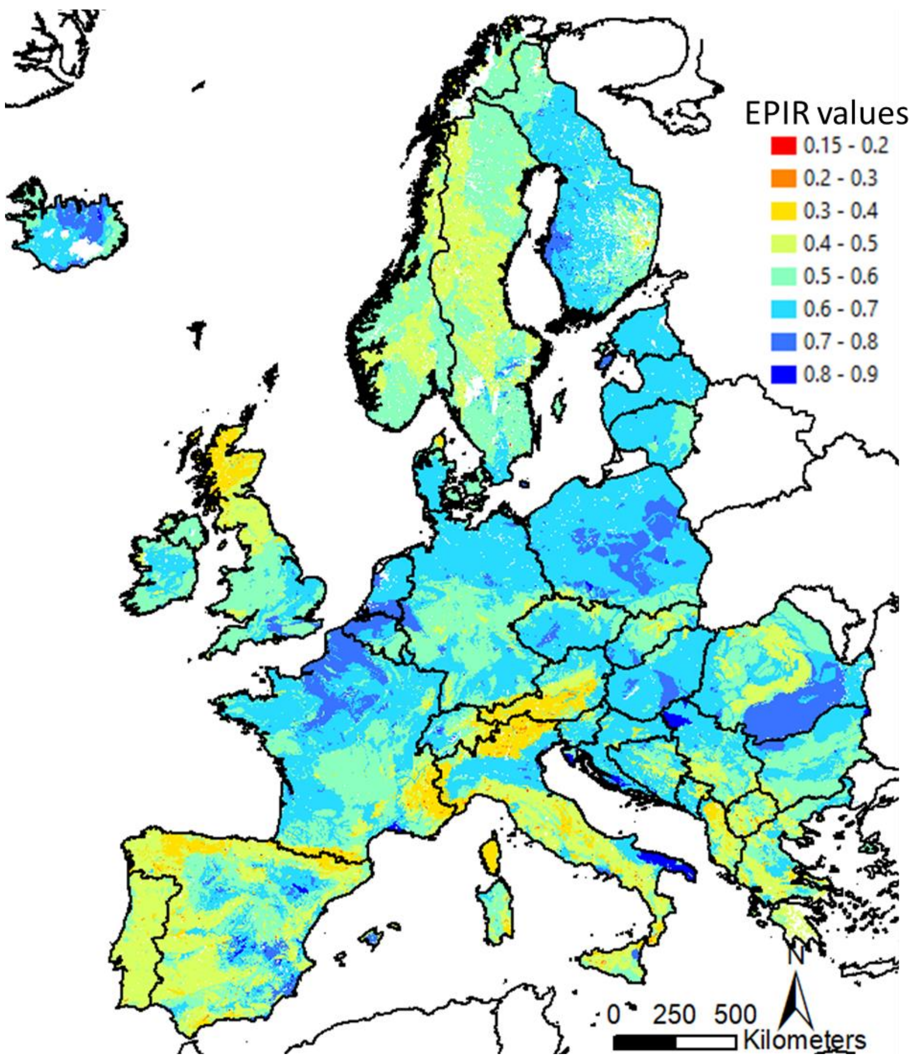


Figure 24: European EPIR (Effective Precipitation Infiltration Ratio) map (hydrogeological unit scale).

Present potential groundwater recharge

Using the European EPIR map, it is posible to compute the dialy potential groundwater recharge from the daily effective precipitation. The resulting mean annual groundwater potential recharge map averaged over the 1981-2010 period, representative of the present situation for Europe is presented in Figure 25. The potential recharge is computed at the IHME groundwater bodies scale (Figure 20) and the resulting values range between 2 mm/year and 2550 mm/year and the average value at the european scale is 180 mm/year. 90% of the IHME groundwater bodies present values lower than 400 mm/year as higher potential recharge values are computed solely over western Norway, Iceland, Ireland, Scotland, northwestern of the Iberian peninsula and over the Alpine mountain chain.

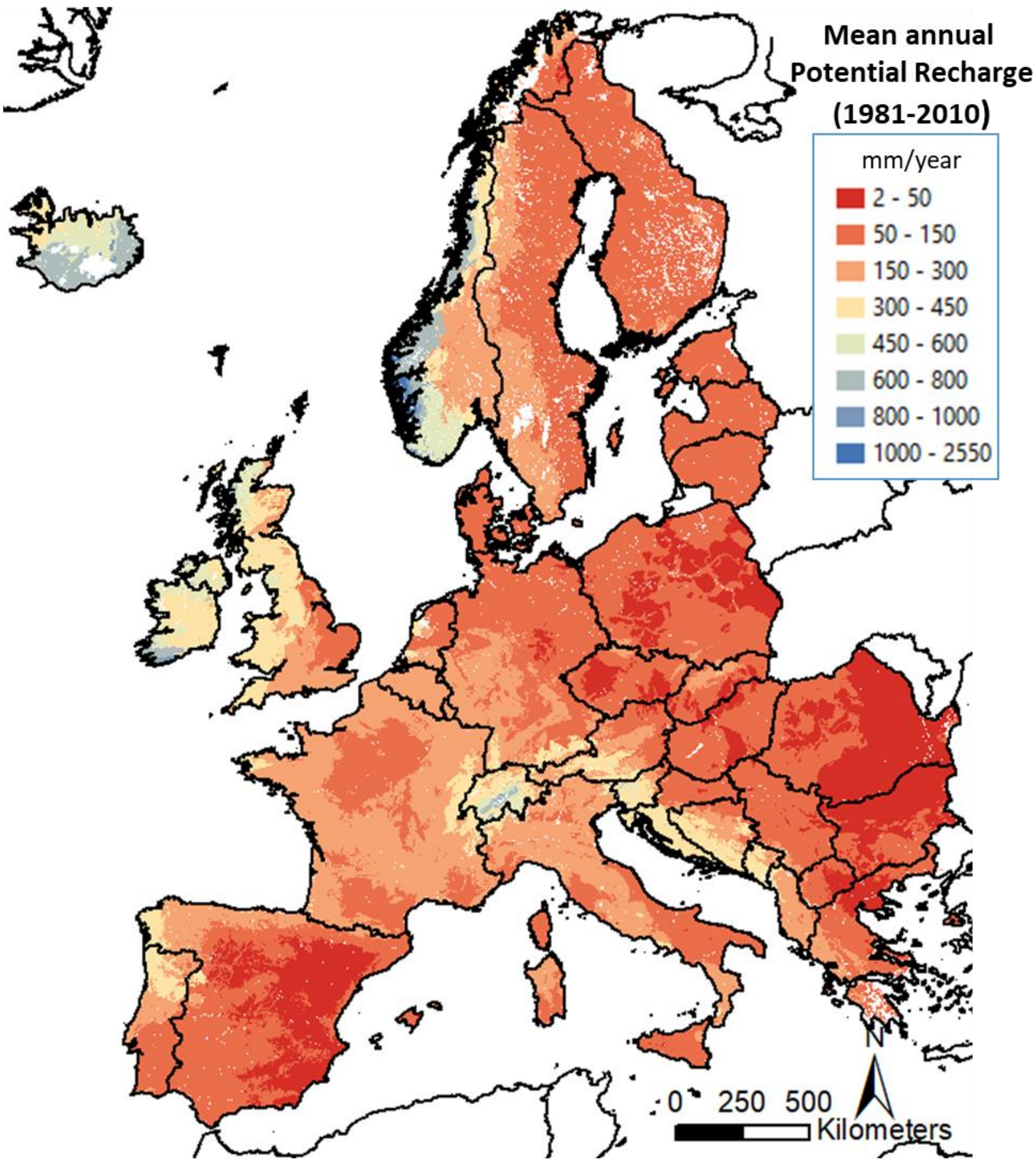


Figure 25: European Potential grounwater recharge map (1981-2010, hydrogeological unit scale)

Future potential groundwater recharge

To explore the future evolution of potential groundwater recharge under climate change, future climate projections from Regional Climate Model (RCM) simulations from the EURO-CORDEX project (Jacob et al. 2020) were used. Projections of GCM/RCM simulated climate variables (p, ta, u10m, rlds, rhds and huss) were bias corrected using the empirical quantile mapping (EQM) bias correction method of the Climate4R package (Iturbide et al., 2019) developed by the Santander Meteorology Group. EQM is a widespread bias correction technique which adjusts empirical cumulative distribution function of modeled data to the observed climatologies. Precipitation (p) and temperature (ta) were bias corrected from E-OBS 0.25° gridded dataset V17 considering the reference period 1979-2005. The remaining variables, required to calculate the Penman-Monteith evapotranspiration but not provided by E-OBS, were bias corrected using WFDEI meteorological forcing dataset (Weedon et al., 2014) over the reference period 1979-2005. The 6 climate projections were used to force the computation of the effective precipitation over Europe using 3 water budget methods leading to a 18 members ensemble simulation. Using the EPIR values considered as constant in the future, the mean annual future potential groundwater recharge was computed.

Different kind of results are presented :

- Inter-annual mean potential groundwater recharge maps for two future periods (2040-2059 and 2080-2099) called respectively 2050 and 2090 horizon (Figure 26) ;
- Maps of relative differences between future potential groundwater recharge and the one for the reference period 1986-2005. These indicators are called potential recharge anomalies, and are calculated for the 2050 and 2090 horizons (Figure 27).

Results for 2050 would lead to an increase of the yearly potential groundwater recharge (+14% on average over the computed domain), positive anomalies beeing projected for almost all european countries except the Iberian peninsula, Italy and Bosnia, Montenegro, Albany and Greece. For those countries however, potential groundwater recharge decreases are projected, that could be severe and reach anomalies lower than -20% (South of Spain, South of Sardinia, Sicilia and Greece).

For 2090, the projected upward trend of annual potential groundwater recharge would remain at the European scale, with a slightly lower mean impact (+12% on average over the computed domain) but with a higher dispersion compared to 2050. For 2090, a large part of southern Europe (south of the Alpine mountain chains, including it) would present negative anomalies of potential recharge compared to present period. The most severe situations would be projected for the south of Spain, Sardinia and Sicilia with negative anomalies ranging between -50% and -80%. To the north of the Alpes, an increase of the potential groundwater recharge would be projected, with values ranging between +50% and +80% from Germany and poland to the north of Europe. It should be noted that such strong increasing trend would also be locally projected in the northeastern Spain (with anomalies higher than +50%), probably due to the very low values of potential grounwater recharge computed on this area, a variation of wich could lead to high anomaly values.

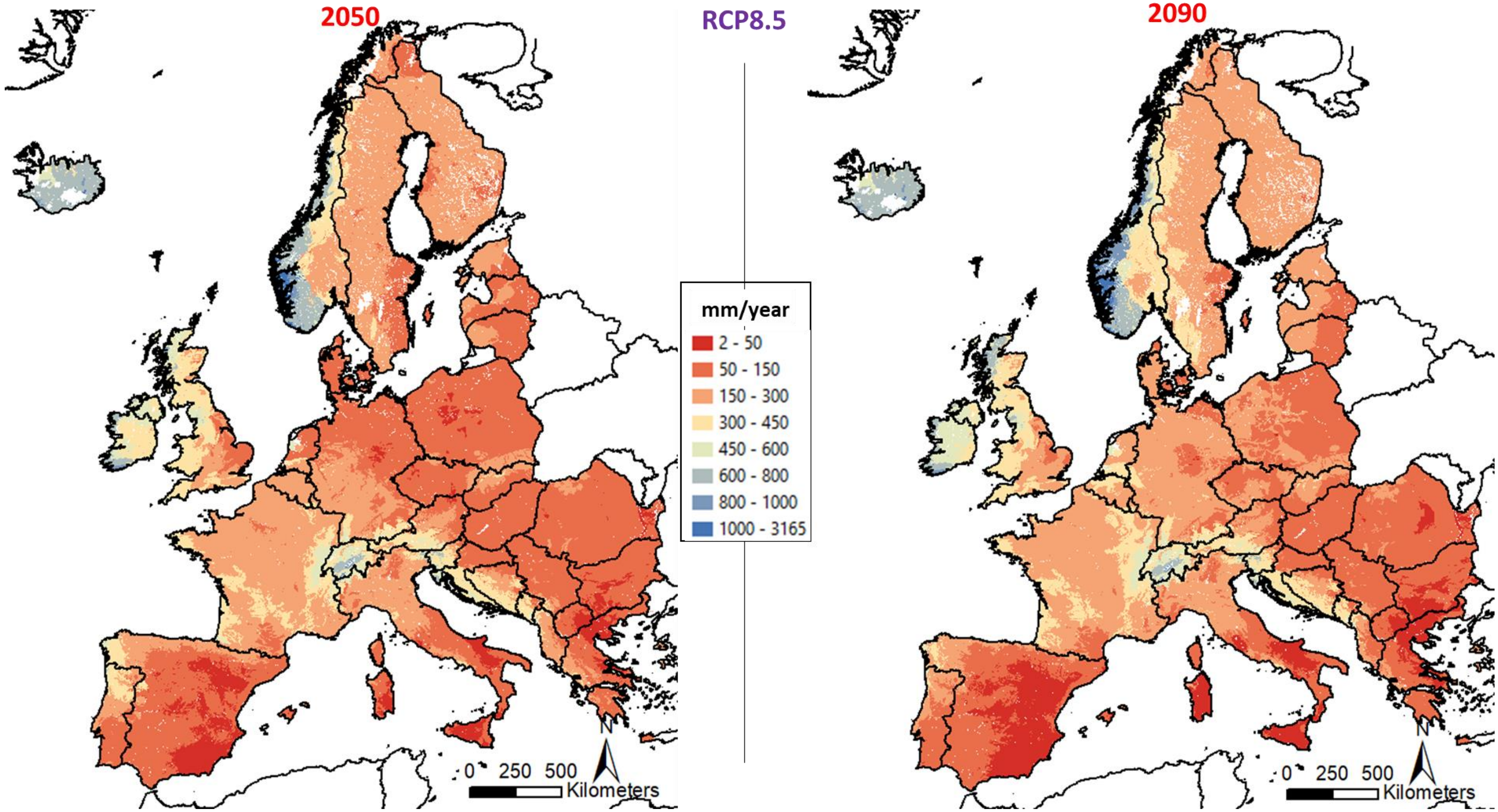


Figure 26: Future potential yearly grounwater recharge maps (RCP8.5 scenario, 2050 and 2090 horizons, hydrogeological scale) for Europe.

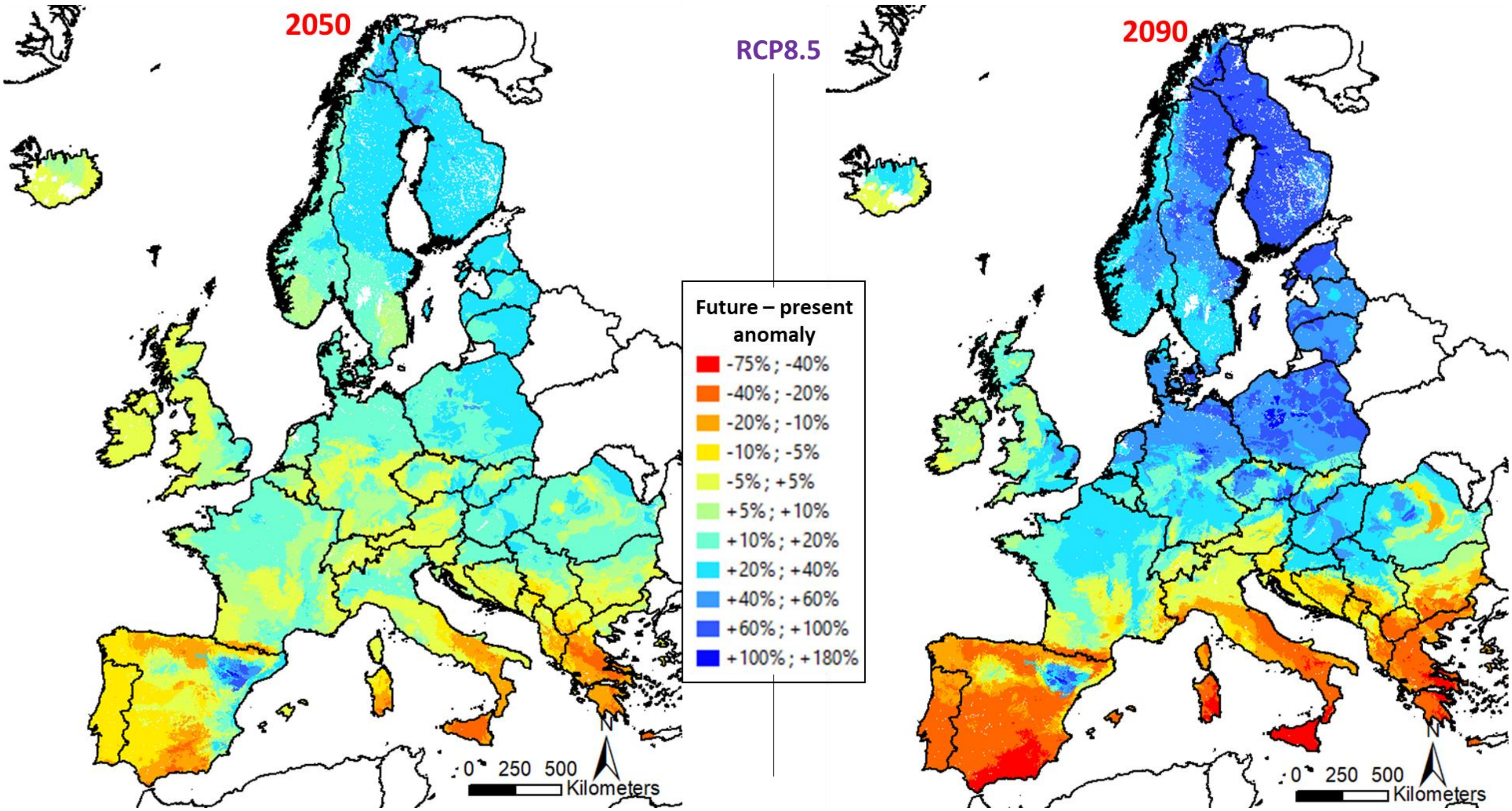


Figure 27: Mean annual potential groundwater recharge anomalies compared to the 1986-2005 reference period.

Conclusions

Potential groundwater recharge has been computed over Europe in the framework of Workpackage 6 of the INDECIS project. Based on meteorological forcing data from E-OBS daily gridded observational dataset (Cornes et al., 2018), effective precipitation has been computed over the E-OBS 0.25° grid using simple water balance methods. The main parameters of the water balance computation are the Soil Water Storage Capacity and the seasonnal Kc coefficient maps accounting for land cover influence on evapotranspiration. An infiltration coefficient (EPIR) has been derived at scale of the IHME 1500 groundwater bodies of Europe by linking the BFI values computed on river discharges to the mean IDPR values of corresponding river basins. Applying the EPIR to the daily effective precipitation allowed computing the potential groundwater recharge for the groundwater bodies of Europe.

Climate projections taken from EURO-CORDEX under RCP8.5 scenario allowed exploring the future situation of potential groundwater recharge. Results show that the chosen projections would lead to an increasing trend at the scale of the whole domain for the end of the century compared to present situation. However, this global trend would mask different evolutions between the north and south of Europe, resulting in important increases (respectively decreases) in the north (respectively in the south).

The computed present and future daily time series of potential groundwater recharge together with the corresponding maps would be of interest to groundwater managers over Europe and could be easely provided and shared through climate services platforms to be developped in the near future.

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